A Component of the U.S. Global Change Research Program

GLOBEC: Southern Ocean Program GLOBEC Workshop on Southern Ocean Marine Animal Populations and Climate Change

U.S. Global Ocean Ecosystems Dynamics

Report Number 5

November 1991

U.S. GLOBEC

Global Ocean Ecosystems Dynamics

A Component of the U.S. Global Change Research Program

GLOBEC: Southern Ocean Program
GLOBEC Workshop on Southern Ocean Marine Animal Populations and Climate Change

Report Number 5

November 1991

This is a report of the U.S. GLOBEC Workshop on Southern Ocean Marine Animal Populations and Climate Change held at Scripps Institution of Oceanography, La Jolla, California, USA on May 9-11, 1991 -- Mark Huntley and Eileen Hofmann, convenors. The workshop and publication were jointly supported by the National Science Foundation and National Oceanic and Atmospheric Administration under NSF Grant OCE90-06957.

Produced by

Joint Oceanographic Institutions Incorporated
1755 Massachusetts Avenue, NW, Suite 800
Washington, DC 20036-2102
phone: (202) 232-3900
tax: (202) 232-8203
telemail: JOI.Inc/OMNET

Additional copies of this report may be obtained from JOI Inc.

Table of Contents

Preface

From 9 to 11 May 1991 a workshop entitled "GLOBEC: Marine Animal Populations and Climate Change in the Southern Ocean" was held at Scripps Institution of Oceanography. Funding for the workshop was provided by the U.S. National Science Foundation and the National Oceanic and Atmospheric Administration-National Marine Fisheries Service. This workshop was one in a series convened as part of the Global Ocean Ecosystems Dynamics (GLOBEC) initiative, which has as its general objective the understanding of processes relating to and controlling variability in marine populations.

The Southern Ocean workshop brought together approximately 40 scientists from 10 countries to develop a science plan that can be used to outline a GLOBECrelated study in the Antarctic. The first day of the workshop consisted of a series of plenary talks that provided overviews on zooplankton, fish, and benthic populations of the Antarctic. Also included were overview presentations on the Fine Resolution Antarctic Model (FRAM), physical oceanography, regional circulation effects on biological distributions, ice cover trends and the paleocirculation/climate of the Antarctic. Following the plenary presentations, workshop participants separated into eight working groups. Discussions of the working groups centered around issues relating to physics and climate, zooplankton and krill, benthos, top predators, modeling, physiological rates, new technology and population dynamics.

From the plenary presentations and working group discussions, it was apparent that the annual retreat and formation of pack ice may be the major determinant of spatial and temporal changes in the structure and function of Antarctic marine communities. Thus, it was recognized that there is a critical need for austral winter observations of populations in the Antarctic and that any study must be of sufficient duration to include several ice cover cycles. In particular, observations are needed for Antarctic krill *(Euphausia superba)* and the salp *(Salpa thompsoni),* which were identified as the key target species. Other suggested target species included a commercially harvested species (e.g. *Champsocephalus gunnari),* a nonharvested holopelagic species (e.g. *Pleurogramma antarctica)* and nonharvested near-shore species (e.g. *Notothenia neglecta).* Other top predators, such as a variety of penguin species, the crab-eater seal and the Antarctic fur seal were recognized to be very important and recommendations were made to include these in a GLOBEC Southern Ocean program.

The consensus of the workshop participants was that a GLOBEC-sponsored initiative be planned for the eastern Bellingshausen Sea adjacent to the Antarctic Peninsula coastal region. This area was chosen because available information indicates that it contains an identifiable gyre which could provide a mechanism to isolate populations with planktonic stages. This region contains relatively large populations of the key species recommended for study, including krill, a variety of benthic species and important species of fish, seabirds and seals. Also, sea ice is a consistent feature in the eastern Bellingshausen Sea, which will allow the study of sea ice dynamics in relation to population dynamics of the key species. Finally, this region is relatively easily accessible by research vessel, and is near the highest concentration of shore-based marine laboratories on the Antarctic continent, which will provide for high-quality logistic and scientific support. Secondary sites recommended for study include the southeastern Weddell Sea, the northern part of the Atlantic sector of the Southern Ocean, the Ross Sea, and the Indian Ocean. The 1996-97 time frame was considered to be reasonable for the implementation of a GLOBEC Southern Ocean initiative.

This report is organized to provide the reader with the results of the Southern Ocean Workshop. An executive summary (Section 1) summarizes the scientific issues addressed at the workshop and the major recommendations from the working groups. This is followed by a more detailed summary of the rationale, objectives and scientific questions set forth at the workshop. Discussions of the international aspects of a GLOBEC Southern Ocean initiative, field program logistics and data management needs are given in sections 4 to 6, respectively. The synopsis of the meeting is followed by a series of overview papers from the plenary presentations that provide general background on many aspects of the physics and biology of the Antarctic system. The reports of the working groups are given in Section 8 in their unabridged form to provide the reader with the details of the discussions at the workshop from which recommendations were obtained. Finally, a glossary and list of meeting attendees are provided as appendices.

Eileen Hofmann
Ithaca, NY
July 17, 1991

Mark E. Huntley

Postscript

At the meeting of the SCAR/SCOR Group of Specialists on Southern Ocean Ecology in Bremerhaven, Germany (17-18 September, 1991), a group of 37 scientists from 14 countries gathered to review proposed and ongoing national and international research initiatives in the Southern Ocean. The Group of Specialists made the formal recommendation that "SCAR, in conjunction with SCOR, seek to participate fully in the further planning and implementation operations concerning Southern Ocean GLOBEC."

The recommendations of this GLOBEC report are consistent with many of those made at a meeting of Antarctic biologists in Trondheim, Norway in 1990, also held under the aegis of SCAR. It is noteworthy that there was little redundancy in the participant lists of these two meetings. One draws the conclusion that the questions highlighted in this GLOBEC document are timely and of general interest. There is strong agreement that we are now poised, both intellectually and logistically, to study the interactions between physical circulation and population dynamics. The scientific community is also well prepared to discover how marine animal populations adapt to austral winter - a critical part of many life cycles for which knowledge is sorely lacking.

If this document can contribute to the unfolding of knowledge of Southern Ocean ecosystems in the context of global change, then it will have achieved its purpose. Thanks are due to the many individuals who contributed to the preparation of the final report, including the authors of background papers; Lynne Claflin and Ron Tipper of JOI, who organized the meeting and the publication of the report; and Sue Stultz, who assiduously typed and edited several versions.

Mark E. Huntley

La Jolla, California
November 15, 1991

1. EXECUTIVE SUMMARY

1.1 Relation of a Southern Ocean GLOBEC study to climate change

Global climate change is predicted to be greatest at high latitudes, with dominant effects anticipated in the form of increased concentrations of atmospheric $C0_2$, increased temperature, and changes in ocean circulation. The Antarctic has a high negative radiation budget; its immense masses of both continental ice and annual sea ice act as a refrigerator, moderating global temperature on a seasonal and multiannual basis.

The continental ice sheet contains 90% of the world's fresh water, representing a potential sea level rise of approximately 60 meters. Major portions of the ice sheet grounded below sea level, such as the current West Antarctic ice sheet are potentially unstable on short time scales. Whether the ice sheet is currently growing or shrinking is unknown.

Seasonal sea ice coverage in the Southern Ocean increases from approximately 4×10^6 km^2 in summer to 20×10^6 km^2 in winter. During the austral summer the sea ice melts back almost to the edge of the Antarctic continent. During the last glacial maximum the sea ice in the Antarctic extended outward an additional 15×10^6 km^2 and its retreat in the summer was much reduced (CLIMAP 1981). These fluctuations in sea ice extent represent one of the most dramatic manifestations of climate change in the Southern Hemisphere. Recent paleoclimate studies have indicated that changes in atmospheric CO_2 may be a major factor in regulating the sea ice extent in the Southern Ocean.

The timing and maximum extent of the sea ice in the Southern Ocean is forced to a large extent by the large-scale atmospheric processes. The same processes also influence the position of the major frontal systems and the strength of the various currents in the Southern Ocean. Since the type and abundance of species can differ on opposite sides of fronts (or in different water masses) a shift in the circulation or change in the intensity of a current can change the type and abundance of prey and predators.

The effect of atmospheric warming in the Southern Ocean may be to reduce the areal extent of annual sea ice, which could reduce total annual photosynthetic carbon fixation, destroy habitats, and disrupt the life cycles of marine zooplankton and animals at higher trophic levels, whose present-day biogeographic ranges are directly related to the extent of sea ice coverage. Increased meltwater input from the continental ice sheet might have a compensatory effect, further extending the coastal production zone.

1.2 The Antarctic marine ecosystem

The Antarctic marine food web is more complex than the simple linear food chain (e.g. diatoms-krill-higher consumers) that has often been described for this system. However, the links in the Antarctic food web are often short and may be dominated by fewer than half a dozen species. The shortness of these trophic connections arises because the basic prey types (e.g. *Euphausia superba)* available to predators in the Southern Ocean is limited and because among the basic prey types, predators tend to concentrate on a core group of species, such as some abundant euphausiids and fish near the base of the food chain. It has been suggested that because of the apparent close coupling between trophic levels, long-term studies focusing on these predator-prey relationships and their environment will not only be critical to understanding variability in Southern Ocean ecosystems in general, but may ultimately form the basis for monitoring the effects of man-induced perturbations on the system.

Long-term fluctuations in the mesoscale abundance of the Antarctic krill are well documented, and although years of low krill biomass have been attributed to krill redistribution by physical forces, the mechanisms controlling abundance are not well understood. Recruitment to the krill population can be very localized, but the processes which determine recruitment success are not understood.

Even the immense spatial extent of the Antarctic marine ecosystem does not provide sufficient buffer against departures caused by global changes in environmental conditions, the stress of pollution, or exploitation of renewable resources. If stress on any segment of the ecosystem continues for long periods of time, the system may be permanently altered. Documentation of natural population cycles and the mechanisms underlying these cycles of natural variability is important if we are to predict how changes in the environment due to such things as global warming impact the biology of the Antarctic ecosystem.

1.3 Site selection

A number of sites were discussed, all with relative merit. If a single site had to be chosen, the Bellingshausen Sea, adjacent to the Antarctic Peninsula coastal region, would be considered the primary site. Although the circulation of the region is not well studied, indications are that it contains an identifiable gyre which would serve as a means to isolate definable populations, including those which have pelagic or benthic larval stages. The Bellingshausen Sea has several other advantages as a study site. First, it contains relatively large populations of the key species recommended for study, including krill, a variety of benthic species, and important species of fishes, birds and seals. Second, the presence of sea ice, the extent of which is anticipated to change in response to global climate change, can be depended upon; this will assure studies of sea ice dynamics in relation to population dynamics and habitat of key species. Finally, this region is not only relatively easily accessible by research vessel, but is near the highest concentration of shore-based marine laboratories on the continent, which will provide for high-quality scientific and logistic support. Secondary sites recommended for study include the southeastern Weddell Sea, the northern part of the Atlantic Sector of the Southern Ocean, the Ross Sea area, and the Indian Ocean Sector.

1.4 Zooplankton, including krill

Target species should emphasize the Antarctic krill *(Euphausia superba)* and the salp *(Salpa thompsoni)* as the key target species. Local populations should be defined by frequent surveys carried out throughout the annual cycle, and molecular and biochemical techniques, with a focus on locating key spawning sites, particularly of krill. A key objective of population dynamics studies is to acquire more data on populations in the winter, and particularly to identify those demographic parameters which may be especially sensitive to climate change, and to temperature increases in particular. Process studies should focus on determining the environmental triggers for metabolic and behavioral events, comparing metabolic responses between environmental extremes, measuring physiological responses to conditions outside the normal environmental range, and determining the relative sensitivity of developmental stages to environmental variables. Historical data should be exploited, particularly with respect to site specific modeling activities. Modeling is required to investigate the life cycles of zooplankton, to develop coupled biological, physical, numerical models for krill and other zooplankton populations, and to develop models regarding the formation, maintenance and dissolution of patches of zooplankton. New technology is particularly required to sample the upper 10 meters of the water column, to sample the abundance and distribution of salps with minimal disturbance to aggregates, to provide noninvasive techniques to observe distributions of krill and other zooplankton, and to sample in and immediately under sea ice.

1.5 Benthos

Target species should emphasize benthic forms with both pelagic and benthic larval stages among the bivalves, echinoderms, and crustaceans. Definable populations should be selected from regions in both the high and low Antarctic, with a particular focus on the Ross Sea, the southeast Weddell Sea, the Davis Sea in the high Antarctic, and the South Orkney/South Shetland Islands and Antarctic Peninsula regions in the low Antarctic. Population dynamics studies should focus on colonization processes in areas exposed by recent calving of major portions of ice shelf, species succession in areas with high iceberg grounding frequency, and emphasize observations during winter. Process studies should identify physical and biological forcing factors including those delivering carbon to the benthos, ice conditions, flow of local currents, temperature and salinity, light regimes, and redox profiles in sediments. Measurements of the response of individuals and populations should be assessed with regard to energy flow, physiological response, population dynamics, and community structure. A large body of historical data exists which should be exploited, particularly from collections made near shore based Antarctic field stations. Modeling studies should evaluate the processes of aggregation, dispersal and settlement of meroplanktonic larvae, and assess the role of climatic change on physiology and population dynamics. New technology is required to quantitatively assess distribution and abundance using video and camera technologies, and to develop methods for determining the age of individuals.

1.6 Top predators

Target species should include a commercially harvested species (e.g. *Champsocephalus gunnari),* a nonharvested holopelagic species (e.g. *Pleurogramma antarctica)* and nonharvested near-shore species (e.g. *Notothenia neglecta).* Other top predators should include a variety of penguin species, the crab-eater seal, and the Antarctic fur seal. Population dynamics studies should focus on better assessment of species distributions in time and space and should use molecular techniques to distinguish populations. There is a need for assessing growth and developmental rates of larval fishes, foraging dynamics of birds and seals, and identification of populations of birds and seals using marking and tracking studies. Process studies should emphasize the effects of temperature on growth and development of early life history stages of fishes, overwintering studies of top predators, and the potential effects of ultraviolet radiation on fish eggs and larvae. Historical data are readily available from a variety of current and past programs; these should be made readily available to principal investigators. Modeling studies should emphasize the effects of the physical environment on the physiological rates and demography of fishes, development of models for the population dynamics of sea birds, models of the movement and dispersal of foraging predators, and the effects of climate and fishing pressure on harvested species. New technology is especially required in the areas of improved acoustical hardware and software as applied to studying fish populations, underwater visual systems for assessing distributions of prey items, and improved satellite methods for tracking other top predators.

1.7. International interactions

Under the terms of the Antarctic Treaty, Antarctica is not the sovereign territory of any nation. Given the long-standing tradition of international research, any scientific program carried out in the Southern Ocean has an unusually high potential for international cooperation. It is expected that a Southern Ocean GLOBEC study will involve participation by many nations. Most countries maintain research establishments devoted exclusively to Antarctic or polar research; examples include the British Antarctic Survey, the Alfred Wegener Institut für Polar- und Meeresforschung, and the National Institute of Polar Research of Japan.

Numerous countries are interested in this region and international groups such as the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR) have an active interest in Antarctic marine studies. Presently the U.S. has several agencies with strong interests or ongoing programs in the Antarctic, including NSF-Division of Polar Programs and NOAA (which holds the responsibility for carrying out US CCAMLR activities). NASA has also been supporting scientific research in this area. Other global geoscience initiatives such as World Ocean Circulation Experiment (WOCE) and Joint Global Ocean Flux Study (JGOFS) have planned, or are now planning, research components in the Southern Ocean. It is expected that JGOFS field studies there will begin in 1994, although the precise locations of the research have not yet been finally agreed upon.

1.8. Field program logistics

Scientists endorsed a broad outline of a field program involving four modes of studying the Bellingshausen Sea region: (1) Quasisynoptic survey cruises; (2) Process oriented cruises; (3) Remote sensing; and (4) Shore based laboratory studies. The emphasis of such a plan would be on observing the entire annual cycle, with a particular emphasis on winter. Such a study would continue for a period of at least three years.

The implementation process will require that an international committee be established to set forth a detailed research plan. This committee, convened under the aegis of SCAR or another appropriate international scientific body, will have to make decisions regarding (1) key elements of the scientific research plan and (2) timing and logistics. If an implementation committee is established in 1992 it is conceivable that an international field research program could begin as early as 1996.

2 SOUTHERN OCEAN FIELD STUDY: SUMMARY & RECOMMENDATIONS

In this section we summarize the recommendations of the GLOBEC meeting on Marine Animal Populations and Climate Change in the Southern Ocean, distilled from the Working Group Reports which are presented in their entirety in Section 7. These recommendations are intended to serve as guidelines for specific GLOBEC studies.

For each taxonomic group - zooplankton, benthos and top predators - the recommendations are organized according to Site Selection criteria, with the exception that criteria relating to climate change are first discussed in general as applicable to all populations considered, and aspects of international, inter-program and inter-agency activity are discussed in a separate section following this one (Section 3). An outline of the suggested logistics of the field study is presented in Section 4.

2.1 Relation to Climate Change

The Southern Ocean is in many respects an ideal region in which to study marine animal populations in the context of global climate change. Meteorological dynamics are likely to impact coastal zones, areas covered by sea ice, and may affect the large-scale circulation. Present ocean-atmosphere models of the earth suggest that the Southern Ocean may be the last part of the ocean to experience warming, but other effects of global atmospheric warming could take precedence.

Coastal ocean regions are believed to be the places in which climate change would most influence marine animal populations, primarily through changes in meltwater input and solar radiation. Meltwater input would be induced by melting of the polar icecap, and solar radiation is expected to decrease over the ocean. Either of these processes will affect water column stability, leading to changes in vertical mixing and the primary productivity which fuels higher trophic levels. Animal populations are most concentrated in coastal regions.

Sea ice covers roughly half of the Southern Ocean during winter and approximately 10% during the summer. The annual cycle of accretion and melting contributes significantly to primary production, again by altering water column stability. Furthermore, the ice edge is a region where marine animals congregate in large numbers. Long term effects of global warming are expected to reduce the seasonality of sea ice and could result in the eventual absence of summer ice. These effects are likely to greatly reduce the productivity and habitat for marine animal populations. Changes in the flow intensity of circumpolar current may also be anticipated, brought on by a reduced temperature contrast between the equator and the poles which would reduce the strength of prevailing circumcontinental westerly winds. It is clear that circumpolar current interacts with ocean bathymetry to yield areas of high primary production, but it is not clear how global climate change would impact overall production in the circumpolar region.

The key recommendations identified with respect to climate change are:

(1) To organize and analyze existing historical data to compensate for the lack of long term observations;

(2) To make consistent and synoptic observations of sea ice and currents in the Southern Ocean, to optimize the ability to detect the effects of a climate change;

(3) To improve the understanding of how meteorological conditions drive variability in sea ice extent; and

(4) To improve observations of coastal circulation, which determines the distribution of marine animal populations.

2.1.1 Approach

The general approach is to undertake studies which will address the role that climate plays in determining local and regional episodic events, mass transport, and total energy of the marine system. Such studies should employ satellites, moored instruments, and drifters. Coupled with a better understanding of how physical mechanisms affect marine populations, this approach will lead to the basis for predicting how climate change will affect population dynamics.

2.2 Zooplankton, Including krill

2.2.1 Target species

Krill *(Euphausia superba)* has clear economic and ecological importance, and is suggested as the primary target species. Other species of primary interest include *Salpa thompsoni*, which can be especially dominant but about which little is known, *Euphausia crystallorophias,* a coastal and high Antarctic species, and two abundant copepod species, *Calanoides acutus* and *Calanus propinquus.* These species together represent the spectrum of different life strategies and the bulk of the zooplankton biomass in the Southern Ocean. Other species of interest would include *Themisto gaudichaudi, Metridia gerlachei, Rhincalanus gigas, Thysanoessa macrura,* and *Sagitta gazellae.*

2.2.2 Definable populations

The Bellingshausen Sea is a region where relatively discrete populations of krill and other holozooplankton might be maintained, by virtue of a regional gyral circulation, which may restrict communication with adjacent seas. An area directly west of the Ross Sea, bounded by the continent to the south, 65°S, and 140° to 160°E, has supported a consistent krill fishery for some time, and may also possess populations definable in space and time. The details of regional circulation in both areas are poorly known, and will require study. However, geostrophic circulation patterns presented in Stein (in press) suggest the presence of two gyres in this region that partly overlay the continental shelf (Figure 1). These features may be persistent. Key objectives of a field study would include:

(1) Sampling surveys of sufficient frequency to define the temporal and spatial extent of discrete populations, and developmental cohorts;

(2) The use of biochemical and genetic marker techniques to clearly identify populations.

2.2.3 Population dynamics

The primary goal of population dynamics studies on krill and other zooplankton is to better define demographic parameters, particularly in the context of regional circulation. Such studies will require year-round sampling, with particular emphasis on the role of sea ice in structuring the community. The following particular studies are indicated:

(1) Much more data are required on populations in the winter, especially on the role of demographic parameters of populations in determining the size of populations during the productive summer season;

(2) Identification and study of those demographic parameters which may be especially sensitive to climate change, and to temperature increases in particular.

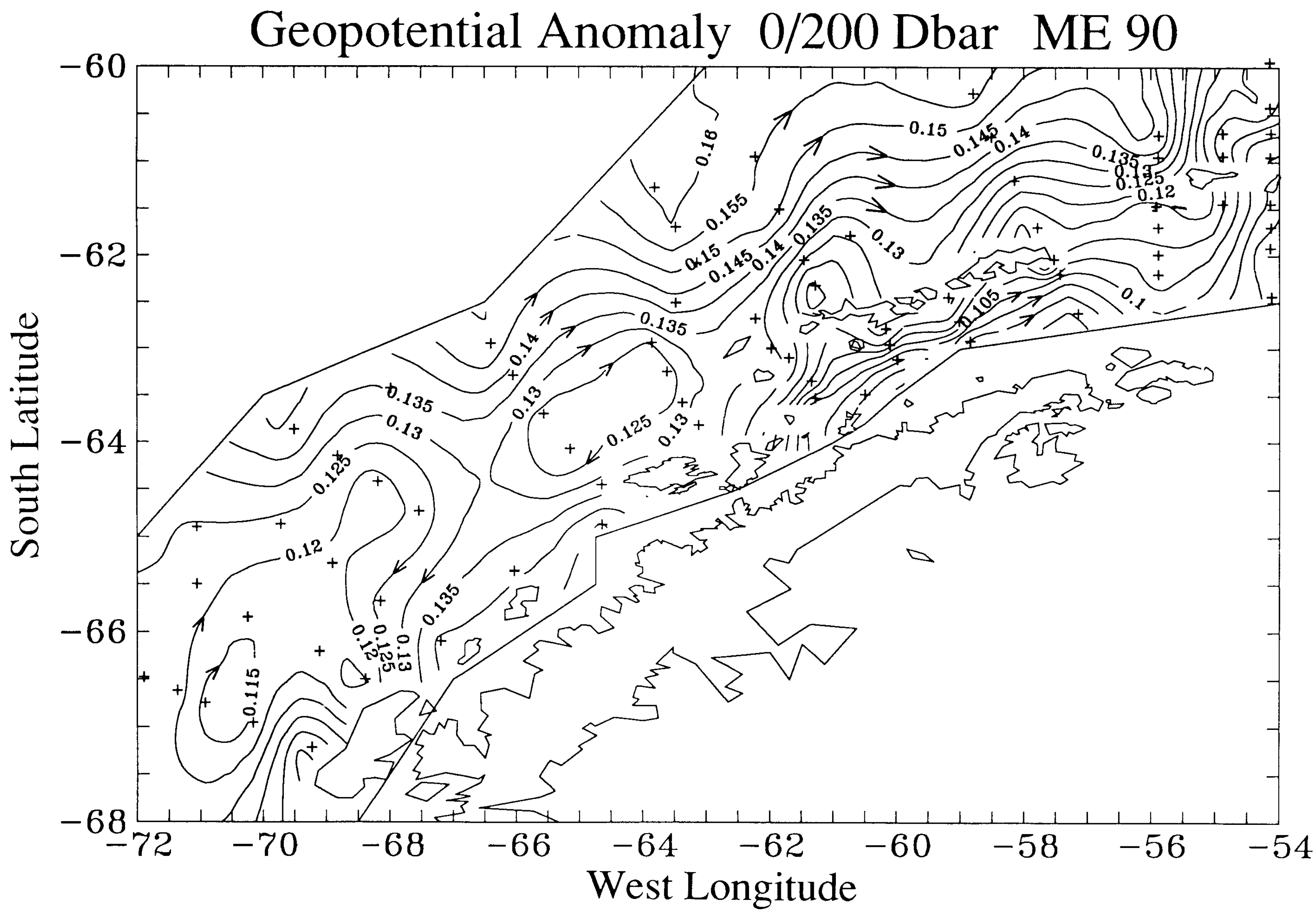

Figure 1 Geopotential anomalies from the recent work of Stein (In Press) suggest the presence of two gyres in the coastal and slope regions of the Bellingshausen Sea.

2.2.4 Focus on process and mechanisms

Process studies would be carried out on cruises designed specifically for that purpose, as well as at the numerous shore-based laboratories in the Antarctic Peninsula region. Particular attention should be paid to measuring rates of metabolism, egg production, feeding, growth and development, as well as investigating the diapause phenomenon. Research might include the following studies:

(1) Determination of the environmental triggers for metabolic and behavioral events, noting that very small changes (i.e., 0.5°C) may trigger change;

(2) Comparison of metabolic responses between extremes in environment (e.g. summer vs. winter);

(3) Measurement of physiological responses to conditions outside the normal environmental range;

(4) Determination of the relative sensitivity of various developmental stages to environmental variables, to understand which stages are most vulnerable.

2.2.5 Historical database

Relatively little information exists on plankton distributions in the Bellingshausen Sea, although the nearby waters of the Antarctic Peninsula region are perhaps the best studied in all the Southern Ocean. This is particularly important because waters from the Bellingshausen Sea provide some of the flow through the northern reaches of the Antarctic Peninsula coastal region, and thus the fauna of the Bellingshausen are already reasonably well known. The BIOMASS data base, centered at the British Antarctic Survey in Cambridge UK, may prove a valuable resource.

2.2.6 Modeling

Specific modeling studies recommended include:

(1) Design of models to investigate life cycles of zooplankton, with particular emphasis on determining the results of different life-history strategies (e.g. seasonally migrating vs. non-migrating species);

(2) Development of coupled biological-physical numerical models for krill and other zooplankton populations at the study site, with particular emphasis on interactions with regional scale circulation, and with finer-scale resolution, especially in the vertical;

(3) Development of models regarding the formation, maintenance and dissolution of patches, with particular emphasis on krill.

2.2.7 Technology

Certain developments in technology will be applicable to all taxonomic categories of interest, particularly in the case of field sampling instruments. Those of special interest to zooplankton and krill studies would include:

(1) Improvement of instrumentation needed to sample the upper 10 m of the water column as well as under sea ice, where current instrumentation is inadequate;

(2) Improvement of large volume sampling techniques to determine the abundance, biomass and distribution of salps with minimal disturbance to aggregates;

(3) Development of non-invasive techniques to observe distributions of krill and other zooplankton in both ice-covered and ice-free areas.

2.2.8 References

Stein, M. 1991. Variability of local upwelling off the Antarctic Peninsula, 1986-1990. *Archiv far Fischwiss.* (In Press)

2.3 Benthos

2.3.1 Target species

Five characteristics were considered as criteria for the selection of benthic species, primarily that the species: (1) have measurable growth parameters, (2) be abundant, (3) have either a wide or restricted distribution, (4) have a known life history, and (5) be amenable to reproductive studies. Given these constraints, the following species are particularly recommended (p and b denote pelagic and benthic larval forms, respectively):

(1) Bivalves: *Adamussium* (p), *Laternula* (p), *Mysella* (b), *Gamardia* (b)

(2) Echinoderms: *Odontaster* (p), *Sterechinus* (p), *Ophionotus* (p), *Diplasteria* (b))

(3) Crustaceans: *Notocrangon* (p), *Chorismus* (p), *Glyptonotus* (p)

2.3.2 Definable populations

Populations that would be definable in time and space would be likely to occur in the following areas, distributed from high to low Antarctic:

High Antarctic:

(1) Ross Sea/McMurdo Sound

(2) Southeast Weddell Sea

(3) Davis Sea

Low Antarctic:

(1) South Orkney/South Shetland Islands

(2) Antarctic Peninsula/Bellingshausen Sea

In particular, genetic studies would be desirable for distinguishing between populations.

2.3.3 Population dynamics

Measurements relative to the population dynamics of benthic species (e.g. recruitment, life history strategies) should be done in conjunction with measurements on physical processes. Particular studies recommended include:

(1) Colonization processes in areas exposed by recent calving of major portions of ice shelf;

(2) Species succession in areas with high iceberg grounding frequency;

(3) Studies that emphasize observations during winter, a period for which little is known.

2.3.4 Focus on process and mechanisms

Studies should be conducted to understand how fundamental parameters of population dynamics, such as growth, reproduction, larval dispersal, behavior, settlement and survival vary directly and indirectly as a function of physical and biological forcing. Particular processes or parameters which should be studied with reference to potential global change include:

(1) Processes delivering carbon to the benthos via vertical flux of particulate matter;

(2) Ice conditions in the overlying water;

(3) Flow of local currents;

(4) Temperature and salinity;

(5) Light regimes; and

(6) Redox profiles in sediments.

Measurements of the response of individuals and populations should be assessed with particular regard to:

(1) Energy flow;

(2) Physiological response, which would provide information on rates and processes;

(3) Population dynamics;

(4) Community structure, which would assess the effects of environmental change on species composition, abundance and biomass.

2.3.5 Historical database

A large body of data exists on benthic communities near a number of Antarctic field stations. Some effort should be made to gather these data and make them available at an accessible central location.

2.3.6 Modeling

Modeling studies are encouraged which

(1) Evaluate the processes of aggregation, dispersal and settlement of meroplanktonic larvae;

(2) Assess the role of large-scale climatic changes on physiology and population dynamics of discrete populations.

2.3.7 Technology

Developments in technology are particularly required in the following areas:

(1) Quantitative assessment of distribution and abundance using video and camera

technology;

(2) Methods for determining the age of individuals.

2.4 Top Predators

2.4.1 Target species

Target species are recommended among fishes, birds and mammals. For fish, these include

(1) Commercially harvested species

Champsocephalus gunnari

Notothenia larseni

Electrona carlsbergi

(2) Non-harvested holopelagic species

Pleuragramma antarctica

Electrona antarctica

(3) Non-harvested nearshore species

Notothenia neglecta

Trematomus hansoni

Harpagifer sp.

Species in the first group occur primarily in the Atlantic sector and are already included in CCAMLR monitoring studies. The second group are species abundant in food webs of the high Antarctic and represent contrasting ecological and life history patterns. The third group contains species which are conveniently collected from shore stations.

Among the birds, key species of interest include Adélie, chinstrap, macaroni and gentoo penguins, cape and Antarctic petrels, Black-browed albatross, grey headed albatross and South Polar skua. It is noted that roughly 2/3 of the Southern Ocean bird biomass is comprised of Adélie penguins; other species are recommended for a variety of specialized reasons.

Target species recommended among the mammals are the crabeater seal and the Antarctic fur seal. Both are largely dependent on krill as a food resource, and occupy habitats analogous to those of Adélie and chinstrap penguins.

2.4.2 Definable populations

In the Atlantic sector of the Southern Ocean, which is generally recommended as a primary study region, it is generally felt that CCAMLR subareas represent reasonable approximations of the distribution of fish populations. Distributions of bird and seal populations may represent distinct populations, but studies are required to verify this assumption. Specific studies should include:

(1) Better assessment of species distributions in time and space; and

(2) Molecular techniques (e.g. mitochondrial DNA) applied to distinguish populations.

2.4.3 Population dynamics

Some of the important demographic parameters for target populations can be acquired directly from the CCAMLR monitoring program. These would include data on spawning stock biomass, growth and reproduction of commercially taken fishes, and the growth rate, breeding success and cohort survival of birds and seals. Studies particularly encouraged under GLOBEC would include:

(1) Assessment of growth and developmental rates of larval fishes as related to biotic and physical environments;

(2) Foraging dynamics of birds and seals, with special emphasis on winter; and

(3) Marking and tracking studies on birds and seals which assist in identifying populations and observing behavior.

2.4.4 Focus on process and mechanisms

Certain key processes are expected to reveal the response of top predator populations to global change. This calls for studies focused on:

(1) Effects of temperature on growth and development of different ontogenetic stages of fishes;

(2) Overwintering studies of top predators to determine critical mortality periods;

(3) Potential effects of UV radiation on near- surface fish eggs and larvae;

(4) Effects of physical circulation on dispersal of early life stages of fishes;

(5) The importance of food availability on physiological condition and reproductive behavior; and

(6) Foraging dynamics of top predators in relation to prey abundance and aggregation behavior.

2.4.5 Historical database

Relatively sound historical databases have been collected through the CCAMLR and BIOMASS programs, as well as through various national programs in the US, UK, Germany, France, Australia, New Zealand and South Africa. Access to these should be made readily to principal investigators conducting studies in the GLOBEC framework.

2.4.6 Modeling

Specific studies recommended for modeling exercises include:

(1) Effects of the physical environment and fluid dynamics on food supply, growth and development rates, survivorship and dispersal of the early life history stages of fish;

(2) Development of a standard population dynamics model for seabirds, integrating physiological data with environmental variables;

(3) Models of movement and dispersal of foraging predators to determine how seabirds and seals locate food patches;

(4) Effects of climate and fishing pressure on harvested species;

(5) Trophodynamic models of multispecies interactions between fish, higher predators, and their prey.

2.4.7 Technology

Special technological advances which could greatly aid studies of top predators in the Southern Ocean include:

(1) Improved acoustical hardware and software for locating, identifying and quantifying the abundance of fish;

(2) Underwater visual systems for assessing the distributions of prey items (e.g. krill and pelagic fishes);

(3) Improved satellite tracking and time-depth recording devices for predators;

(4) Improved techniques for remote sensing of sea ice, either by satellite or aircraft, which yield higher resolution and which better differentiate sea-ice conditions;

(5) Biochemical methods for evaluating fish condition factors;

(6) Genetic markers for determining stock identity; and

(7) Increased use of Lagrangian drifters to observe current transport and advective processes.

2.5 General Modeling Issues

Many of the issues relevant to modeling marine populations in the Antarctic have already been considered as part of the discussions for each taxonomic group. However, there are additional issues that are relevant to a GLOBEC program in the Southern Ocean.

First, it is now apparent that many of the components of the Antarctic food web are dependent on sea ice during some or all of their life history. The time scales of this dependence range from days (for phytoplankton) to years (for seals and marine birds) and extend over space scales of a few meters to 100s of kilometers. Thermodynamic models of sea ice, that describe the annual growth and melting of an uniform ice field, are reasonably well developed. Schemes for incorporating thermodynamic sea ice models into general circulation models exist. However, the existing sea-ice models are simple and do not include processes such as rafting of sea-ice, and the existing coupled ocean-ice models do not consider flow underneath the ice, which can be important for biological populations. Assuming that climate change effects in the Antarctic will be reflected in the variability and extent of sea-ice cover, then the development of realistic sea-ice models that can be interfaced with circulation and biological models is a critical area of research. Also models that incorporate the feedbacks between sea-ice cover and higher predators, that are decoupled from the flow field (e.g. penguins) need development.

Second, any GLOBEC initiative planned for the Southern Ocean will likely have a regional focus, i.e., Bellingshausen Sea. However, the circulation models developed for regional studies will need to include the effects of the larger scale circulation of the Southern Ocean. Thus, techniques for combining the results of large-scale circulation models (e.g. FRAM) with results from regional circulation models need development. A related problem is that the space and time scales resolved in physical models are often inappropriate for biological processes. In particular, the vertical resolution of circulation models is frequently not consistent with that needed to adequately model biological processes. Thus, methods for scaling between circulation and biological models need development.

Third, there is a need for the development of models that can simulate the aggregation behavior of animals such as krill. Considerable theory on modeling animal aggregation and swarming behavior has been developed for terrestrial systems. Efforts need to be made to transfer and adapt this theory for marine populations.

3 INTERNATIONAL ASPECTS OF GLOBEC

A new era of international cooperation began in Antarctic marine research with the advent of the BIOMASS program in the early 1980s. Under the aegis of this program, promoted and sponsored by the Scientific Committee on Antarctic Research (SCAR), two key multinational field programs were initiated with the principal aim of studying krill distributions - which has been the principal historical rationale for studying Southern Ocean marine ecosystems. The first of these, the First International Biomass Experiment (FIBEX), took place in 1980-81, involving the countries of Argentina, Chile, USA, Germany, Poland and the United Kingdom in a broad study of the southwestern Atlantic Sector, and involving Japan, Australia, France, and other member nations in studies of the Indian Ocean and Pacific Sectors. The second study, Second International Biomass Experiment (SIBEX), took place in 1983-85, and focused on describing seasonal dynamics in the Antarctic Peninsula region. BIOMASS field studies are now ended, and data have been contributed to the BIOMASS Data Centre at British Antarctic Survey in Cambridge, UK.

The Federal Republic of Germany has spearheaded many important research expeditions during the past decade, first in the Antarctic Peninsula region and more recently in the Weddell Sea, many having a focus on the marine planktonic ecosystem. The FRG has made available their primary research vessel, the R/V Polarstern, for the ongoing EPOS European Polarstern Study) program.

Until the 1980's, most oceanographic research in the Southern Ocean was aimed at describing the structure rather than the functioning of ecosystems. Two important programs initiated in the last decade shifted the emphasis to a study of rates and processes. The Antarctic Marine Ecosystem Research at the Ice-Edge Zone (AMERIEZ) program undertook studies of the biological, chemical and physical dynamics of the marginal ice zone; this program has now provided a greater understanding of how ice-edge ecosystems function through most seasons. The Research on Antarctic Coastal Ecosystem Rates (RACER) program was carried out as a pilot experiment during the late 1980s to examine the physico-chemical processes giving rise to high productivity at all levels of the Antarctic coastal food web; research is continuing at higher time and space resolution through 1992. Recently the US National Science Foundation funded a Long Term Ecological Research (LTER) program for Palmer Basin, which is designed to provide long-term observations of physical and biological processes affecting krill population distributions.

Climate variability, through feedbacks on physical and chemical processes in oceanic environments, affects and possibly controls variability of oceanic ecosystems and their component plant and animal populations. Marine plankton play a major role in the transfer and/or modulation or amplification of perturbations (natural or anthropogenic) through the marine food web. At present, the role of marine zooplankton in global change is not properly addressed by any existing large-scale international programs, e.g. JGOFS. The scientific basis necessary for understanding and predicting the consequences of these interactions is beyond the capability of any one national effort. Individual national studies, within an international framework, can provide greater resources, more geographical coverage, and greater potential for successful completion of the project goals. Therefore, an international structure is being proposed to be established by SCOR (Scientific Committee on Oceanic Research) and IOC (Intergovernmental Oceanographic

Commission) to expand the focus of GLOBEC. The overall goal of this international program would be to understand the effects of physical processes on predator-prey interactions and population dynamics of zooplankton, and their relation to ocean ecosystems in the context of the global climate system and anthropogenic change. The program would:

1) improve understanding of the relationship between plankton and variability of fish stocks and other living resources, including the response to climate change;

2) quantify the influence of zooplankton on biogeochemical cycles, through grazing control of the phytoplankton;

3) utilization of modern sampling technology;

4) lead ultimately to a capability to model and predict ocean ecosystem dynamics on regional and global scales.

4 FIELD PROGRAM LOGISTICS

The GLOBEC Southern Ocean Field Study is anticipated to begin in 1995 or 1996 and to continue for a period of approximately three years. In general terms it is recommended that there be four principal and complementary sampling modes:

(1) Quasisynoptic survey cruises

(2) Process oriented cruises

(3) Remote sensing

(4) Shore based laboratory studies

Physical oceanographic studies and biological investigations would be carried out in each of these sampling modes. Where possible attempts should be made to coordinate these cruises with ongoing cruises in the region. Cruises should be scheduled so as to provide maximal coverage of the entire annual cycle, with moorings operating continuously for the entire duration of the field program.

Field program logistics are described here using the Bellingshausen Sea as an example site. A second site in the Indian Ocean sector may also be favorable and the general field program logistics described below would apply to this area as well. Specifics of the field program appropriate for the chosen site remain to be determined.

4.1 Quasisynoptic Survey Cruises

4.1.1 Survey domain and resolution

Survey cruises would cover a grid of approximately 20 km interline spacing extending from the coastal region of the Bellingshausen Sea to well offshore into open ocean regions. In addition, selected transects should be run deep into the circumpolar Antarctic current and occasionally into areas of the more well studied Bransfield Strait region; this will enable better comparative studies of regionally separate populations.

4.1.2 Timing

In any intensive field year, during which coverage of the entire annual cycle is required, a total of six to 10 survey cruises, each of two to three weeks duration, should be conducted. This amount of time is required to sample the region at the appropriate resolution. Cruises of similar duration, but at lower frequency, may be sufficient to characterize the system in nonintensive field sampling years.

4.1.3 Critical measurements

Working groups agreed that the survey sampling procedures of mutual interest would require the following general types of collections:

(1) Vertical distribution, abundance and physiological condition of target species; for a number of species depth distributions to a depth of 1000 meters would be necessary;

(2) Vertical distribution and abundance of food (the definition of which depends upon the species of interest);

(3) Distribution and abundance of top predators;

(4) Physical, chemical and biological properties focusing on vertical profiles of salinity, temperature, inorganic nutrients, beam transmission, downwelling irradiance, and current velocities.

Key instrumentation may involve multiple net samplers (e.g. MOCNESS), optical plankton counters, acoustics, towed video Systems, box corers, and bottom trawls. Physical, chemical and biological properties could be sampled by a group of instruments including CTD, radiometer, beam transmissometer, ADCP, and chemical analysis of water samples collected by rosette. Innovative methods in biochemistry and biotechnology which are sufficiently developed would also be incorporated for assessing the physiological condition of specimens.

4.2 Process Oriented Cruises

4.2.1 Domain and resolution

Location of the process oriented cruises would be determined on the basis of preliminary results gained from initial survey cruises.

4.2.2 Timing

The exact timing of the cruises will depend to a great extent on the determination of which periods are deemed to be critical to understanding population dynamics of the target species being studied. This may be anticipated beforehand to some degree by the application of modeling results, as well as from historical data.

4.2.3 Critical measurements

Measurements should focus primarily on processes at different time and space scales. Certain types of studies are envisioned as essential and can be described as follows:

- Zooplankton/krill:

  (1) Data is particularly required on overwintering physiology and life history strategies;

  (2) Studies on patch formation, maintenance and dissolution are particularly required.

- Benthos:

  (1) Critical studies require measurements of carbon flux, carbon mineralization in the sediments, and bioturbation;

  (2) Measurements of physiological rates conducted in conjunction with environmental conditions.

- Top predators:

  (1) More information is required on the effect of temperature on growth and development rates of early life history stages of fishes;

  (2) Overwintering studies are needed to understand the critical mortality period of higher predators;

Measurements would concentrate particularly on shipboard and in situ estimates of physiological rates such as egg production, growth and feeding, as well as key population dynamics parameters such as mortality. The theme of these cruises would be to attempt to follow localized aggregations of marine animals and to monitor key changes in their demography, physiology, and distribution as they are affected by physical processes and behavior through time. A variety of background physical, chemical and biological measurements made during the process oriented cruises would provide continuity with data generated from the survey cruises.

4.3 Remote Sensing

4.3.1 Domain and resolution

Remote sensing here is taken broadly to include techniques ranging from satellite oceanography to moored sampling devices. Therefore, the domain will range from localized point samples to broad coverage of the entire sampling region, and resolution will range from that dictated by the limits of satellite and airborne sensors to the temporal resolution dictated by the limitations of hardware located on bottom moorings.

4.3.2 Timing

Moorings could be deployed at the outset of the first field season and be maintained for the entire duration of the sampling study. It is anticipated that moorings would be brought on line at new locations as the field program progresses, but these should presumably be located at sites both on the coastal shelf as well as on the continental slope.

4.3.3 Critical measurements

It is recommended that each mooring site include a heavily instrumented mooring and possibly peripheral moorings with relatively few instruments. The central moorings might include Acoustic Doppler Current Profilers (ADCPs) and a variety of hydrographic, bio-optical and bioacoustical sensors, whereas peripheral moorings would include only current meters.

Local weather and sea surface conditions and ocean color could be detected using either satellite-borne or airborne sensors. These remote sensing devices should be flown in conjunction with either the process oriented or the survey scale cruises. There should be close coordination between GLOBEC and WOCE concerning meteorological and physical oceanographic data for study areas.

Lagrangian drifter studies should also be included to measure components of the near-surface circulation, and to assess other parameters pertaining to the biology of local waters, including transmission, fluorescence, and possibly acoustics.

Selected process studies should be conducted in the vicinity of mooring sites; similarly, survey cruise transects should be brought fairly close to these sites.

4.4 Shore-based Laboratory Studies

One of the great advantages of a GLOBEC study site in the Bellingshausen Sea is that it is situated close to a very high concentration of shore-based laboratories belonging to a large number of countries. These laboratories would prove useful for both scientific and logistic reasons. A wide variety of process oriented studies, particularly focused on physiology, could be contemplated at these various laboratories. The existence of such facilities provides the opportunity for continued studies throughout the entire period of the GLOBEC research program, which would focus on experimental evaluations of physiological rates.

5 DATA MANAGEMENT

Given the international nature of any GLOBEC initiative planned for the Southern Ocean, the development of protocols for data handling and exchange is critical. These protocols must be fair to scientists but yet foster the timely exchange and use of data. In keeping with the suggestion arising from the GLOBEC Northwest Atlantic workshop, data should generally be available within one year of its preparation. Implementation of a protocol that will encourage such an exchange will require international cooperation and coordination from the outset. The protocols developed for other international Global Geoscience initiatives (e.g. WOCE and JGOFS) could serve as a model for GLOBEC.

Procedures for data handling and exchange need development. These must take into account the varied and disparate data sets (hydrography to higher predator abundances) that will arise from a GLOBEC initiative. Some of the problems involved in handling and exchanging these data types have been addressed during the establishment of data centers, such as the BIOMASS and CCAMLR data centers. The policies and procedures implemented by these data centers could provide a starting point for the development of GLOBEC data policies. It is important that future data be acquired and reported in a manner that is consistent and transferable between computer systems. Procedures for doing this must be in place prior to any field program. It is also important that methods for handling the large data sets produced by instruments such as acoustic or optical plankton recorders and satellite sensors be available prior to field studies.

Considerable historical data exist on the structure of the marine planktonic ecosystem of the Southern Ocean. In the 1920s and 1930s Britain undertook the extensive, circumcontinental Discovery expeditions; more than 12,000 plankton samples were analyzed, and physical and chemical oceanography of many regions were studied. In the mid-1960s the United States sampled hundreds of stations in the Drake Passage and nearby waters on numerous expeditions of the RV Eltanin. The Federal Republic of Germany sampled more than 500 stations in the same region during the 1970s. Chile, Poland, Argentina, Japan, New Zealand, Australia, USSR and other Antarctic Treaty member nations have all staged independent oceangoing expeditions in various parts of the Southern Ocean over the past few decades, the combined data from which has produced a large, if somewhat fragmented, picture of the marine ecosystem.

As a result of these programs, historical data bases that include observations relevant to the goals of GLOBEC exist for some regions of the Southern Ocean, most notably the Bransfield Strait and Antarctic Peninsula region. However, these data sets are often incomplete and/or are in forms that are not easily obtained or analyzed. In particular, much of the available data on krill distribution and abundance, fisheries and regional hydrography are in forms that are difficult to use. These data provide a good starting point for the development and testing of data handling and exchange policies. Analysis of existing data is a necessary component of planning future Southern Ocean initiatives. However, it is unlikely that a single program will provide all of the necessary measurements and observations. Therefore, it is important that GLOBEC data bases be coordinated with those that will arise from WOCE, JGOFS, NOAA and any other international programs planned for the Southern Ocean.

6 BACKGROUND PAPERS

6.1 Zooplankton/Krill

by Sigrid Schiel

The Antarctic growth season has long been regarded as a brief but productive period characterized by large diatoms efficiently grazed by a short food chain - krill -whales. This view has changed. It is now accepted that the ice-free period is not exceptionally productive and that the flagellate-dominated community type is more characteristic than phytoplankton blooms of large species, which only occur in restricted areas such as the inshore waters, the edge of the seasonally retreating pack-ice and frontal zones (e.g. Sakshaug and Holm-Hansen 1984). However, the largest part of the Antarctic is oceanic and oligotrophic. There, the proportion of small flagellates and pennate diatoms (<20 µm) contribute more than 50% to phytoplankton standing crop and primary production, and the standing crop of heterotrophic nanoflagellates, dinoflagellates and ciliates is relatively high (v. Bröckel 1981). Over vast regions of the Antarctic, Chl a-concentration under ice-free conditions rarely rises above 0.3 mg m^{-3}. Under the ice cover, water column values are lower by an order of magnitude. However, the sea ice and the ice/water interface is much richer in phytoplankton biomass; Chl a concentration between 40 and 300 mg m^{-3} is a common feature.

The Southern Ocean is well known for its latitudinal zonation. Three very different large-scale subsystems have been described: the ice-free West Wind drift dominated by copepods, the seasonal pack-ice zone with krill *Euphausia superba* as the main component, and the permanent pack ice zone where copepods and the ice krill *Euphausia crystallorophias* are the major plankton elements (Hempel 1985).

The differences mentioned above are large scale variations, but there are, of course, also variations on smaller geographical scales. In the Weddell Sea for example, different patterns in the distribution of zooplankton species as well as in community structures occur in the upper 300 m during summer. In agreement with topography and water mass distribution, three distinct communities have been defined (Fig. 1). (Boysen-Ennen and Piatkowski 1988). In winter and early spring surface zooplankton was only one tenth of the summer population in the eastern Weddell Sea (Hubold and Hempel 1987).

The zooplankton assemblage in waters off the Antarctic Peninsula during summer can be distinguished by differences in species composition and abundance widely attributed to different water masses. Euphausiids and copepods greatly predominate the zooplankton assemblages (Jazdzewski *et al.* 1982). However, they can be outnumbered by salps (mainly *Salpa thompsoni)* as found in austral summer 1983/84 (Montú and Oliveira 1986). Based on four expeditions to the Antarctic Peninsula region at different seasons, Siegel and Piatkowski (1990) could statistically define three distinct macrozooplankton communities: an oceanic, a neritic and a mesopelagic one. A so-called transitional cluster represents a mixing zone created by frequent occurrence of species from both the oceanic and the neritic community (Fig. 2).

The pelagic system - especially within the seasonally ice-covered regions like the eastern Weddell Sea and the Antarctic Peninsula region - is exposed to considerable variations in primary production.

How does the zooplankton respond to the distinct seasonality which is, according to Clarke (1983) the most important factor influencing zooplankton life cycles and adaptations?

The ontogenetic migration of the major copepod species largely influences the zooplankton standing stock in the surface water during summer (Foxton 1956). He described two seasonal surface maxima of zooplankton concentration, one in November/December and the second one in February/March. The first peak is attributed to the overwintering population, e.g. older copepodite stages arising to the top water layers, while the second maximum is due to a new generation consisting mostly of young developmental stages (Voronina 1968).

Voronina (1968) concluded that the timing of reproduction occurred earliest in the north and then proceeded southward later in the year. Results for the top 1000 m in November/December

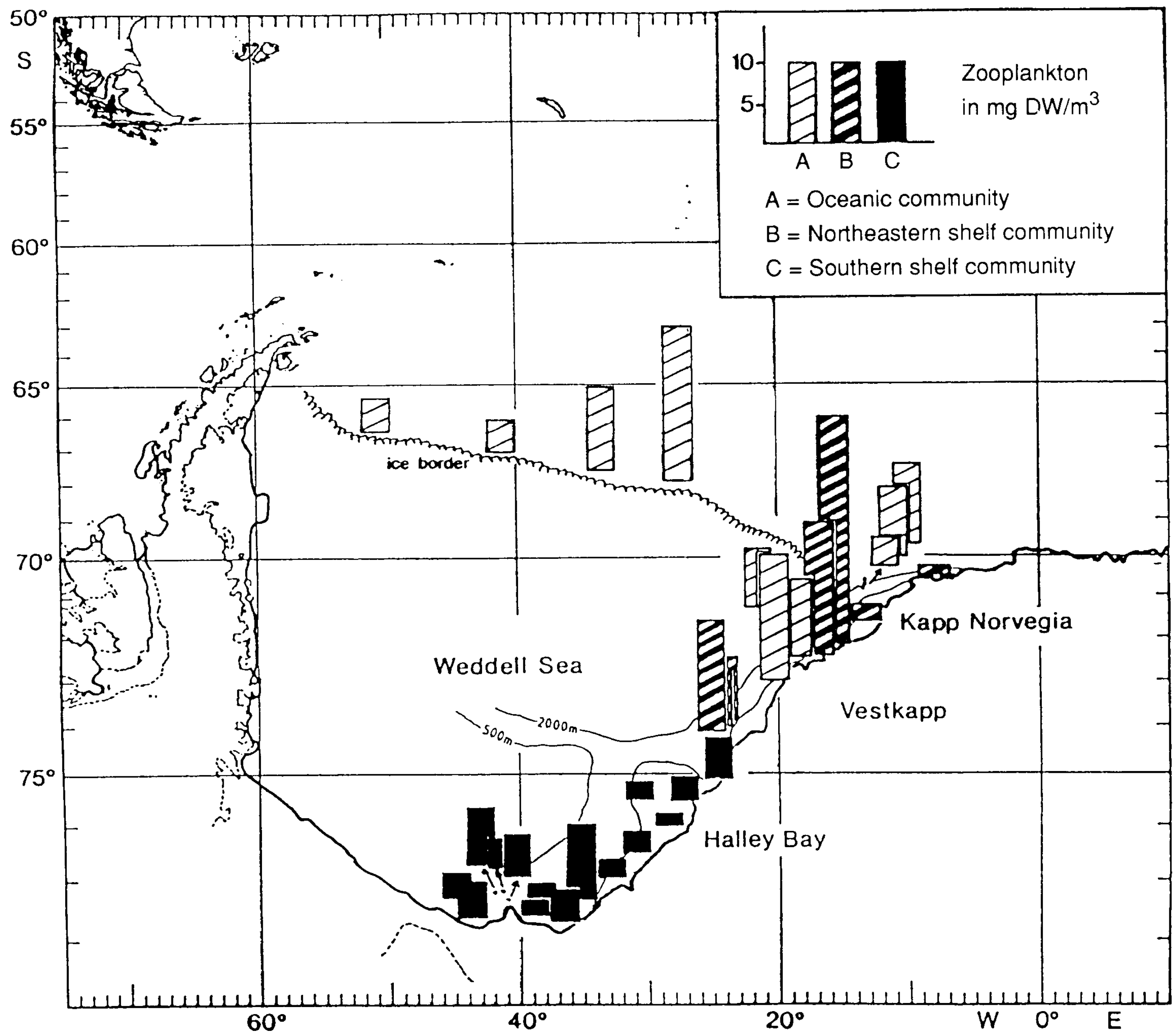

Figure 1 Zooplankton communities of the Weddell Sea (Boysen-Ennen and Piatkowski, 1988).

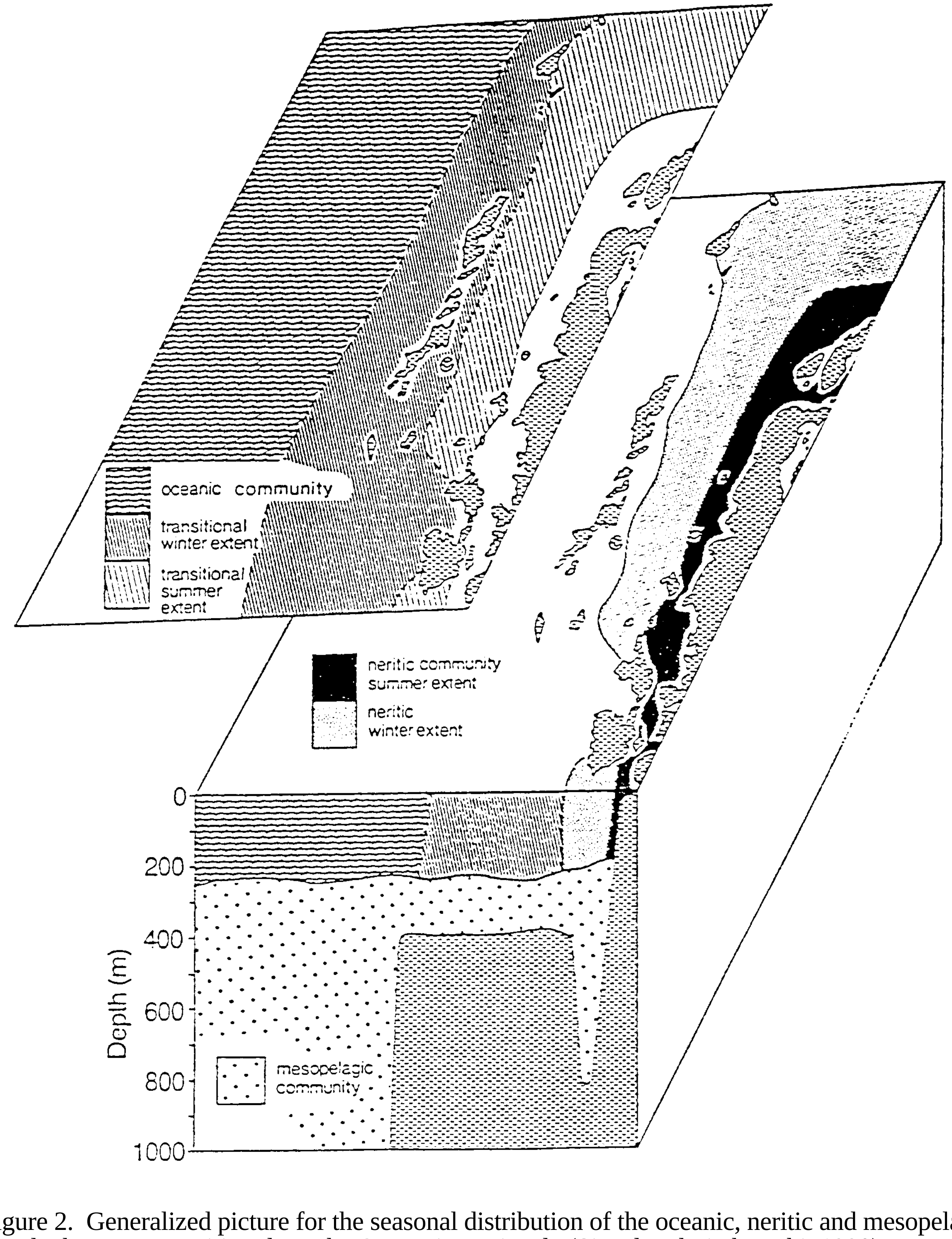

Figure 2. Generalized picture for the seasonal distribution of the oceanic, neritic and mesopelagic zooplankton communities along the Antarctic Peninsula (Siegel and Piatkowski, 1990).

1988 obtained during European Polarstern Study (EPOS) confirmed the latitudinal shift (Fig. 3): *Calanoides acutus* occurred in greater numbers in the upper 300 m of the water column at the station in the Scotia Sea, whereas the bulk of the population was found in deeper layers in the Weddell Sea. In the Weddell/Scotia Confluence zone, the majority was restricted to even the top 50 m. The composition of the developmental stages changed also from north to south with younger stages (new generation) in the north and older ones in the south. A similar pattern was observed by Marin (1987), who showed within the top 200 m January/February 1985, that the summer development of *Calanoides acutus* and *Calanus propinquus* was more advanced in the Scotia Sea than in the adjacent Weddell Sea. *Calanoides acutus* and *Calanus propinquus* are dominant circumpolar distributed copepod species. *Calanoides acutus* performs a distinct ontogenetic vertical migration (Fig. 4) (e.g. Andrews 1966). *Calanus propinquus,* by contrast, does not show such a distinct ontogenetic vertical migration pattern, and. part of its population remains in the surface waters in winter (Marin 1988, Nöthig *et al.* in press).

The reproductive cycle of the mainly herbivorous zooplankton species is strongly influenced by the distinct seasonal cycle of primary production. During the short phytoplankton productive period food is consumed and stored as depot lipids. These metabolic energy reserves are used for survival during overwintering and reproduction. Wax esters are considered to be suited to species being exposed to a short season of food availability followed by a long period of starvation. Thus, wax esters are the main reserve in herbivorous zooplankton, especially calanoid copepods and euphausiids. In contrast, triacylglycerols are the main lipid reserve in carnivorous organisms and suggest feeding year round (Sargent *et al.* 1981).

There are striking differences in the lipid data between *C. acutus* and *C. propinquus.* Lipids in *C. acutus* were accumulated as wax esters, whereas *C. propinquus* stored their energy as triacylglycerols, which may indicate feeding throughout the year (Fig. 5, Schnack-Schiel et al. 1991). Like *C. propinquus,* the Antarctic krill, *Euphausia superba,* is rich in triacylglycerols but wax-ester deficient; underwater observations revealed *E. superba* living in pack-ice during winter/spring and feeding on ice algae (Daly and Macaulay 1988). It is unknown whether *C. propinquus* can also utilize this food source. Hopkins and Torres' (1989) data from the ice-covered northern Weddell Sea indicate feeding of *C. propinquus* and *E. superba* in March on metazoans.

The presence of huge stocks of the euphausiid *Euphausia superba* is possibly the most characteristic feature in the Southern Ocean. Krill's summer distribution is circumpolar, bounded to the north by the Antarctic Polar Front Zone. The southern limits of distribution in summer and winter are unknown, although a significant proportion of the population occurs under the ice, which extends almost to the Polar Front Zone in some places during winter. The summer distribution of krill coincides with that of the sea ice cover in winter. In the Indian and Pacific Sectors, krill seem to be concentrated mostly in the East Wind Drift, particularly in the vicinity of the Antarctic Divergence Highest densities in the West Atlantic were recorded in the Bransfield Strait, Scotia Sea and near South Georgia. The general picture to emerge is that the high densities of krill found in the West Atlantic are usually associated with bottom topography and with frontal discontinuities and eddies such as the zone of the Antarctic Divergence and the Weddell/Scotia Confluence. Krill is also said to occur in high densities in proximity to the ice-edge.

Krill swarms can extend horizontally from a few meters to over 500 m and are several meters to about 20 m thick (Hamner 1984). Great variability between swarms occurs independent of distance. Accordingly, swarms close together can have as many differences as swarms far apart; at least part of the variability in swarms can be generated by sorting mechanisms (Watkins *et a!.* 1986). Krill were found to be sorted by size, sex or moult stage due to different swimming speeds or sinking rates.

Euphausia superba is able to feed on a wide variety of particles, including small ones like nanoflagellates as well as large organisms such as copepods or its own larvae, and can be cannibalistic (e.g. Ikeda 1984). Quetin and Ross (1985) suggested a change in phytoplankton species composition towards nanoflagellates in the field due to preferential feeding on larger cells by krill. Differences in concentration and composition of the phytoplankton population were found in field studies by Holm-Hansen and Huntley (1984) with a marked decrease in larger phytoplankton cells but not in smaller ones.

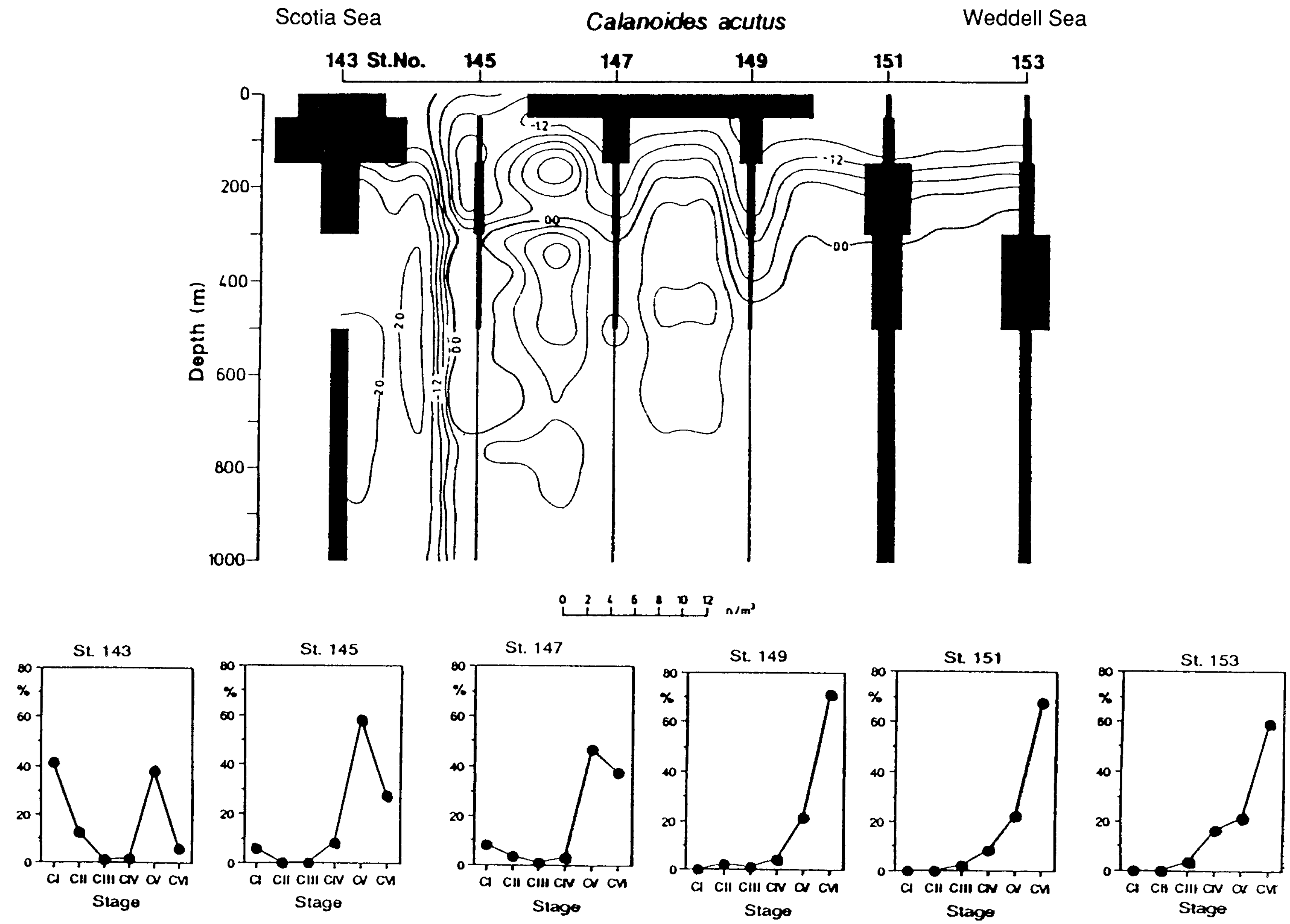

Figure 3 Vertical distribution and relative composition of developmental stages of *Calanoides acutus* in the top 1000 m along a transect from the Scotia Sea (St. 143) across the Weddell/Scotia Confluence (St. 145 - 149) to the Weddell Sea (St. 151 - 153) in November 1988 (Schnack-Schiel, unpubl.).

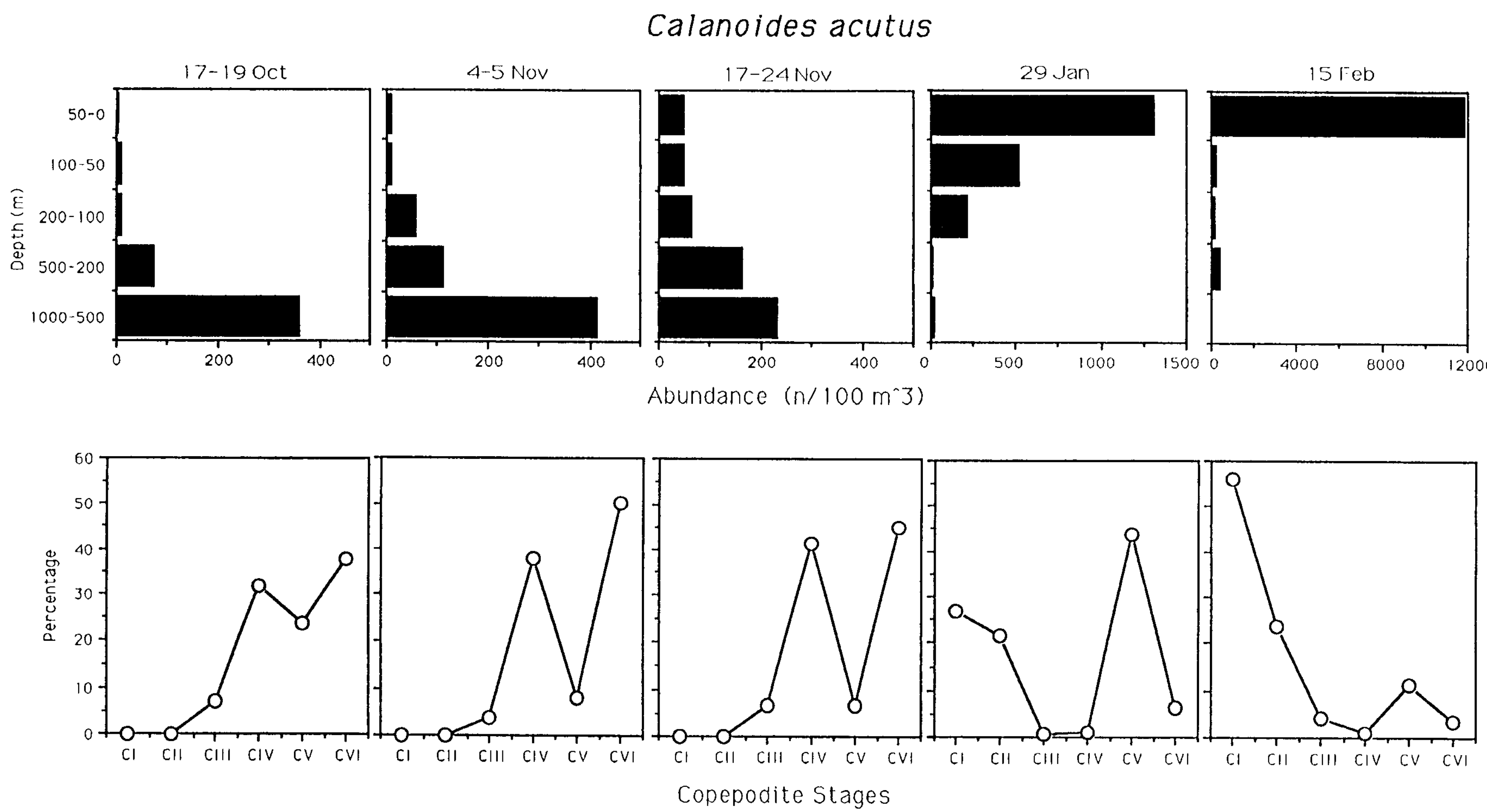

Figure 4 Seasonal vertical distribution and relative composition of developmental stages of *Calanoides acutus* in the top 1000 m in the southeastern Weddell Sea (Schnack-Schiel *et al.*, 1991).

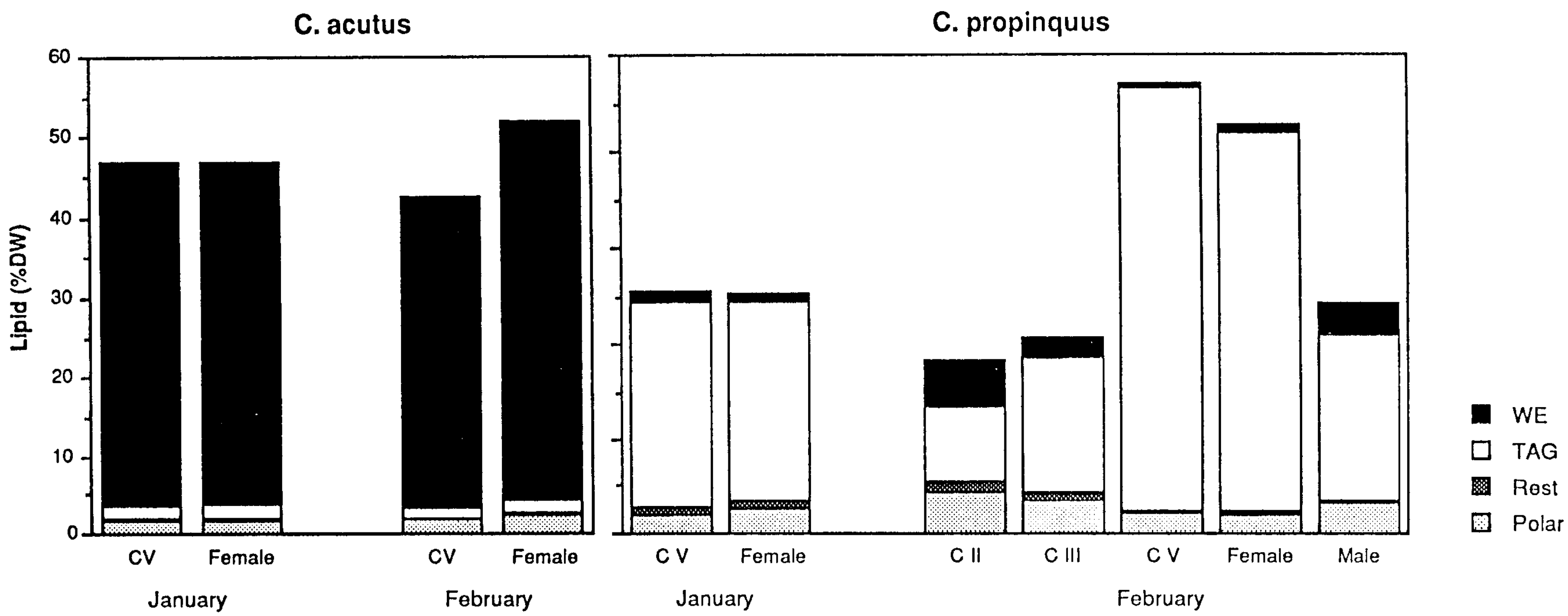

Figure 5 Lipid content and composition of *Calanoides acutus* and *Calanus propinquus* in the southeastern Weddell Sea, summer 1985. WE: wax esters; TAG: triacylglycerols; Polar: polar lipids. (Schnack-Schiel *et al.*, 1991).

The ability of krill to feed on a wide range of organisms can be very important, as the few studies on ozone depletion up to now suggest that the ozone hole will probably lead to a change in phytoplankton species composition as more tolerant species replace sensitive ones, i.e., an increase in incident ultraviolet light levels will most likely result in changes in the taxonomic structure of communities. Krill itself has a relatively high concentration of UV absorbing mycosporine amino acids (MAA's) which may act as natural ultraviolet filter system (Karentz et al. 1991).

Large seasonal variances in krill biomass occur, but also high interannual changes in the abundance (e.g. Heywood *et al.* 1985). Such variation where krill abundance is drastically reduced at localities normally recognized as areas of high biomass, cannot be attributed to intrinsic features of krill biology, and redistribution of krill outside their usual location by physical forces is suggested (Priddle *et al.* 1988). The winter preceding summer seasons of krill paucity had anomalous pressure distribution patterns over the Weddell and Scotia Seas. Priddle *et al.* (1988) suggest that an ocean-atmosphere mechanism, in which southward air flow forces surface (top 100 m) water to the south in the Scotia Sea and northern Weddell Sea and disrupts eddy activity. The two seasons with extremely low krill abundances (1977/78 and 1983/84) followed years when strong El Niño-Southern Oscillation (ENSO) events occurred. These events extended not only through the Pacific but also affected Atlantic areas such as the Benguela Current. It will be interesting in the future to see if strong ENSOs are followed by similar krill paucities.

The interannual variation in the extent and duration of ice cover seems also to affect the stock size of krill. During FIBEX, in January-March 1981 very high concentrations of krill ("superswarm") and of krill larvae were found (Brinton and Townsend 1984). The richest catches were obtained north of 60°S, e.g. north of the Weddell-Scotia Confluence, where water depth exceeded 2000 m and surface water temperature was above 1°C (Rakusa-Suszsewski 1984). This area is characterized by low larvae concentrations in other years, when krill larvae mainly occurred but in much lower densities in the eastern part of the Bransfield Strait, in the Antarctic Sound, and in the vicinity of Elephant Island (Brinton *et al.* 1986). The extent of ice cover in the previous winter stands out as well above that of the other years recorded. More data are required before causal relationships of this type can be formulated (Smetacek *et al.* 1990).

In winter swarming is minimal and krill are scarce in the water column (Siegel 1988). Field observations by divers indicate that krill live and feed under the ice during winter and spring (Stretch *et al.* 1988). The underside of the sea ice provides feeding grounds for adult krill preparing to reproduce and nursery grounds for krill larvae. In shallow waters in Lützow-Holm Bay krill were observed to overwinter in the layer close to the sea bottom feeding on detrital material on the sea bed (Kawaguchi *et al.* 1986).

In summary, *Euphausia superba* appears to be optimally adapted to the environmental conditions of the Southern Ocean. The animals form mobile swarms in summer, feed heavily on phytoplankton blooms and respond quickly with rapid growth. They are also adapted to the long Antarctic winter by being able to utilize relatively low phytoplankton densities, to feed on nanoflagellates, detritus and metazooplankton, and scraping ice algae underneath the ice floes (Fig. 6).

6.1.1. References

Andrews, K. J. H. 1966. The distribution and life history of *Ca!anoides acutus* (Giesbrecht). Discovery Rep. 34, 117-162.

Boysen-Ennen, E. and U. Piatkowski. 1988. Meso- and macrozooplankton communities in the Weddell Sea. Polar Biol. 9,9-31.

Brinton, E. and A. W. Townsend. 1984. Regional relationship between development and growth in larvae of Antarctic krill, *Euphausia superba*, from field samples. J. Crustacean Biol. 4, 224-246.

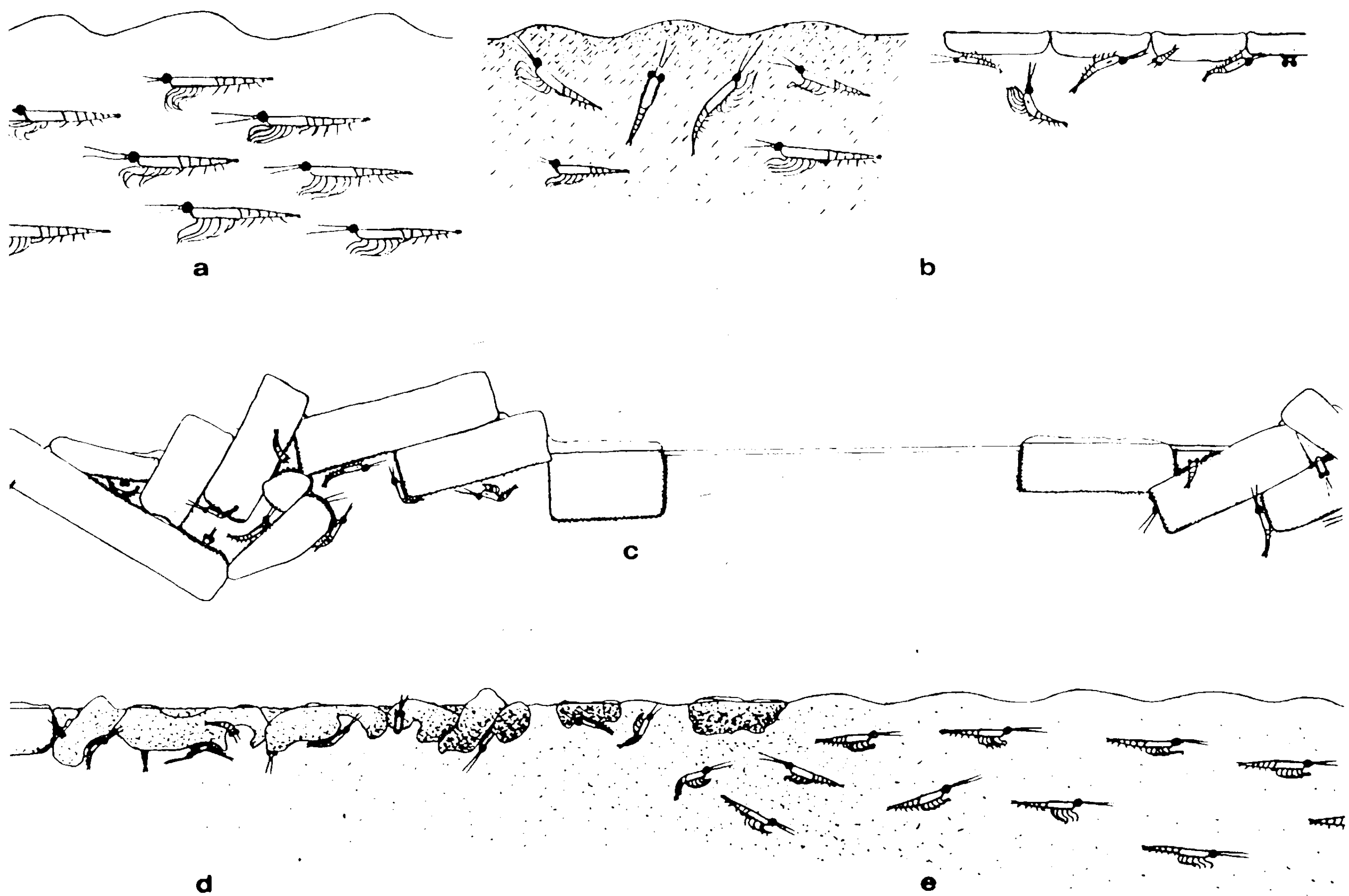

Figure 6 Hypothetical annual cycle of krill. The diagrams are either drawn from direct observation (a, c, d) or document processes that inevitably occur, assuming that krill prefer the ice cover to the open sea (b, e). a: Compact swarms forage for food in the open water in the absence of ice. b: During establishment of ice cover, frazil ice (dashes) consolidates to pancake ice collecting algal cells (dots) in the process. These algae can be efficiently utilized by adult and juvenile krill attracted to the ice. c: Krill congregate under ridges because of protection against predators and improved food supply. Productivity of ice algae under ridges is greater than under flat ice because of increased surface area and light-trapping properties of the ridge which functions as a light dome. d: Increased algal production in rotting ice provides a rich food source prior to water column blooming. e: Melting ice can stabilize a shallow surface layer in which blooms rapidly develop. Krill switch from scaping ice algae to filtering phytoplankton (Smetacek *et al.*, 1990).

Brinton, E., M. Huntley, and A. W. Townsend. 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.

Bröckel, K. v.1981. The importance of nanoplankton within the pelagic Antarctic ecosystem. In: G. Rheinheimer, H. Flügel, J. Lenz, B. Zeitzschel (eds.), *Lower Organisms and Their Role in the Food Web,* Kieler Meeresforsch. Sonderheft 5, p.61-67.

Clarke, A. 1988. Life in cold water: the physiological ecology of polar marine ectotherms. Oceanogr. Mar. Biol. Ann. Rev. 21, 341-453.

Daly, K. L. and M. C. Macaulay. 1988. Abundance and krill in the ice edge zone of the Weddell Sea, austral spring 1983. Deep-Sea Res. 35, 21-41.

Foxton, P. 1956. The distribution of the standing crop of zooplankton in the Southern Ocean. Discovery Rep. 28, 191-236.

Hamner, W. M. 1984. Aspects of schooling in *Euphausia superba.* J. Crustacean Biol. 4, Spec. No.1, 67-74

Hempel, G. 1985. On the biology of polar seas, particularly the Southern Ocean. In: J. S. Gray and M. E. Christiansen (eds.), *Marine Biology of Polar Regions and Effects of Stress on Marine Organisms,* John Wiley & Sons Ltd., Chichester, p.3-33.

Heywood, R. B., I. Everson and J. Priddle. 1985. The absence of krill from the South Georgia zone, winter 1983. Deep-Sea Res. 32, 369-378.

Holm-Hansen, O. and M. Huntley. 1984. Feeding requirements of krill in relation to food sources. J. Crustacean Biol. 4, Spec. No.1, 156-173.

Hopkins, T. L. and J. J. Torres. 1989. Midwater food web in the vicinity of a marginal ice zone in the western Weddell Sea. Deep-Sea Res. 36, 543-560.

Hubold, G. and I. Hempel. 1987. Seasonal variability of zooplankton in the southern Weddell Sea. Meeresforschung 31, 185-192.

Ikeda, T. 1984. Sequences in metabolic rates and elemental composition (C, N, P) during the development of *Euphausia superba* Dana and estimated food requirements during its life span. J. Crustacean Biol. 4, Spec. No.1, 278-284.

Jazdzewski, K., W. Kittel, and K. Lotocki. 1982. Zooplankton studies in the southern Drake Passage and in the Bransfield Strait during austral summer (BIOMASS-FIBEX, February-March 1981). Polar Res. 3, 203-242.

Karentz, D., F. S. McEuen, M. C. Land and W. C. Dunlap. 1991. Survey of mycosporine-like amino acid compounds in Antarctic marine organisms: potential protection from ultraviolet exposure. Mar. Biol. 108, 157-166.

Kawaguchi, K., S. Ishikawa and 0. Matsuda. 1986. The overwintering strategy of Antarctic krill *(Euphausia superba* Dana) under the coastal fast ice off the Ongul Islands in Lützow-Holm Bay, Antarctica. Mem. Nati. Inst. Polar Res., Spec. Issue 44, 67-85.

Marin, V. 1987. The oceanographic structure of the eastern Scotia Sea - IV. Distribution of copepod species in relation to hydrography in 1981. Deep-Sea Res. 34, 105-121.

Marin, V. 1988. Qualitative models of the life cycles of *Calanoides acutus, Calanus propinquus* and *Rhincalanus gigas.* Polar Biol. 8,439-446.

Montú, M. and I. R. Oliveira. 1986. Zooplanktonic associations, trophic relations and standing stock of krill and other groups of the community near Elephant Island (February-March 84/85). Nerita 1, 111-129.

Nöthig, E.-M., U. Bathmann, J. Jennings, E. Fahrbach, R. Gradinger, R. Gordon and R. Makarov (In press). Regional relationships between biological and hydrographical properties in the Weddell Gyre in late austral winter 1989. Marine Chemistry, Special Vol.

Priddle, J., J. P. Croxall, I. Everson, R. B. Heywood, E. J. Murphy, P. A. Prince and C. B. Sear. 1988. Large-scale fluctuations in distribution and abundance of krill - a discussion of possible causes. In: D. Sahrhage (ed.), *Antarctic Ocean and Resources Variability,* Springer-Verlag, Berlin, p.169-182.

Quetin, L. B. and R. M. Ross. 1985. Feeding by Antarctic krill, *Euphausia superba:* Does size matter? In: W. R. Siegfried, P.R. Condy and R. M. Laws (eds.), *Antarctic Nutrient Cycles and Food Webs,* Springer-Verlag, Berlin, p. 372-377.

Rakusa-Suszczewski, 5. 1984. Krill larvae in the Atlantic sector of the Southern Ocean during FIBEX 1981. Polar Biol. 3, 141-147.

Sakshaug, E. and 0. Holm-Hansen. 1984. Factors governing pelagic production in polar oceans. In: O. Holm-Hansen, L. Bolis and R. Gilles (eds.), *Marine Phytoplankton and Productivity,* Springer-Verlag, Berlin, p.1-18.

Sargent, J. R., R. R. Gatten and R. J. Henderson. 1981. Lipid biochemistry of zooplankton from high latitudes. Oceanus 7, 623-632.

Schnack-Schiel, S. B., W. Hagen and E. Mizdalski. 1991. Seasonal comparison of *Calanoides acutus* and *Calanus propinquus* (Copepoda: Calanoida) in the southeastern Weddell Sea, Antarctica. Mar. Ecol. Prog. Ser. 70, 17-27.

Siegel, V. 1988. A concept of seasonal variation of krill *(Euphausia superba)* distribution and abundance west of the Antarctic Peninsula. In: D. Sahrhage (ed.), *Antarctic Ocean and Resources Variability,* Springer-Verlag, Berlin, p.
219-230.

Siegel, V. and U. Piatkowski. 1990. Variability in the zooplankton community off the Antarctic Peninsula. Polar Biol. 10, 373-386.

Smetacek, V., R. Scharek, and E.-M. Nöthig. 1990. Seasonal and regional variation in the pelagial and its relationship to the life history cycle of krill. In: K. R. Kerry and G. Hempel (eds.), *Antarctic Ecosystems, Ecological Change and Conservation,* Springer-Verlag, Berlin, p.103-114.

Stretch, J. J., P. P. Hamner, W. M. Hamner, W. C. Michel, J. Cook and C. W. Sullivan. 1988. Foraging behavior of antarctic krill *Euphausia superba* on sea ice microalgae. Mar. Ecol. Prog. Ser. 44, 131-139.

Voronina, N. M. 1968. The distribution of zooplankton in the Southern Ocean and its dependence on the circulation of water. Sarsia 34, 277-284.

Watkins, J. L., D. J. Morris, C. Ricketts and J. Priddle. 1986. Differences between swarms of Antarctic krill and some implications for sampling krill populations. Mar. Biol. 93, 137-146.

6.2 Benthos

6.2.1 Introduction

In lieu of a formal background paper on benthic research in the Antarctic, a bibliography of some of the recent articles in this area is provided. These papers should give the interested reader a good background. We thank Dr. Wolf Arntz for providing the reference list.

6.2.2 Recent articles on benthic research in Antarctica

Arnaud, P. M. 1985. Essai de synthèse des particularités éco-biologiques (adaptations) des invertébrés benthiques antarctiques. Oceanis 11, 75-142.

Arnaud, P. M. 1987. Les écosystèmes benthiques des plateaux péri-insulaires des îles françaises du sud de l'océan Indien. *Actes du colloque sur la recherche française dans les Terres Australes.* Strasbourg, 129-138.

Clarke, A. 1983. Life in cold water: the physiological ecology of polar marine ectotherms. Oceanogr. Mar. Biol. Ann Rev. 21, 341-453.

Clarke, A. 1987. Temperature, latitude and reproductive effort. Mar. Ecol. Prog. Ser. 38, 89-99.

Clarke, A. 1988. Seasonality in the Antarctic marine environment. Comp. Biochem. Physiol. 90B(3), 461-473.

Clarke, A. 1990. Temperature and evolution: Southern Ocean cooling and the Antarctic marine fauna. In: K. R. Kerry and G. Hempel (eds.), *Antarctic Ecosystems. Eco.* Springer, Berlin, 9-22.

Clarke, A. 1991. What is cold adaptation and how should we measure it? Amer. Zool. 31, 81-92.

Clarke, A. and J. A. Crame. 1989. The origin of the Southern Ocean marine fauna. In: J. A. Crame (ed.), *Origin and Evolution of the Antarctic Biota.* Geol. Soc. Spec. Publ. 47, 253-268.

Dayton, P. K. 1990. Polar benthos. In: W. 0. Smith (ed.), *Polar Oceanography. Part B: Chemistry, Biology, and Geology.* Academic Press, London, 631-685.

Gallardo, V. A. 1987. The sublittoral macrofaunal benthos of the Antarctic shelf. Environment International 13, 71-81.

Lipps, J. H. and C. S. Hickman. 1982. Origin, age, and evolution of Antarctica. G. Morin (eds.), *The Environment of the Deep Sea, Vol.2.* Prentice-Hall, Englewood Cliffs, NJ, 324-356.

Pearse, J. S., J. B. McClintock and I. Bosch. 1990. Reproduction of Antarctic benthic marine invertebrates: tempos, modes, and timing. Amer. Zool. 30, 147-186.

Picken, G. B. 1984. Marine habitats - benthos. In: W. N. Bonner and D.W.H. Walton (eds.), *Key Environments: Anatarctica.* Pergamon Press, Oxford, 154-172.

Picken, G. B. 1985. Benthic research in Antarctica: past, present and future. In: J. S. Gray and M. E. Christiansen (eds.), *Marine Biology of Polar Regions and Effects of Stress on Marine Organisms. Proc. 18th EMBS Symp.,* John Wiley & Sons, London, 167-184.

Quiltry, P. G. 1990. Significance of evidence for changes in the Antarctic marine environment over the last 5 million years. In: K. R. Kerry and G. Hempel (eds.), *Antarctic Ecosystems. Ecological Change and Conservation.* Springer, Berlin, 4-8.

White, M. G. 1984. Marine benthos. In: R. M. Laws (ed.), *Antarctic Ecology, vol.2.* Academic Press, London, 421-461.

6.3 Fish

by Inigo Everson

6.3.1 Introduction

The main aims of this workshop are to identify those aspects of Southern Ocean fish biology that are most sensitive to climatic change and then to select those aspects which are likely to be good indicators of climatic change. The topic can be considered from two perspectives, using the exercise to find out more about the fish

a topic of considerable importance since many species are currently heavily exploited, and secondly to use fish to monitor climatic change. For both of these approaches the key to success must lie in an appreciation of the scales, spatial and temporal, that are affecting both the fish and the environment. The best indicators are likely to be those in which similar temporal and spatial scales are operating in both. This topic is well covered in a paper by Murphy *et al.* (1988). Although that paper deals primarily with krill the same general principles can be applied to fish.

A further point that should be borne in mind is that many of the effects that we identify are direct because the resultant change in the fish can be directly attributed to a change in the environment. Examples of such changes might be variations in distribution patterns arising from changes in oceanic circulation patterns. There are also indirect effects as for example, variation in condition index of the fish brought on by a change in food supply which was itself caused by some climatic effect.

In this paper my aim has been to consider all aspects of fish life history and try to identify interactions suitable for monitoring change. In this quest I have tried to find data that indicate the level to which such an interaction can be practically monitored. In order to achieve this it is useful to consider the life history of fish in a series of divisions. The divisions I have chosen for this paper are: egg, yolk-sac larvae, post yolk-sac larvae, juvenile and mature fish. I have also included a brief discussion on growth.

6.3.2 The environment

This topic is being covered by other papers in the meeting. The following is a summary of my perceptions on the marine environment relevant to climate change and fish.

Water circulation is prone to significant variation both in the short and long term. This will affect the way passive particles are transported in the system and it is here that we are likely to find the most significant interactions. Variables to consider here are:

i. variations in "local" circulation
ii. timing and duration of primary production bloom
iii. development of "fish food" types such as copepods and euphausiids.

Ice cover is a further topic that intuitively is of relevance because of indirect effects through the timing and extent of primary production, provision of habitats and affording protection from some predators.

6.3.3 Biological characteristics of fish likely to be affected by climate change

6.3.3.1 Egg stage

Although far from complete, considerable progress has been made in recent years over the identification of the eggs and larvae of Southern Ocean fish. Many species are covered by the key and identification notes prepared by North and Kellermann (Kellermann 1989).

Antarctic fish characteristically produce large yolky eggs which take several months to hatch

(Fig. 1, Everson 1984). Typically these eggs are laid on the seabed, frequently in nests (Kellermann 1989). Since the eggs are immobile and unlikely to be affected much by temperature change at the spawning location, it is probably safe to assume that there is little variation in the time from spawning to hatching. Few studies have been undertaken on this subject and hence there is room for further experimental research. Laboratory studies on *Notothenia neglecta* indicate that at Signy Island it takes about 150 days from spawning to hatching whilst at South Georgia, where the temperature is slightly warmer, the same process takes 103 days (White *et al.* 1982). This difference is probably due to the geographical location because the temperature variation at each site during this period is very much less than the temperature difference between the two sites.

Daniels (1978) reported accumulations of eggs together with nest building and brood protection in *Harpagifer* at Arthur Harbour, Antarctic Peninsula. This was confirmed by observations of newly fertilized eggs of *Harpagifer* sp. at Signy Island and *Parachaenichthys georgianus* at South Georgia which have shown that the eggs increase in volume, become adhesive, and stick together in a mass on the seafloor (White *et al.* 1982).

During the same study, the eggs *of Notothenia neglecta* when fertilized did not swell or become adhesive but remained buoyant. In an experiment at Signy Island the eggs became negatively buoyant after 14 days whereas in a similar experiment at South Georgia they floated throughout the whole period of development.

There are records of these eggs being taken in the open ocean in the surface water (Kellermann 1989) suggesting that the eggs float for part, if not all of the development phase. It is not clear how typical this phenomenon is but these eggs must be considered as passive particles with the result that hatching location and subsequent development will be dependent on water circulation. Information on the frequency of occurrence of eggs in plankton samples should provide some indication of the extent of the phenomenon.

Spawning seasons are fairly well described for many species and therefore, assuming that egg development proceeds at a constant rate in relation to temperature, we need to question whether hatching will occur within a brief, predictable time period. The large yolk-sac reserves probably allow many species to cater for some variation in timing of the start of the production season (Kellermann 1989). However, for a system with such marked seasonality in its production season it is clearly important that the eggs hatch near the optimum time for larval development and growth. Since it is unlikely that the duration of egg development changes much, hatching date must be most closely related to spawning date and this is likely to be a function of the condition of the adult fish in the preceding months. This topic is considered again later.

6.3.3.2 Yolk-sac stage

Newly hatched larvae go through a period of development when they are growing, largely at the expense of their yolk-sac, a process taking about one or two months depending on species and location. It seems reasonable to assume that at this time the larvae are pelagic, although there are very few published records. Kellermann and Kock (1988) have provided a good description of spatial and temporal variation in this and the post-yolk sac larval phase, but because this paper considers both stages it is discussed in the next section.

The larvae have a limited ability to swim at this stage and must therefore be carried more or less passively on ocean currents. It is possible that at this time they are demersal and, being beyond the range of plankton nets, are difficult to sample. Such a strategy would, however, make them particularly vulnerable to predation by benthic invertebrates and demersal fish.

During this phase their main nutritive supply is obtained from the yolk-sac and hence they are not directly dependent on the time of the primary production bloom or the availability of microplankton. It is to be assumed that there is a smooth transition from this stage of the post-yolk-sac larval stage and also that at this time they begin to feed actively.

6.3.3.3 Post-yolk-sac larval stage

Following on from the yolk-sac stage there are a series of post-yolk-sac larval stages during which

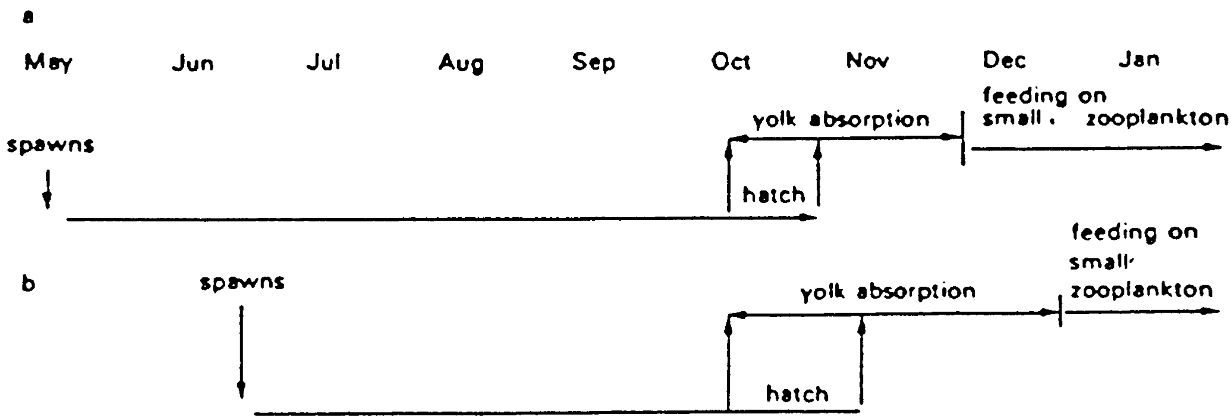

Figure 1. Schematic representation of egg and larval development in two Antarctic fish: (a) *Notothenia neglecta* and (b) *Harpagifer antarticus*.

time the young fish becomes totally dependent on external food supplies. The body musculature develops so that the larvae are able to swim, although probably not sufficiently well as to maintain position against the current. In their paper Kellermann and Kock (1988) have shown that there is considerable variation in the abundance of larval *Nototheniops larseni, Notothenia kempi* and *Pleuragramma antarcticum.* These results indicate a strong within season variation, where there is some evidence for a spring buildup followed by a summer decline in numbers and, on top of this, a strong inter-annual variation.

Considering the within season component first, results from the 1977/78 season for *Nototheniops larseni* show high abundance during November/December in the Bransfield Strait and Elephant Island region. This was followed by a decline during January/February leading to a complete absence from Elephant Island in March and lower density elsewhere (Fig. 2). The differences between the successive monthly series can be attributed to several causes such as:

1. Development of the larvae to a point where they can avoid the net
2. Predation by nekton and birds
3. Passage through the region in the circumpolar current.

All of these are possible and warrant study. The first is a common phenomenon encountered with plankton sampling but assuming it can be quantified it can be taken into account. The other two, if quantified, can also provide useful information.

If now we include interannual variation we see that in some instances this is as great as that within a season (Fig. 3). For example the start of the 1977/78 season appears particularly good for *Nototheniops larseni.* In that season also, the northern limit of pack ice was well north. In January/February the 1981/82 season seems slightly poorer whilst the return of the pack ice in March 1981 is coincident with high concentrations in the vicinity of Elephant Island. Thus although the early life history stages are regularly found in this area the extent and amounts are subject to considerable variation.

Examination of the results from the other species, *Nototheniа kempi, Pleuragramma antarcticum* and *Electrona antarctica* (Fig. 4) indicates a similar story. At this stage it is impossible to differentiate between variability in abundance of the fish and variation in the water circulation patterns; both almost certainly contribute to the picture. Kellermann and Kock (1988) considered the distribution of catches with respect to water circulation and concluded that the distribution of *Nototheniа kempi* was controlled by a large cyclonic gyre to the west of the Antarctic Peninsula which transports larvae over the shelf area and as a result may act as a retention area. They also note that larvae of the same species around Elephant Island are likely to be carried out of that immediate area by wind driven surface currents. Development from the larval stages is more or less continuous and results in the production of juveniles having similar form to the adult fish.

6.3.3.4 Juvenile stage

By the time they reach the juvenile stage they are able to swim actively both against the current and in pursuit of prey. In theory this should be the phase when the demersal fish return to the shelf area. For those species living more or less within a basin area such as Bransfield Strait this may present few problems, but, for example, further east in the South Orkneys or at South Georgia the juveniles could easily have been carried considerable distances from suitable shelf areas. For example *Notothenia neglecta* and *N. rossii* fingerlings were found widely dispersed over the Scotia Sea, well away from the nearest shelf (Fig. 5).

During this phase the fish are dependent on planktonic food. It is therefore reasonable to hypothesize that their distribution and growth are likely to be related to the distribution and abundance of major food sources such as copepodid stages and euphausiid larvae.

6.3.3.5 Adult stage

The adult phase of the life-history of notheniids is typically demersal. This is not true of all since

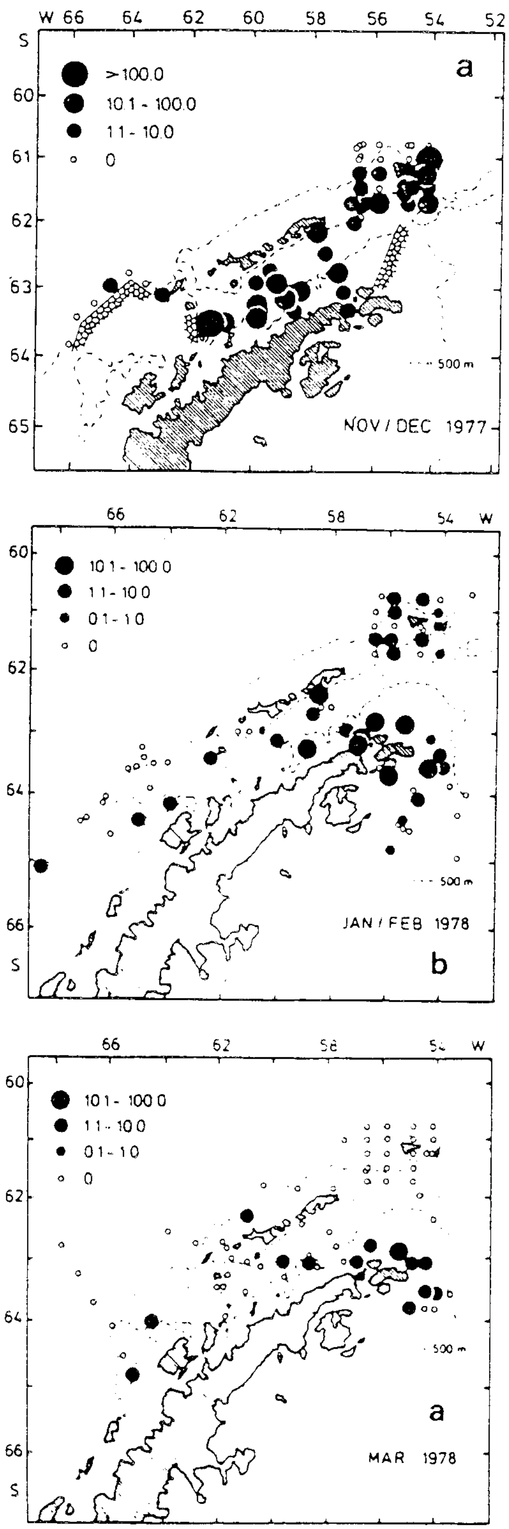

Figure 2. Quantitative distribution (number per 10^3 m^3 of post yolk-sac larval *Nototheniops larseni* during the 1977/78 season (Kellermann and Kock, 1988).

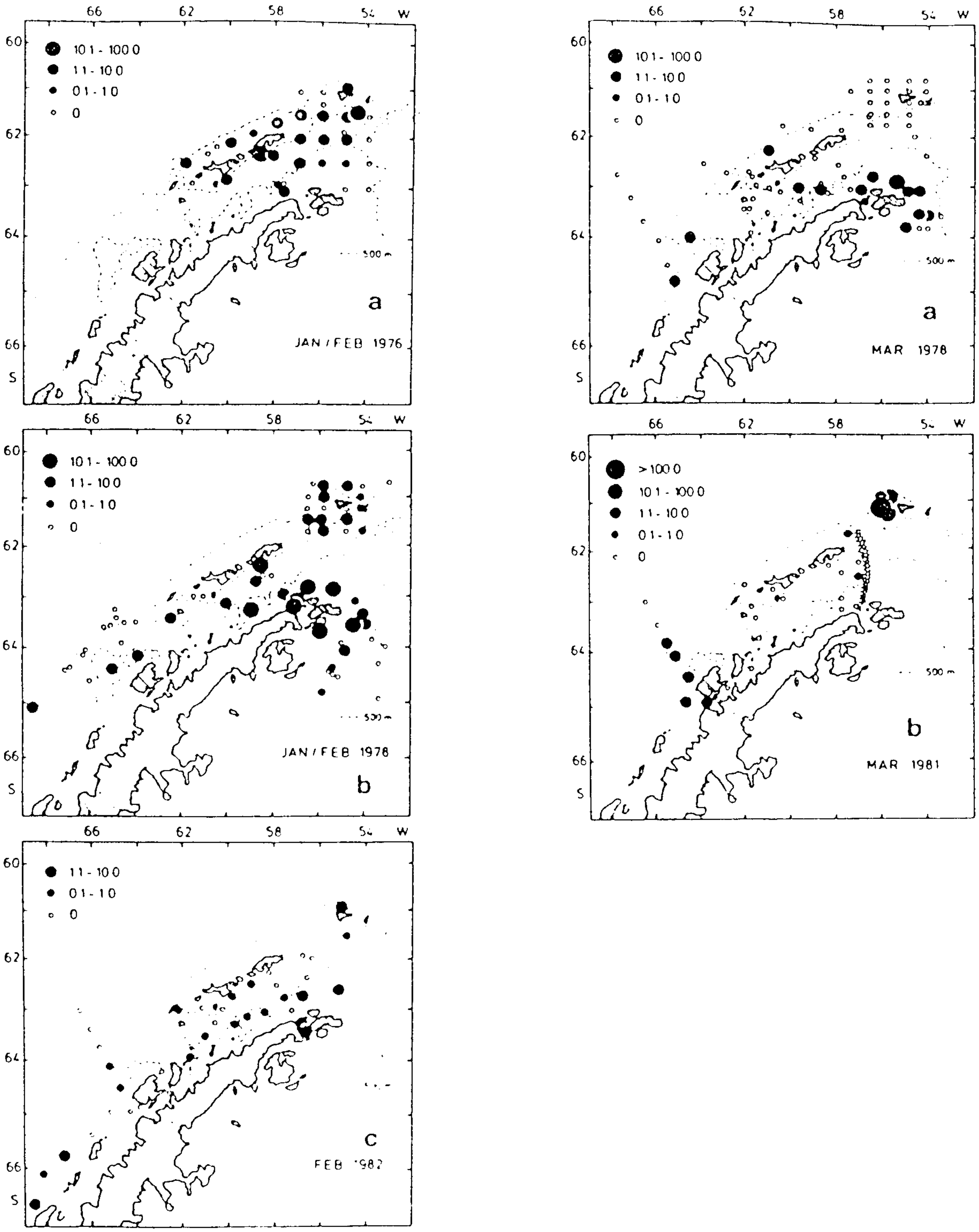

Figure 3. Quantitative distribution of post yolk-sac larval *Nototheniops larseni* at similar periods in different seasons (Kellermann and Kock, 1988).

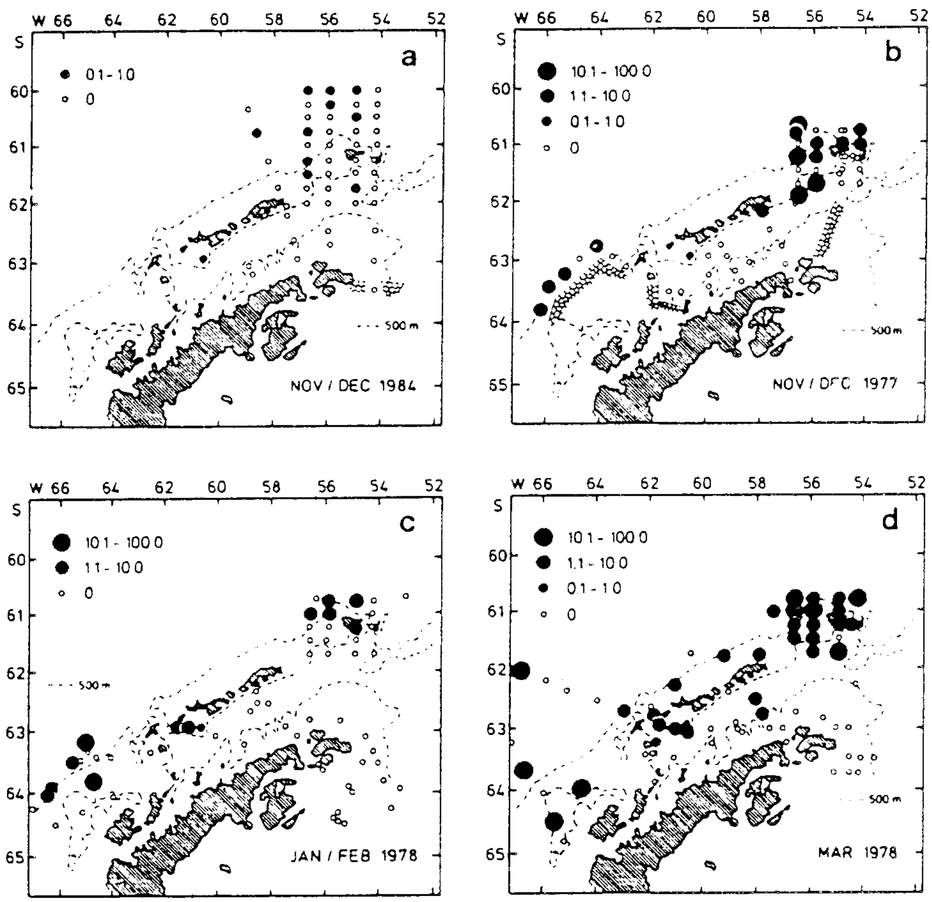

Figure 4a. Quantitative distribution of early stages of *Electrona antarctica* (Kellermann and Kock, 1988).

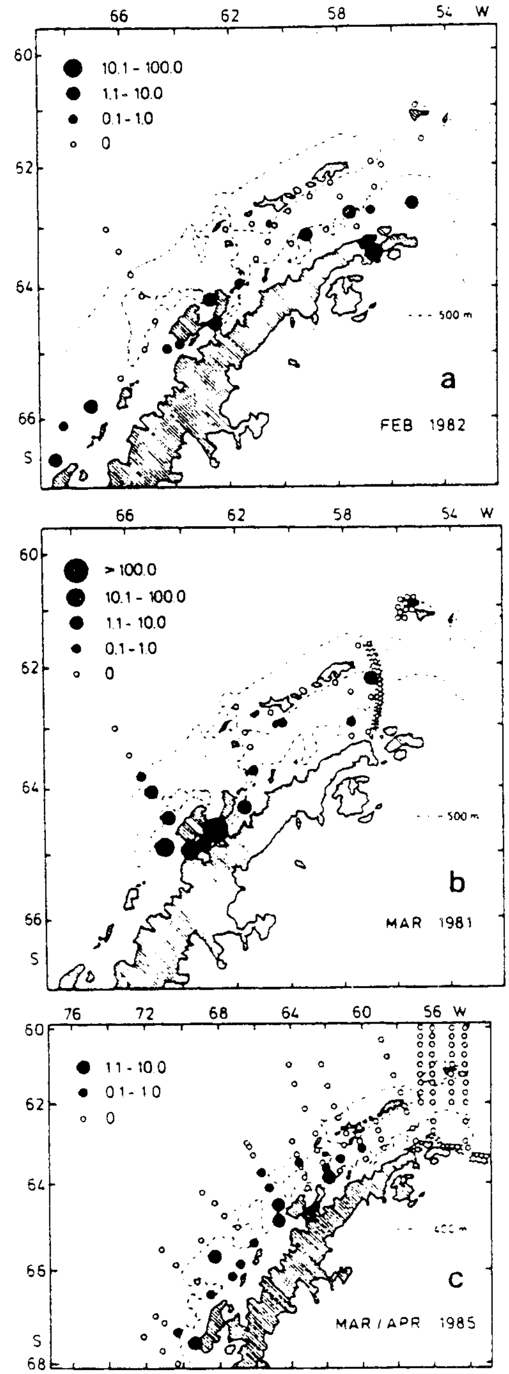

Figure 4b. Quantitative distribution of post yolk-sca larval *Pleurogramma antarcticum* (Kellermann and Kock, 1988).

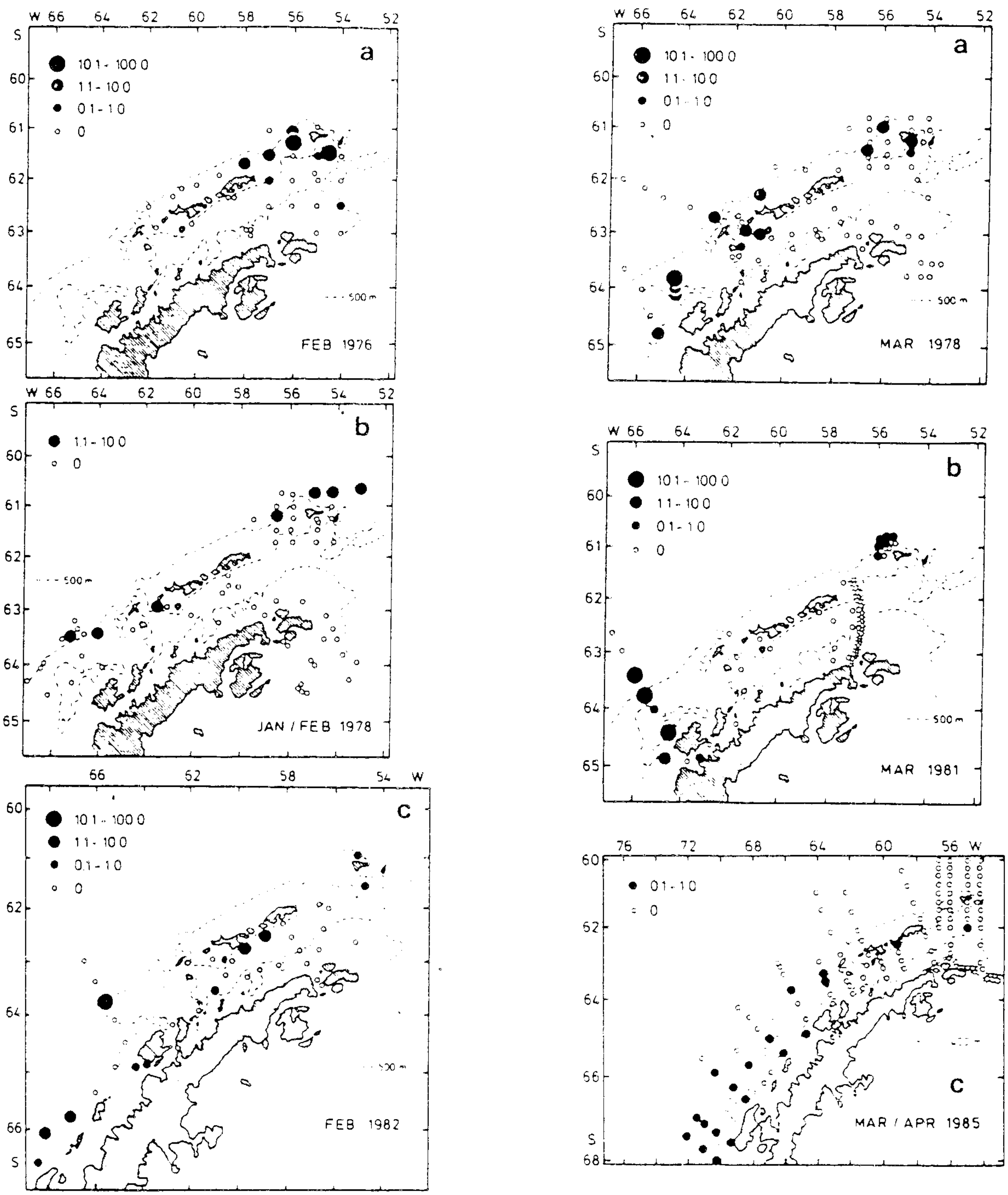

Figure 4c. Quantitative distribution of post yolk-sac larval *Notothenia kempi* (Kellermann and Kock, 1988).

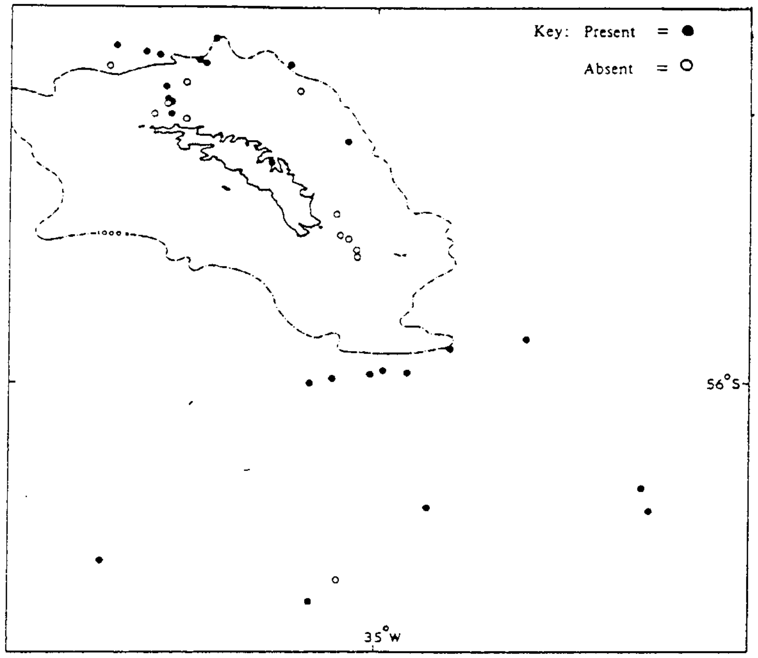

Figure 5. Distribution of pelagic phase postlarval *Notothenia neglecta* in the Scotia Sea from neuston samples (White et al., 1982).

Pleuragramma antarcticum is holopelagic along with the Myctophidae.

Consider first the holopelagic. *Pleuragramma* is a high latitude species which lives for about the first two years of its life in the surface water of the iceshelf zone feeding on small zooplankton (Fig. 6). From about age two they migrate offshore where they feed on krill; finally they migrate inshore to spawn, by which time they are feeding largely on *Euphausia crystallorophias* (Hubold 1985).

At lower latitudes the Myctophidae are widespread in the open ocean. Interest in the group has increased following the development of an experimental fishery for *Electrona carlsbergi* in the 1980's (CCAMLR 1990a). This species is known to occur in the polar frontal zone. Dense concentrations are formed during the summer season (December - February) in the 50-100 m depth layer while in the winter (June) they are dispersed at a depth greater than 200 m (Kozlov *et al.* 1990). Further information on the distribution of life-history stages is postulated by Zemsky and Zozutia (1990) who, based on a series of research cruise data, suggest that *E. carlsbergi* feeds in the polar frontal zone but spawns in the subtropical frontal and subtropical zones to the north. In the Atlantic sector this is presumed to take place as a result of a large gyre off the Argentine shelf (Gorchinskiy *et al.* 1990). From this information it is clear that the distribution of *E. carlsbergi* is controlled by oceanic circulation and that variations in circulation pattern brought on by climatic change are likely to have a major effect both directly and indirectly by controlling the amount of copepods, their main food (Gerasimova 1990), that are available. An understanding of these interactions is clearly of importance since this species is currently the subject of an expanding fishery in the Atlantic sector.

The majority of Southern Ocean fish are predominantly demersal when fully grown, although many do undertake diurnal vertical migrations to feed on krill. Two such examples are *Champsocephalus gunnari* and *Notothenia rossii.* When mature they are unlikely to be affected directly by climatic change but if such changes affect the amount of food brought to their area then indirect effects are clearly possible.

During a demersal fish survey at South Georgia in January and February this year we noted that very few of the *Champsocephalus* had been feeding on krill and few krill swarms were identified on the echosounder. Added to this only a small proportion of the fish large enough to spawn had gonads which were undergoing the final maturation process, suggesting that food may have been in short supply for some time previously. It is known that in some years not all the mature fish spawn (Kock 1990). It is not clear what proportion of the mature fish will spawn this year but only about ten percent had gonads developing in such a way that spawning could take place at the normal time in March or April (Fig. 7). There is therefore the possibility that a significant proportion of the population may be spawning late or not at all. A late spawning coupled with a more or less fixed egg development phase would mean that the larvae would be entering the plankton later than normal.

There are clear implications here that a predator/prey link involving *Champsocephalus* and krill may be operating. Predator/prey relationships involving krill traditionally have looked towards the warm-blooded predators such as penguins, albatross and fur seal (CCAMLR 1990b) but this information indicates that some fish species need also be considered.

6.3.3.6 Growth

Growth can be described by the general equation:

$$G=I-E-B-A-R$$

where, in energetic terms, G = growth, I = ingestion, E = unabsorbed energy, B = basal metabolism, A = activity and R = reproduction.

All of the factors on the right hand side of the equation are likely to be influenced by temperature and therefore it is to be expected that, on balance, growth will also be affected by temperature. For a given species B and A probably will not vary much from year to year, however the balance, which must be partitioned between somatic growth and development of gonads may well be strongly influenced by the fish's ability to find suitable food.

The energy that is ingested (I) depends on the type and amount of food that is available. Even though benthos feeders may have food available year round this may not always be utilized and may

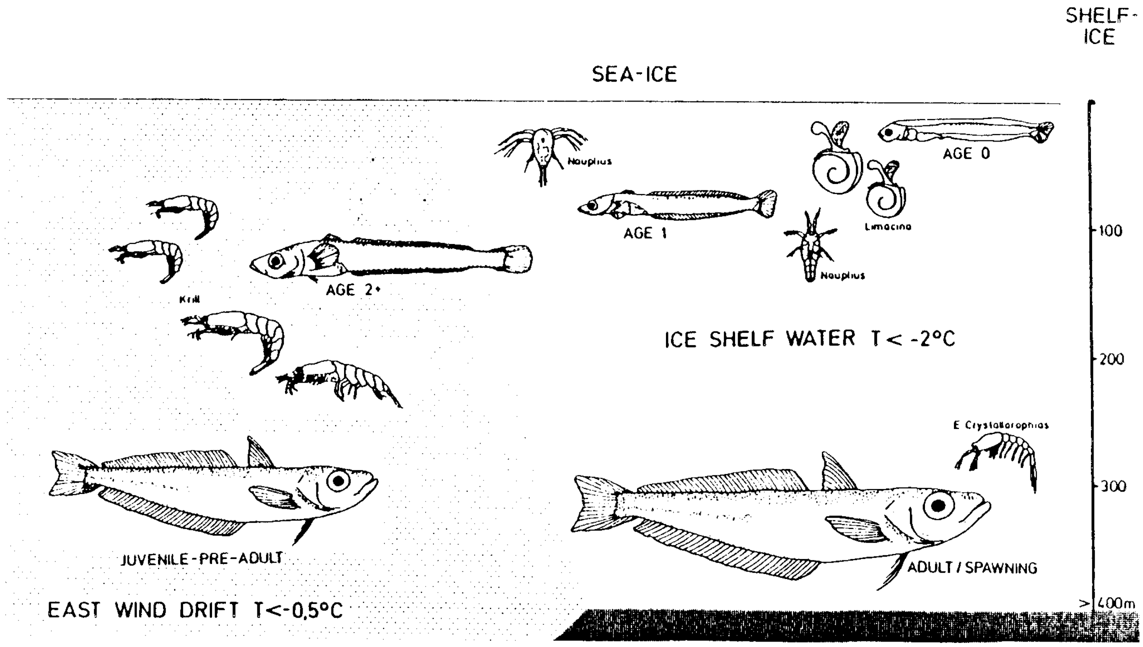

Figure 6. Schematic life-cycle of *Pleurogramma antarcticum* in the Weddell Sea (Hubold, 1985).

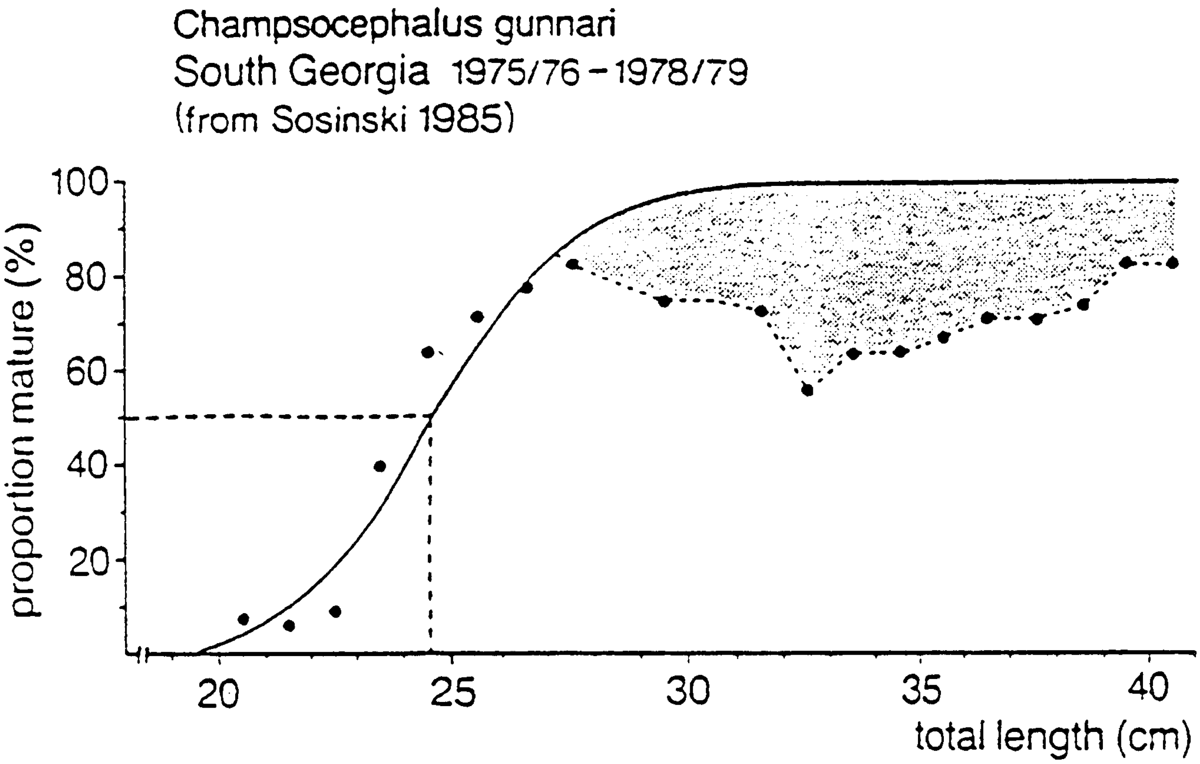

Figure 7. Spawning maturity surve for *Champsocephalus gunnari* (both sexes combined) around South Georgia in 1975/76 (Kock, 1990).

itself be of varying quality (see Fig. 8). Demersal fish that are pelagic feeders are dependent on food being brought to them.

This may pose problems particularly since the supply of one such dietary component, krill, may not be continuously available. Typical fish that fall into this latter category are *Notothenia rossii* and *Champsocephalus gunnari*. Thus in "good krill years" they may grow at a normal rate with all mature fish spawning at the normal time. Conversely in "bad krill years" growth may be slow with few mature fish spawning. Size-at-age keys have been published for both species and these show differences between years (Tables 1, 2). Part of this variation is probably due to differences in the interpretations used by individual workers but underlying this is almost certainly variation caused by the environment. Clearly there is scope to investigate this to determine the "normal" levels so as to be able to detect deviations from it.

6.3.4 Potential study activity within GLOBEC

While there are very many species of fish present in the Southern Ocean it is important when considering those suitable for addressing the aims of GLOBEC to restrict this list to a few key species. Bearing in mind that much information on the status of individual species can be derived from fishery data, species of current commercial interest should be of highest priority. This list should be supplemented by species of major ecological significance or those which are convenient to study. As a first step I would suggest the following species:

Species of commercial interest:

Champsocephalus gunnari
Chaenocephalus aceratus
Pseudochaenichthys georgianus
Chaenichthys sp.
Chionodraco
Notothenia gibberifrons
Notothenia rossii
Dissostichus eleginoides
Dissostichus mawsoni
Electrona carlsbergi

Species that are of scientific interest or are convenient to study:

Harpagifer sp.
Notothenia neglecta
Pleuragramma antarcticum
Electrona antarctica

Using these species various projects can then be defined. For the most part these are process-oriented investigations aimed at gaining a better understanding of the dynamics of the ecosystem. Irrespective of their value in detecting climate change such studies could provide valuable science and have considerable application within CCAMLR. Based on the discussion above I would suggest the following experimental and field studies would be of particular relevance to GLOBEC.

Improve documentation of egg stage
Identify those species with demersal and those with pelagic eggs
Determine time from spawning to hatching and hatching date
Determine growth rates of early life-history stages
Identify main food sources for early life-history stages
Determine growth rates of all life history stages
Determine preferred food types

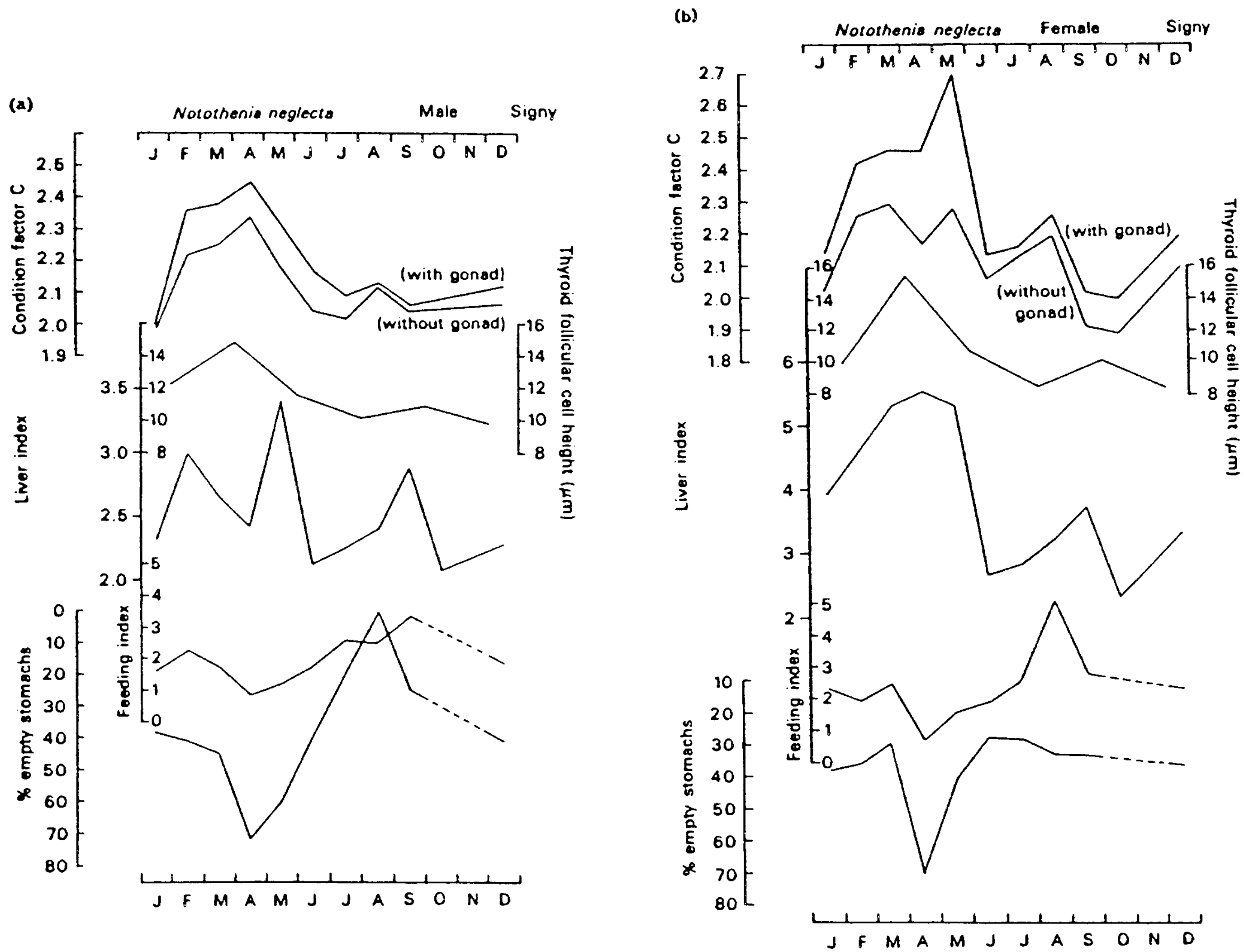

Figure 8 Some seasonal cycles in *Notothenia neglecta*. (a) male and (b) female.
Liver index = 100 x liver weight/(total weight-gonad weight); Feeding index = 100 x food weight/total weight.

locality	L_{∞} cm	W_{∞} (g)	K	t_0	data source
South Georgia	42.1	-	0.3978	-1.3557	Evaluated from OLSEN (1955)
South Georgia	65.1	2133	0.1570	0.3849	KOCK (1981)
South Georgia	64.3	2046	0.1528	0.2673	KOCK (1981)*
South Georgia ♂	177.7	-	0.032	-0.687	Evaluated from KOCHKIN (1982)
South Georgia ♀	131.6	-	0.043	-0.632	"
South Georgia	45.55	663	0.3542	0.4040	SOSINSKI (1981)
South Georgia	58.0	1384	0.196	-0.272	Evaluated from GUBSCH (1982)
S. Orkney Is.	42.23	496	0.5942	1.0427	SOSINSKI (1982)
S. Orkney Is.	49.26	853	0.399	0.272	Evaluated from GUBSCH (1982)
Elephant I.	40.54	434	0.6887	1.1355	SOSINSKI (1981)
S. Shetland Is.	53.95	-	0.428	0.488	Evaluated from GUBSCH (1982)
Bouvet	92.41	-	0.160	0.880	"
Kerguelen	34.05	231	0.7144	0.9447	SOSINSKI (1981)
Kerguelen	40.0	364	0.3702	-0.3505	DUHAMEL (unpubl.)**

* evaluated by non-linear regression

** estimated by PETERSEN method from length frequency distribution

Table 1.

Values of parameters of the von Bertalanffy growth equation for *Champsocephalus gunnari* from various localities. (Kock, Duhamel and Hureau 1985)

age class	SOUTH GEORGIA OLSEN (1955)	SOUTH GEORGIA KOCK (1981)	SOUTH GEORGIA SOSINSKI (1981)	SOUTH GEORGIA KOCHKIN (1982)	SOUTH GEORGIA GUBSCH (1982)	S. ORKNEY ISLANDS SOSINSKI (1981)	S. ORKNEY ISLANDS GUBSCH (1982)	ELEPHANT ISLAND SOSINSKI (1981)	S. SHETLAND ISLANDS King George SOSINSKI (1981)	S. SHETLAND ISLANDS Deception SOSINSKI 1981)	S. SHETLAND ISLANDS King George GUBSCH (1982)	BOUVET GUBSCH (1982)	KERGUELEN SOSINSKI (1982)	KERGUELEN DUHAMEL (unpubl.)
0	-	6.6	-	-	-	-	-	-	-	-	-	-	-	4.2
I	-	15.8	-	(13.5)	-	-	-	-	-	-	-	-	17.27	15.6
II	-	22.3	21.27	18-21	-	-	23.8	-	-	25.23	25.4	26.5	26.90	24.4
III	27.1	27.9	27.97	21-25.5	26.7	30.31	30.5	34.95	34.00	34.87	34.6	35.4	30.03	28.0
IV	32.8	33.3	32.75	26.1-30.2	29.4	34.69	39.2	37.66	38.61	38.25	42.7	45.4	32.95	32.2
V	35.1	37.7	36.66	30.0-34.2	37.3	38.03	42.7	39.13	41.09	39.0	46.5	51.6	-	34.5
VI	36.9	43.2	39.11	34.5-39.6	40.9	39.47	43.8	39.78	42.2	-	48.6	-	-	-
VII	37.6	46.0	40.32	36.0-43.0	44.4	41.22	-	42.0	43.12	-	-	-	-	-
VIII	39.3	48.1	41.63	40.5-46.0	48.4	43.33	-	45.0	46.45	-	-	-	-	-
IX	41.2	-	42.75	48.5-49.0	48.2	(41.00)	-	-	44.33	-	-	-	-	-
X	40.5	-	44.46	52-57	-	(44.00)	-	-	(46.00)	-	-	-	-	-
XI	41.5	-	44.75	-	-	-	-	-	(50.00)	-	-	-	-	-
XII	42.5	-	44.67	(57.5)	-	-	-	-	-	-	-	-	-	-
XIII	-	-	48.71	(61.5)	-	-	-	-	-	-	-	-	-	-
XIV	-	-	48.86	-	-	-	-	-	-	-	-	-	-	-
XV	-	-	51.40	-	-	-	-	-	-	-	-	-	-	-
XVI	-	-	-	-	-	-	-	-	-	-	-	-	-	-
XVII	-	-	(45.0)	-	-	-	-	-	-	-	-	-	-	-
XVIII	-	-	(58.0)	-	-	-	-	-	-	-	-	-	-	-
XIX	-	-	(54.0)	-	-	-	-	-	-	-	-	-	-	-

Table 2.

Mean length (cm) for each age class in *Champsocephalus gunnari* from various localities. (Kock,Duhamel and Hureau 1985)

Armed with basic information on the key processes associated with climate change, monitoring programmes can be defined. These need to be defined in terms of time and space scales and should include a sampling protocol. Some projects that would address the aims of GLOBEC are listed below.

a. Small area during the critical one or two months of egg and larval development

Undertake egg and larval surveys in selected shelf areas (e.g. North 1987)

b. CCAMLR subarea scale during period of egg and larval development

Determine main water movement m these selected areas

c. Shelf area relevant to demersal species during period of final gonad maturation

Determine distribution and availability of main food sources
Determine spawning dates
Determine proportion of mature fish that are spawning each season
At selected sites monitor growth rate of individual year classes

d. Southern Ocean throughout year

Monitor commercial fishing activity (this is in progress through CCAMLR)

6.3.5 Collaboration with other organisations

The main aims of GLOBEC may be interpreted as providing information on the natural variation within many fish species. Such information is of direct relevance to CCAMLR as it is likely to provide background information against which information on commercial operations can be considered for the development of conservation measures.

A fish component of GLOBEC is also of interest to CCAMLR through its Ecosystem Monitoring Programme (CEMP) in providing information on the status of several species that are important prey items for birds and seals.

6.3.6 Acknowledgments

I am grateful to Dr. Tony North for taking time to discuss the subject matter with me and for his comments on an early draft of the manuscript.

6.3.7 References

CCAMLR 1990(a). Report of the Working Group on Fish Stock Assessment. SCCAMLR-JX, Annex 5, 185-187.

CCAMLR 1990(b). Report of the Ninth Meeting of the Scientific Committee. SCCAMLR-IX, para. 5.1-5.52

Everson, I. 1984. Fish biology. In: R. M. Laws (ed.), *Antarctic Ecology*, Vol.2, Academic Press, London, 491-532.

Gerasmimova, 0. V. 1990. Feeding and food intake of *Electrona carlsbergi* (Taning) (Myctophidae). CCAMLR WG-FSA-90/18, 9 pages.

Gorchinsky, K. V., V. M. Kiselva and A. A. Film. 1990. Comparative biological characteristics of *Electrona carlsbergi* (Taning) (Myctophidae) from the notal and Antarctic areas in the Southern Ocean Atlantic sector. CCAMIR WG-FSA90/21, 18 pages, 10 figs.

Kellermann, A. (ed.). 1989. *Identification Key and Catalogue of larval Antarctic fishes.* BIOMASS Scientific Series No.10, 136pp.

Kellermann, A. and K.-H. Kock. 1988. Patterns of spatial and temporal distribution and their variation in early life stages of Antarctic fish in the Antarctic Peninsula Region. In: D. Sahrhage (ed.), *Antarctic Ocean and resources Variability*, Springer Verlag, Berlin, pp.147-159.

Kock, K.-H. 1990. Reproduction of the mackerel icefish *(Champsocephalus gunnari)* and its implications for fisheries management in the Atlantic sector of the Southern Ocean. SC-CAMLR-SSP/6, 51-68.

Kock, K.H., G. Duhamel and J.-C. Hureau. 1985. *Biology and Status of Exploited Antarctic Fish Stocks: A Review.* BIOMASS Scientific Series, Vol. 6, 143 pp.

Kozlov, A. N., K. V. Shust, and A. V. Zemsky. 1990. Seasonal and annual variability in distribution of *Electrona carisbergi* in the southern polar front area with the South Georgia area taken as an example. CCAMLR WG-FSA-90/35, 7 pages, 18 figs.

Murphy, E. J., D. J. Morris, J. L. Watkins and J. Priddle. 1988. Scales of interaction between Antarctic krill and the environment. In: D. Sahrhage (ed.), *Antarctic Ocean and Resources Variability,* Springer-Verlag, Berlin, 120-130.

North, A. W. 1987. Distribution of fish larvae at South Georgia: horizontal, vertical and temporal distribution and early life history relevant to monitoring year-class strength and recruitment. SC-CAMLR-SSP/4, 107-141.

Zemsky, A. V. and S. A. Zozutia. 1990. Functional subdivision of the habitat area of *Electrona carlsbergi* (Taning, 1932) family Myctophidae, taking into account longitudinal zones of the Southern Ocean. CCAMLR WG-FSA-90136, 12 pages, 13 figs.

6.4 Birds and Mammals

by William R. Fraser

6.4.1 Introduction

A central tenet of Antarctic ecology suggests that increases in the populations of many Southern Ocean upper trophic level predators during the last four decades resulted from an increase in prey availability brought on by the decrease in baleen whale stocks due to commercial exploitation (Laws 1985). Based on a recent analysis of long-term surface temperature trends and changes in penguin populations on the Antarctic Peninsula, satellite images of ocean ice cover, and winter data from the Scotia and Weddell seas, Fraser *et al.* (in press) questioned this tenet. As an alternative hypothesis, they proposed that increases in the populations of these predators were due to a gradual decrease in the frequency of cold years with extensive winter sea ice cover resulting from environmental warming. In this contribution, my aim is to provide a summary of the data presented by Fraser *et al.* (in press) and relate them to GLOBEC-stated objectives. For the sake of brevity, portions of the original manuscript have been condensed or excluded from this contribution. Readers are encouraged to consult the original manuscript for more detail on the topics and ecological principles presented here.

6.4.2 Changes in penguin populations on the Antarctic Peninsula and the whale-reduction hypothesis

Among the many krill-eating, Southern Ocean predators that inhabit the Antarctic Peninsula and islands of the Scotia Arc, the increase in the abundance of Chinstrap Penguins *(Pygoscelis antarctica)* has been conspicuous. At some localities, numbers have increased by as much as 500% in the last 20 years (Rootes 1988). Chinstraps have also expanded their range southward along the western side of the Antarctic Peninsula into areas not previously known to hold breeding populations of the species (Poncet and Poncet 1987; Fig. 1). The long-standing hypothesis on why Chinstrap Penguins have increased so dramatically is based on the fact that the dominant component in the summer diets of both Chinstraps and baleen whales is the Antarctic krill *(Euphausia superba).* This hypothesis rests on the assumption that the depletion of whale stocks due to commercial whaling simply led to a "krill surplus" that was used by other krill-eating predators when competitive release altered the existing patterns of consumption (Laws 1985).

Although commercial whaling did result in the near depletion of baleen whale stocks close to the Antarctic Peninsula and islands of the Scotia Arc, not all populations of krill-eating penguins found in that region exhibited the increases shown by Chinstrap Penguins. Notable among these, are populations of their sympatric (Fig. 1), most closely related congeners, Adéle *(P. adeliae)* and Gentoo*(P. papua)* penguins. Alike in size and general appearance, these species exhibit broad ecological similarities with Chinstraps, not the least of which is a predominance of krill in their summer diets (Volkman *et al.* 1980; Trivelpiece *et al.* 1990). When compared to Chinstrap Penguins, however, population increases in these two species have been negligible. Indeed, because Adélie Penguin populations have actually exhibited a noticeable decline at several localities on the Antarctic Peninsula (Poncet and Poncet 1987), an interesting challenge to the whale reduction hypothesis is presented: If the decrease of baleen whale stocks actually led to a krill surplus, why have populations of these ecologically similar species residing in the same geographical areas shown such different responses?

6.4.3 Species-specific winter habitat preferences and climate change

The answer to the question posed above, as Fraser *et al.* (in press) suggest, may not rest with the idea of a krill surplus. Instead, they propose that a long-term decrease in the frequency of cold years with extensive ice cover induced by environmental warming has changed the relative availability of critical wintering habitats for these penguins, thus altering patterns of recruitment

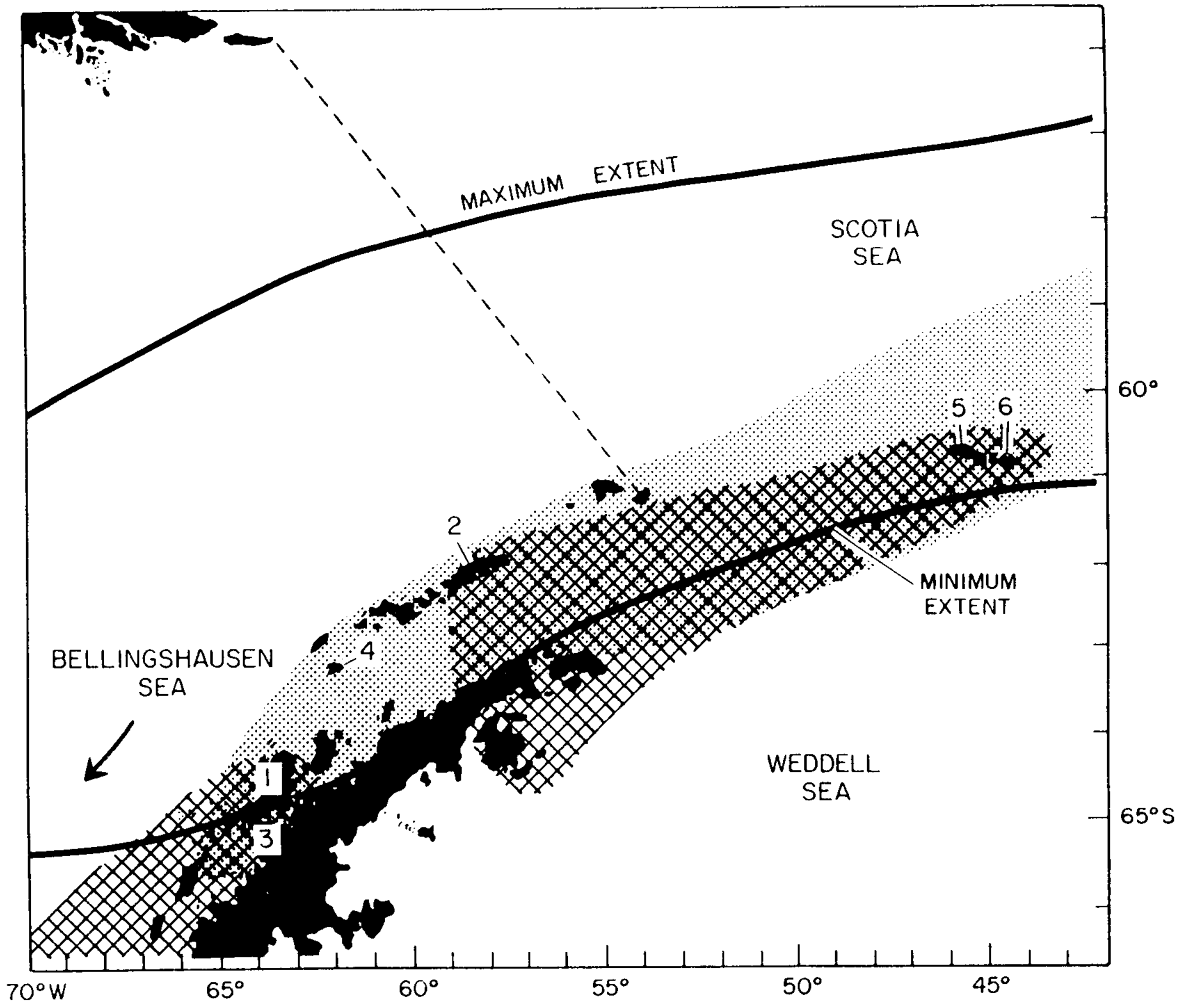

Figure 1. The Antarctic Peninsula and environs showing the ranges of Chinstrap (light shading) and Adélie penguins (crosshatching); the extremes of ice cover during September (when cover reaches maximum); study sites (Arthur Harbor, Anvers Island—1 and Admiralty Bay, King George Island—2); stations where complete weather records have been recorded since 1944 (Faraday—3, Bellingshausen—4, Signy—5, Islas Orcadas—6; and the (dashed) line along which the northward extent of the pack ice was compared in Figure 4.

and population growth.

It has long been thought that these ecologically similar species also shared similar wintering habitats, namely, the pack ice that seasonally develops around Antarctica (Murphy 1936). Early evidence that this assumption was flawed, however, came from long-term studies on penguin demography at Admiralty Bay, King George Island (Fig. 1). As shown in Fig. 2, the extent of winter and spring sea ice cover was coincident with the direction and magnitude of change in the breeding populations of Chinstrap and Adélie penguins; Chinstrap Penguins increased during years when sea ice extent decreased and vice-versa. The opposite was true for Adélie Penguins, suggesting that each species was responding differently to similar winter sea ice conditions. These data remained enigmatic until 1988 when a winter cruise in the Weddell Sea *(cf.* Ainley and Sullivan 1990) resolved the issue. As shown in Fig. 3, Chinstrap and Adélie penguins actually resided in completely different habitats. Adélies were indeed obligate inhabitants of the pack ice, but Chinstraps occurred almost exclusively in open water. Moreover, unlike either of these two species, Gentoo Penguins were subsequently found to winter in-shore; that is, they were not migratory, but instead remained in sheltered bays and open channels close to their breeding sites (Fraser *et al.* 1989; Trivelpiece *et al.* 1990).

With each of these species exhibiting such differences in their choice of winter habitats, the trends evident in Fig. 2 raised the possibility that a strong link exists between annual changes in sea ice extent and overwinter survival in these penguins. Because of its potential impact on recruitment, overwinter survival can play a key role in driving long-term change in wildlife populations (Ricklefs 1973), which in view of the historical differences evident in the growth of these penguin populations, invites the following question: Has the relative availability of these species' preferred wintering habitats been changing during the last four decades in a way that has favored Chin straps but not Adélies or Gentoos?

As shown in Fig. 4, mean annual surface air temperatures have been increasing in the Antarctic Peninsula region since approximately 1950 (see also Lewis-Smith 1990). What long-term impacts this warming trend has had on sea ice, however, is unfortunately incomplete because reliable satellite images are available only since 1973. Nevertheless, coupling the post-1977 data on trends in surface air temperatures with those on sea ice extent, and extrapolating to the longer-term temperature record, suggest a mechanism by which increases in Chinstrap populations could have been mediated. Since 1973, sea ice has been minimal during years when surface air temperatures averaged at four stations (Fig. 1) have been warmer than -4.3°C (Fig. 4), a pattern consistent with thermodynamic models of sea ice formation and cover in the Antarctic Peninsula/Weddell Sea region (Parkinson and Bindschadler 1984; Hibler and Ackley 1987; Husby *et al.* 1989). The key to the longer term extrapolation, however, is not whether temperatures and sea ice have shown a perfectly coupled response, but whether the frequency of cold/warm years, and thus extensive/reduced ice years, has changed sufficiently and over a long enough period of time to influence resident penguin populations. As shown in Fig. 4, the frequency of cold years has in fact changed during the last 45 years, from an average of 4 out of 5 during mid-century, to an average of only 1 or 2 out of five during the last two decades.

6.4.4 Discussion and Conclusions

The trends shown in Fig. 4 suggest that the number of years with minimal winter sea ice in the Antarctic Peninsula region have indeed increased during the last four decades, a positive development for the ice-avoiding Chinstraps, but not for the ice-dependent Adélies. For Gentoo Penguins, which throughout their range have exhibited the least evidence of long-term population change (Poncet and Poncet 1987), the implications are that winter habitat availability has remained stable. This is consistent with the fact that they are the least pelagic of the three species, actually wintering in-shore near areas defined, in part, by the proximity of their breeding sites.

The affinities for pack ice and ice edge/open water habitats shown by Adélie and Chinstrap penguins, also characterize the winter habitat preferences of some krill-eating marine mammals, notably Crabeater *(Lobodon carcinophagus)* and Southern Fur *(Arctocephalus gazella)* seals (Fraser *et al.* 1989; Ribic *et al.* in press). Based on diet characteristics alone, these mammals are not only the

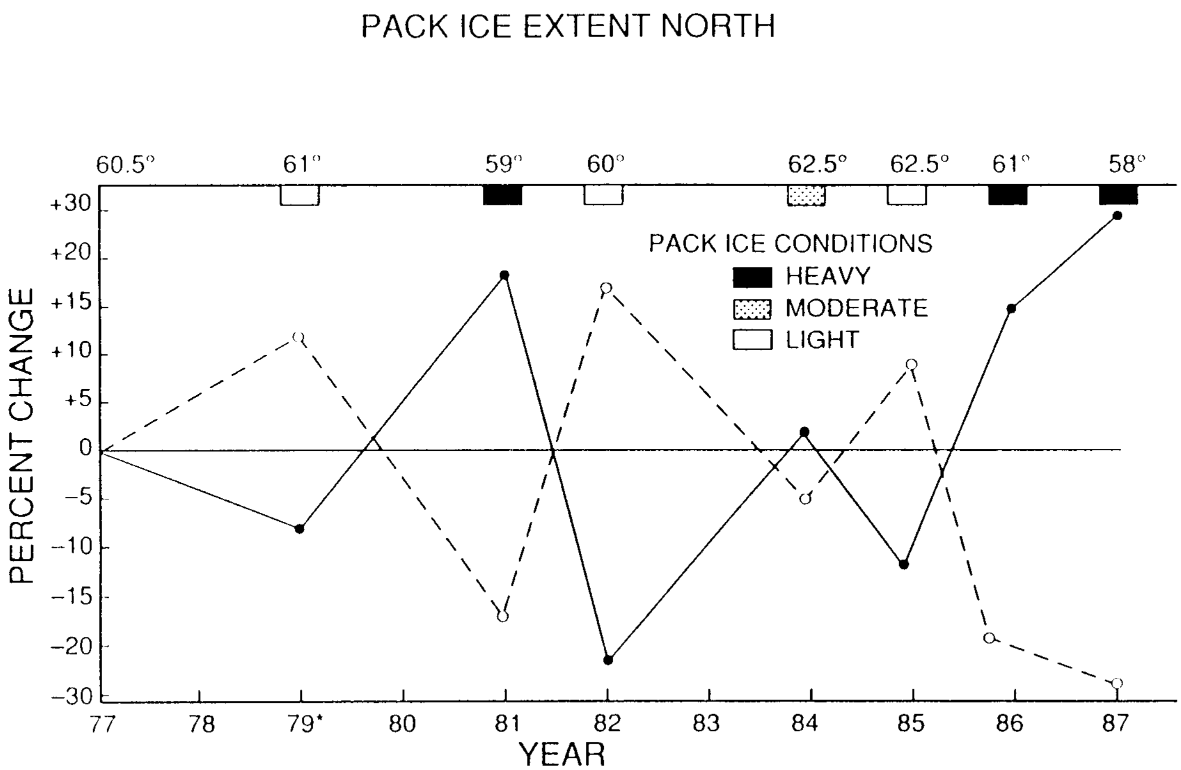

Figure 2. Percent change in the number of Adélie (closed circles) and Chinstrap (open circles) penguin breeding pairs on King George Island, Antarctica. The magnitude and direction (increasing or decreasing) is calculated relative to the preceding year's census. Whenever more than one year elapsed between censuses, the resultant change was divided by the number of years since the previous count to give an average percent annual change over the intervening period. Pack ice conditions are based on local ice cover during peak egg laying; the northern position of the ice edge in September, when it reaches its annual maximum, is shown on the top horizontal axis.

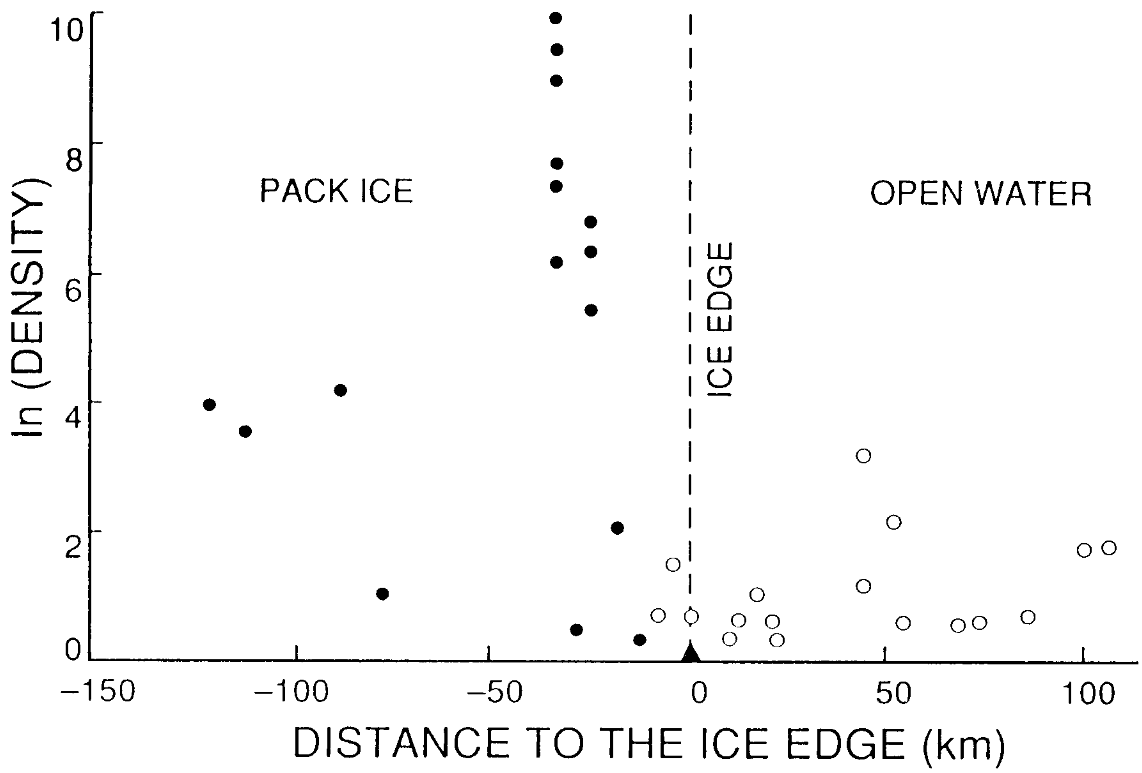

Figure 3. Density and distribution of Adélie (closed circles) and Chinstrap (open circles) penguins relative to the ice edge in the Weddell Sea, Antarctica. Positive kilometers represent open water.

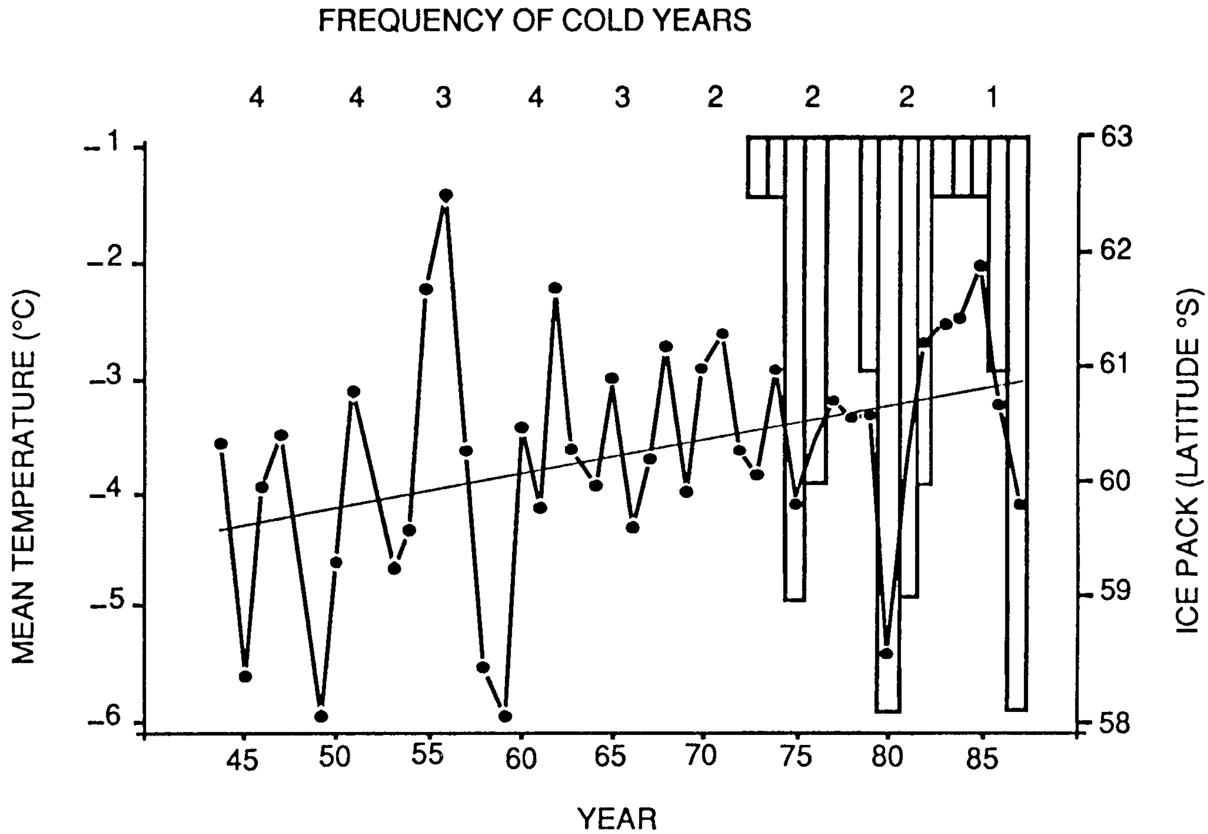

Figure 4. Mean temperature at four stations (Faraday, Bellingshausen, Signy and Islas Orcadas) in the Antarctic Peninsula region compared, for the 1973-1987 period, to the latitude of northward extent of pack ice during September (indicated by bars). No satellite data for 1977 or 1978; 1987 extent from personal observation. Numbers at the top show the number of years per respective five-year period that mean temperature was less than or equal to -4.3°C, the temperature during the 1973-87 period when pack ice reached northward to at least 60°50'S. Formula for the regression line is: temperature = 5.551 + 0.0278 (yr), $F = 5.720$, $p = 0.021$. The relationship of ice extent to temperature is highly significant; Spearman rank correlation, $r = 0.886$, $t = 6.337$, $P < 0.001$.

most direct, potential competitors for krill with penguins (Croxall *et al.* 1985; Croxall and Pilchner 1984), but, according to recent models, may in fact have been in a trophically superior position to "replace" baleen whales in the system due to their size and behavior (Murphy *et al.* 1988). Nevertheless, as in Adélies, the most recent censuses suggest that the ice-dependent Crabeaters are now exhibiting declining populations (Erickson and Hanson 1990). The ice-avoiding Fur Seals however, like Chinstraps, are experiencing significant population growth (Laws *1985).* This is also true of a number of other predators that avoid sea ice habitats but are not necessarily krill consumers (Fraser *et al.* in press).

Habitat availability rather than diet may thus be a key variable driving population changes in many upper trophic level Southern Ocean predators. Three important conclusions are implied by these results. First, it may be prudent to realize that sea ice may ultimately mediate the outcome of many Southern Ocean trophic interactions, including but not limited to, the availability of krill. Second, research that advocates a direct causal link between krill availability and changes in predator populations may be based on assumptions that do not fully consider the potential complexity of Antarctic trophic interactions. This could seriously compromise the interpretation of data being gathered as part of long-term monitoring programs to detect ecosystem changes resulting from increased human activity, because the effects of climate change on trophic interactions are predicted to be amplified at high latitudes (Bolin *et al.* 1986). And third, given that climate change issues are moving to the forefront in planning global research programs related to the Antarctic and elsewhere, programs that do not incorporate upper trophic level predators will be ignoring potentially sensitive biological indicators of climate change. Indeed, in view of how some Southern Ocean predator populations seem to have tracked their environment, it would appear that climate change actually became an "issue" in Antarctica as early as 1950, much sooner than the current interest in the subject would lead us to believe. It was at this time that some of the first evidence of change in penguin populations was detected (Sladen 1964). Notably, these early changes were documented at the fringes of each species' range, a pattern consistent with subsequent predictions on how climate change might affect wildlife populations and biodiversity (see Wilson 1988).

6.4.5 Acknowledgments

The work cited in this paper was funded by a series of research grants from the National Science Foundation, Division of Polar Programs. A comprehensive list of the individuals and organizations that helped with the original manuscript can be found in Fraser *et al.* (in press).

6.4.6 References

Ainley , D. G. and C. W. Sullivan. 1990. AMERIEZ 1988: a summary of activities on board M/V Polar Duke. Antarct. J. US , 24, 19-22.

Croxall, J. P. and N. Pilchner. 1984. Length-frequency distribution and sex ratio of krill eaten by Antarctic Fur Seals *Arctocephalus gazella* at South Georgia. Br. Antarct. Surv. Bull., 63, 117-125.

Croxall, J. P., P. A. Prince and C. Ricketts. 1985. Relationships between prey life-cycles and the extent, nature and timing of seal and seabird predation in the Scotia Sea. In: W. R. Siegfried, P. R. Condy and R. M. Laws (eds.), *Antarctic Nutrient Cycles and Food Webs.* Springer-Verlag, Berlin, pp.516-533.

Erickson, A. W. and M. B. Hanson. 1990. Continental estimates and population trends in Antarctic ice seals. In: K. R. Kerry and G. Hempel (eds.), *Ecological Change and the Conservation of Antarctic Ecosystems. Proc. 5th SCAR Symp. Antarct. Biol., Hobart, August-September 1988.* Springer-Verlag, Berlin, pp.253-264.

Fraser, W. R., R. L. Pitman and D. G. Ainley. 1989. Seabird and fur seal responses to vertically migrating winter krill swarms in Antarctica. Polar Biol.,10, 37-41.

Fraser, W. R., W. Z. Trivelpiece, D. G. Ainley and S. G. Trivelpiece. Increases in Antarctic penguin populations: Reduced competition with whales or a loss of sea ice due to environmental warming. Polar Biology (In press)

Hibler, W. B. III and S. F. Ackley. Numerical simulation of the Weddell Sea pack ice. J. Geophys. Res., 88(C5), 2873-2887.

Husby, D. M., R. D. Muench and J. T. Gunn. 1989. Oceanographic observations in the Scotia Sea marginal ice zone June-August 1988. NOAA Tech. Mem. NMFS, NOAA-TM-NMFS-SWFC-12 7.

Laws, R. M. 1985. The ecology of the Southern Ocean. *Am. Sci., 73,* 26-40.

Lewis-Smith, R. I. 1990. Signey Island as a paradigm of biological and environmental change in Antarctic terrestrial ecosystems. In: K. R. Kerry and G. Hempel (eds.), *Ecological Change and the Conservation of Antarctic Ecosystems. Proc. 5th SCAR Symp. Antarct. Biol., Hobart, August-September, 1988.* Springer-Verlag, Berlin, pp.32-SO.

Murphy, E. J., D. J. Morris, J. L. Watkins and J. Priddle. 1988. Scales of interaction between Antarctic krill and the environment. In: D. Sahrhage (ed.), *Antarctic Ocean and Resources Variability.* Springer-Verlag, Berlin, pp.120-130.

Murphy, R. C. 1936. Oceanic birds of South America. Macmillan, New York.

Parkinson, C. L. and R. A. Bindschadier. 1984. Responses of Antarctic sea ice to uniform atmospheric temperature increases. In: J. E. Hansen and T. Takahashi (eds.), *Climate Processes and Climate Sensitivity.* Amer. Geophys. Union, Washington, D.C., pp.254-264.

Poncet, S. and J. Poncet. 1987. Censuses of penguin populations of the Antarctic Peninsula, 1983-87. Br. Antarct. Surv. Bull., 77, 109-129.

Ribic, C. A., D. G. Ainley and W. R. Fraser. Marine mammal habitat associations in the marginal ice zone of the Scotia/Weddell confluence region. Antarctic Science (In press)

Ricklefs, R. E. 1973. *Ecology.* Chiron Press, Portland.

Rootes, D. M. 1988. The status of birds at Signey Island, South Orkney Islands. Br. Antarct. Surv. Bull., 80, 87-119.

Sladen, W.J.L. 1964. The distribution of the adélie and chinstrap penguins. In: R. Carrick, M. W. Holdgate and J. Prevost (eds.), *Biologie Antarctique.* Hermann, Paris, pp.359-365.

Trivelpiece, W. Z., S. G. Trivelpiece, G. R. Geupel, J. Kjelmyr and N. J. Volkman. 1990. Adéie and chinstrap penguins: their potential as monitors of the Southern Ocean marine ecosystem. In: K. R. Kerry and G. Hempel (eds.), *Ecological Change and the Conservation ofAntarctic Ecosystems. Proc. 5th SCAR Symp. Antarct. Biol., Hobart, August-September 1988.* SpringerVerlag, Berlin, pp.191-202.

Volkman, N. J., P. Presler and W. Z. Trivelpiece. 1980. Diets of pygoscelid penguins at King George Island, Antarctica. Condor, 82, 373-378.

Wilson, E. 0. (ed.). 1988. *Biodiversity.* National Academy Press, Washington, D.C., 521 pp.

6.5 Large Scale Physical Oceanography of the Southern Ocean

by John M. Klinck

6.5.1 Introduction

This paper is an overview of physical oceanography in the Southern Ocean. No attempt is made to be inclusive, rather three length scales are considered, with examples, to illustrate the behavior of the Southern Ocean at these scales. For a more complete discussion of the Antarctic Circumpolar Current (ACC) and other parts of the Southern Ocean, see Nowlin and Klinck (1986).

The three example length scales are large scale, frontal scale and local scale. The large scale physical oceanography considers the circulation throughout the Southern Ocean, with lengths on the order of thousands of kilometers. The frontal scale is on the order of the internal radius of deformation (10 to 20 km) where fronts tend to be a few internal radii in width. Even though the fronts in the ACC are circumpolar in nature, the frontal scale processes are different from those governing the current system as a whole. Finally, the local scale is defined by circulation in subareas within the Southern Ocean and the length depends on the specific area being studied, which can be as large as the polar gyres (about 1000 km) or as small as narrow fjords and inlets (about 10 km). The specific example discussed here is the area around the Antarctic Peninsula including the Bransfield Strait and the Bellingshausen Sea.

In addition to describing the observed state (steady climatology) of each of these systems, the observed time variability is also considered. It is important to realize that fluctuations have been observed for each of these length scales and that these variations are important for ecosystem processes.

The next section describes the large scale general circulation of the Southern Ocean, specifically, the ACC. Some comments are presented on the forcing of this current along with illustrations of the horizontal and vertical structure. The time variability of the current is also discussed. Section 3 examines the nature of the fronts that are imbedded in the ACC. Evidence for their global extent is presented. Time variability of the fronts is examined from two different observations. Section 4 covers circulation and water masses in the Bellingshausen Sea and Bransfield Strait. A steady coastal current is also discussed. The last section is a short summary.

6.5.2 Large scale circulation

The large scale physical oceanography of the Southern Ocean deals mainly with the Antarctic Circumpolar Current which circles the Antarctic Continent between 50°S and about 65°S.

A. Description of Antarctic Circumpolar Current

The structure of the current is best seen with dynamic topography of the surface relative to some depth, say 1000 m (Fig. 1). The same general circulation pattern is obtained for other choices of reference depth. The current is everywhere eastward and generally zonal except near continents and over bathymetry, e.g. South America, Kerguelen Plateau, Campbell Plateau and the East Pacific Rise. The bathymetry of the Southern Ocean has a major influence on the circulation. The forcing for this circulation is the surface wind stress due to the strong westerlies at these latitudes. The force is generally eastward throughout the Southern Ocean with the maximum stress reaching 0.25 $N\ m^{-2}$.

The Southern Ocean has a relatively weak vertical density stratification (Fig. 2). On the larger scale, the water is denser with depth and with distance south. Because of this weak stratification, relatively strong currents exist throughout the water column. On shorter space scales, there are zones of strong horizontal density gradients separated by regions of weak density gradients. The strong gradient zones correspond to the various fronts that exist in this current. These issues will be discussed below in Section 3.

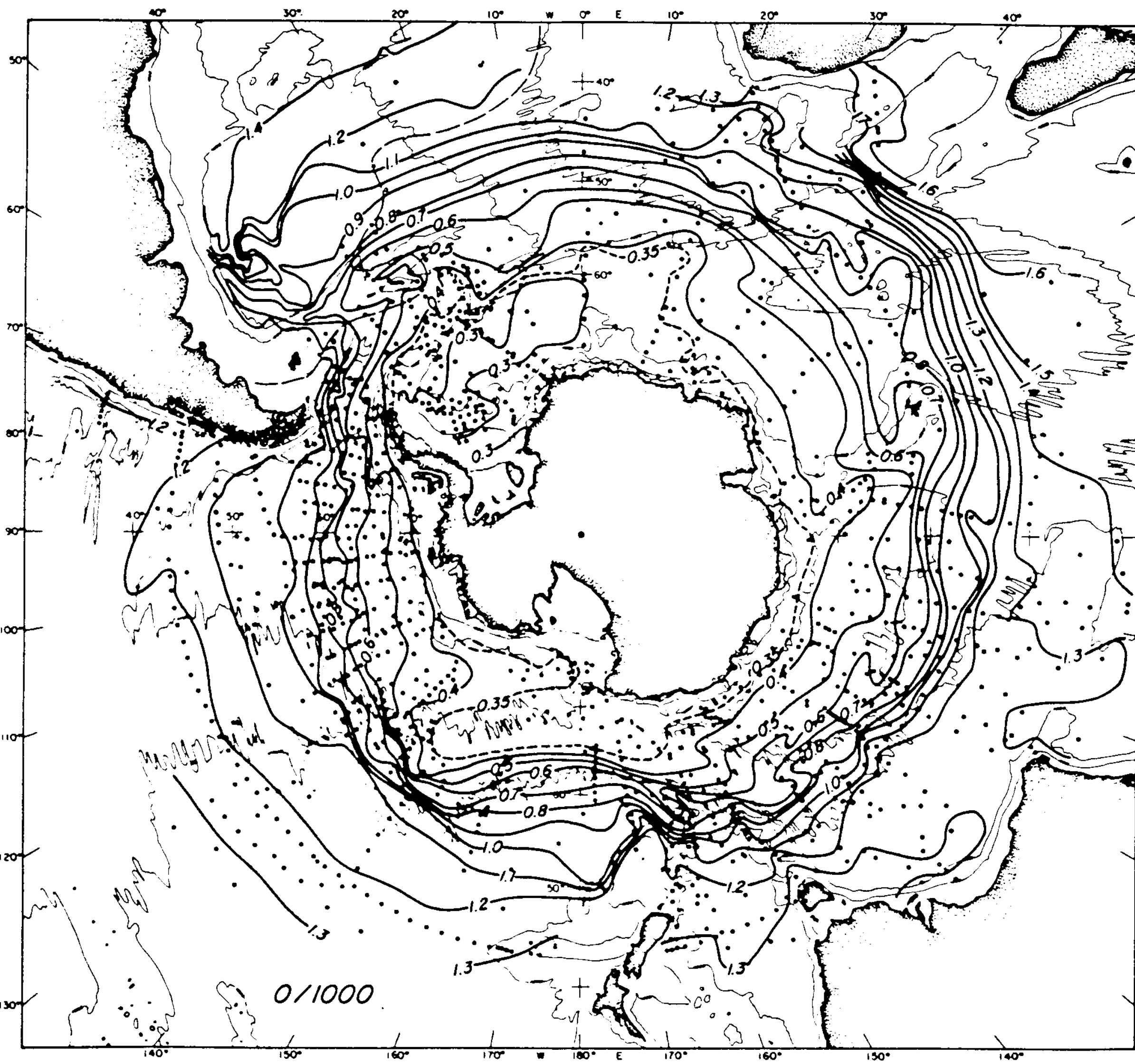

Figure 1 Anomaly of geopotential height of the sea surface relative to the 1000-dbar level, expressed in dynamic meters. Stations used in preparing this chart are shown. The southwest Atlantic region north of the dashed line is taken from Reid *et al.* (1977).

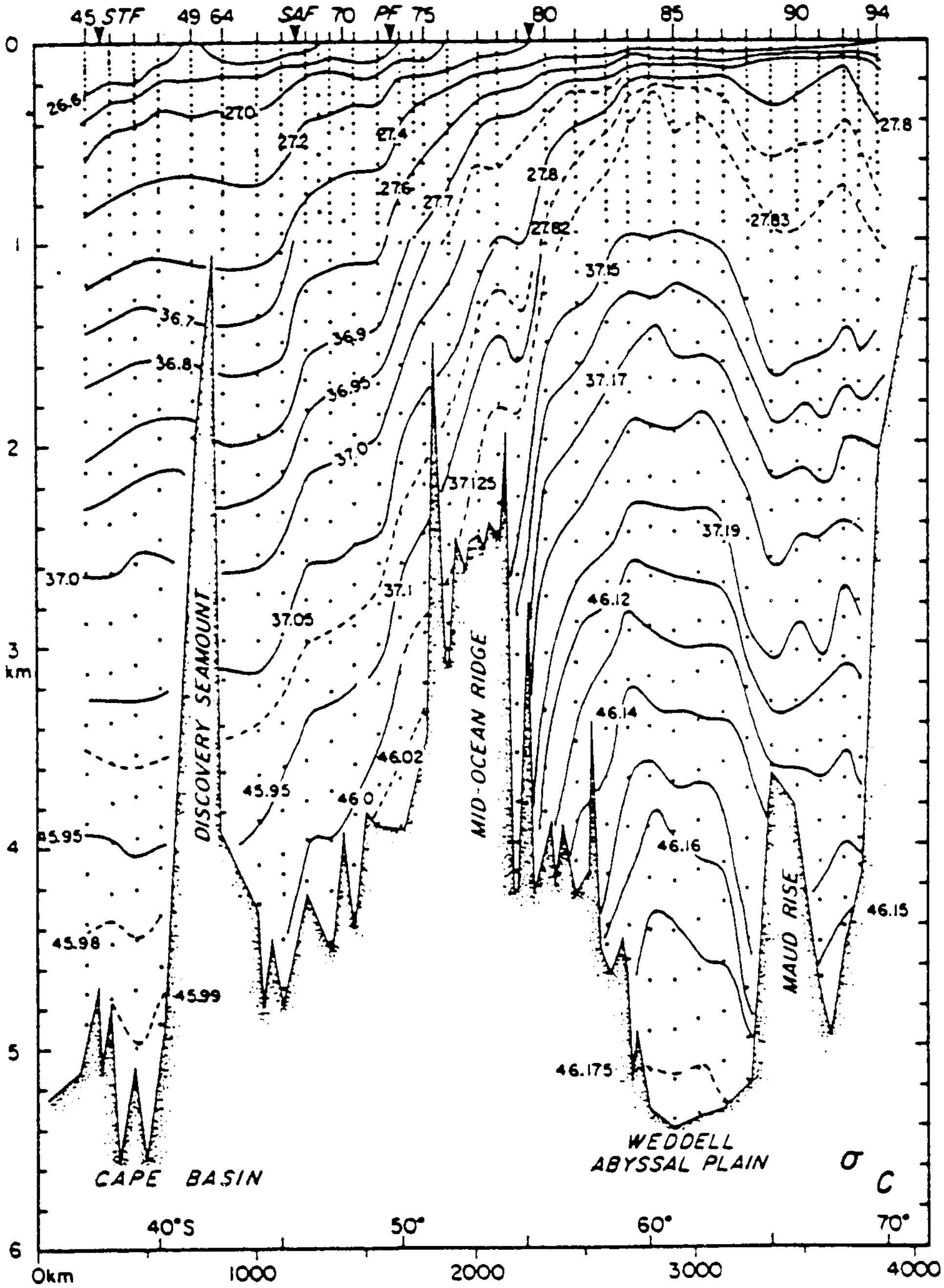

Figure 2. Density structure of the South Atlantic Ocean along the Greenwich Meridian (Whitworth and Nowlin, 1987).

B. Time changes of the Antarctic Circumpolar Current

The surface wind stress over the Southern Ocean has a predominantly semi-annual variation with the strongest stress occurring in the spring and fall (Trenberth *et al.*, 1989). Directly measured transport at Drake Passage (Whitworth and Peterson, 1985) over a 5 year span reveals a generally semi-annual change. However, considerable variability occurs from year to year. The general pattern has high transport in the spring and fall but observations show that the peak transport can occur in almost any month (Whitworth and Peterson, 1985).

6.5.3 Frontal scale

The next general length scale to consider is the radius of deformation which characterizes the narrow baroclinic jets that exist in the ACC. Additionally, eddies, which have the same scale, have been observed near the ACC but these will not be discussed here.

A. Description of fronts in the Antarctic Circumpolar Current

From a series of observations taken in Drake Passage in the late 1970's, a general view of the water structure has developed; there are three narrow fronts, with associated jets, in the ACC (Fig. 3). This general picture is illustrated by density sections across Drake Passage (Whitworth, 1979), which clearly show the northern (Subantarctic Front), middle (Polar Front) and southern (Continental Water Boundary) fronts.

An extensive hydrographic data set was used to characterize the general location of these fronts in the South Atlantic (Peterson and Whitworth, 1989). These data show that the location and separation distance of the Subantarctic and Polar Fronts varies considerably. Rings, that must have been the result of flow instability, are also observed.

The circumpolar nature of the fronts is implied by the fact that they have been found at all longitudes in the Southern Ocean where closely spaced observations exist. A study of the FGGE drifters (Hofmann, 1985) is consistent with the observation that the fronts are convergence zones at the surface and furthermore, the surface drifters tend to accumulate along the fronts. Strong evidence of the circumpolar extent of the fronts is given by the number of buoys that pass through each 10 square. Occasional gaps in the bonded structure are produced by lateral migration of the fronts.

B. Time variability of the fronts

The fact that the fronts in the Southern Ocean migrate is generally accepted but direct observation is rare. One indication of frontal motion is the magnitude of sea level variance in bands around the Southern Ocean. The rms surface variability relative to a one year mean sea surface from Geosat (Zlotnicki *et al.* 1989, their color plate 2) clearly shows that large amplitudes exist in the ACC. Particularly strong changes occur east of Drake Passage, south of Africa and over Campbell Plateau.

A direct observation of the motion of individual fronts is afforded by moored observations in Drake Passage (Hofmann and Whitworth, 1985). The year-long variability in the across-passage temperature distribution at 500 m shows that the Subantarctic and Polar Fronts shift over periods of weeks and, occasionally, spawn eddies. There also is a shift in the mean position of the fronts about every 3 months; that is, the fronts shift north and south over distances of 100 km or more about four times a year. These shifts may be associated with the semi-annual changes in the transport but the link has not been analyzed to date.

6.5.4 Local scale -- Bransfield Strait and Bellingshausen Sea

Since there are parts of the Southern Ocean that have a specific local character, it is important to

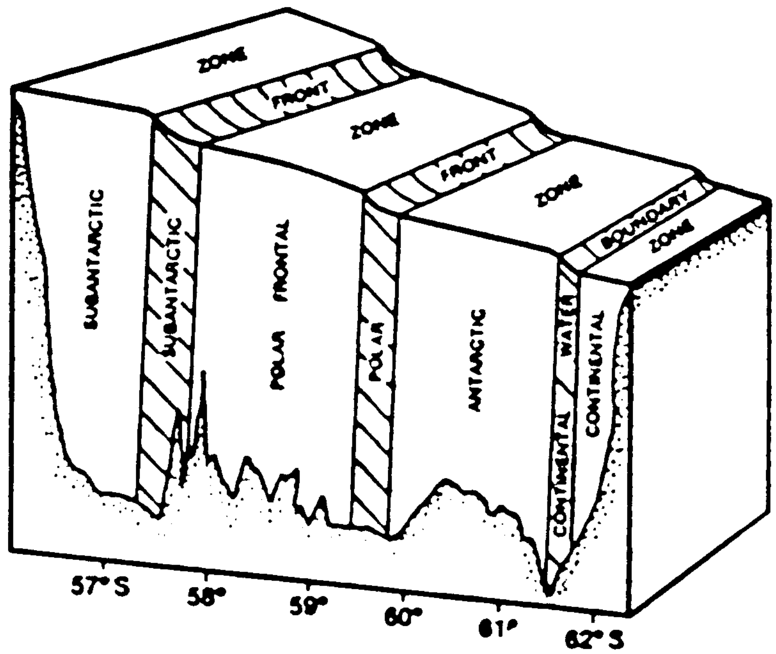

Figure 3. Schematic representation of the location and width of fronts in Drake Passage (Nowlin and Clifford, 1982).

have some idea of local processes. An illustration of such a region is the Bransfield Strait and the Bellingshausen Sea. The descriptions of the physical oceanography below are necessarily sketchy and indicate that more work is required for a better understanding of this area.

A. Circulation near the Antarctic Peninsula

The general surface circulation near the Antarctic Peninsula is indicated by two FGGE drifters that traveled through the area (Fig. 4), both of which entered from the southwest. One drifter traveled east, then south, and finally southwest suggesting a cyclonic circulation in the Bellingshausen Sea. The second drifter traveled to about Livingston Island before turning south and entering the Bransfield Strait. Once in the Strait, the drifter traveled in a cyclonic path. Therefore, there is indication of a cyclonic (polar) gyre adjacent to the Antarctic Peninsula and in the Strait between the peninsula and the continent.

B. Temperature structure in Bransfield Strait

There is a marked temperature difference between Drake Passage and the Bransfield Strait. The general temperature structure has a near surface layer that is relatively warm in the summer and quite cold in the winter. Below this seasonal layer, the water is warm (up to 3°C) in Drake Passage, indicating the warm, salty Circumpolar Water while the temperature in the Bransfield Strait is close to the freezing point of water (less than -1°C) (Capella *et al.,* 1991).

C. A coastal current

A persistent, narrow, subsurface coastal current exists on the southern side of Drake Passage. Current meter records from different locations (one off Elephant Island and the other off Livingston Island) indicate a persistent westward flow that exhibits only minor changes over a year (Nowlin and Zenk, 1988). The width of this current is about 15 km and it has a distinct temperature signature (Fig. 5). The cold water in the core indicates that it is water from the Weddell Sea and the Bransfield Strait that has leaked into Drake Passage. Coriolis force will push this water to the left (westward) and hold it against the coast.

Two points about this narrow current are 1) it would be easy to miss in widely spaced hydrographic observations and 2) it may be very important in transporting nutrients, eggs, larvae, etc. This current may extend for considerable distances around the continent. It is also possible that other narrow boundary trapped currents exist in the Southern Ocean.

6.5.5 Concluding remarks

This overview is designed to show that spatial and temporal variability exists in the Southern Ocean on a variety of scales from thousands to tens of kilometers and from decades (and longer) to a few days. Each of these variations will have some influence on the ecology. Therefore, it is important that measurements of the physical environment be taken as an integral part of an ecological study. Furthermore, the horizontal length scales may be as small as a few kilometers so closely spaced observations are critical in surveying the Southern Ocean.

6.5.6 Acknowledgments

This work was done with the financial support of the National Science Foundation under Grant OCE 89-96235.

6.5.7 References

Capella, J. E., R. M. Ross, L. B. Quetin and E. E. Hofmann. 1991. On the thermal structure of the upper ocean in the Bransfield Strait-South Shetland Island region. Deep Sea Res., submitted

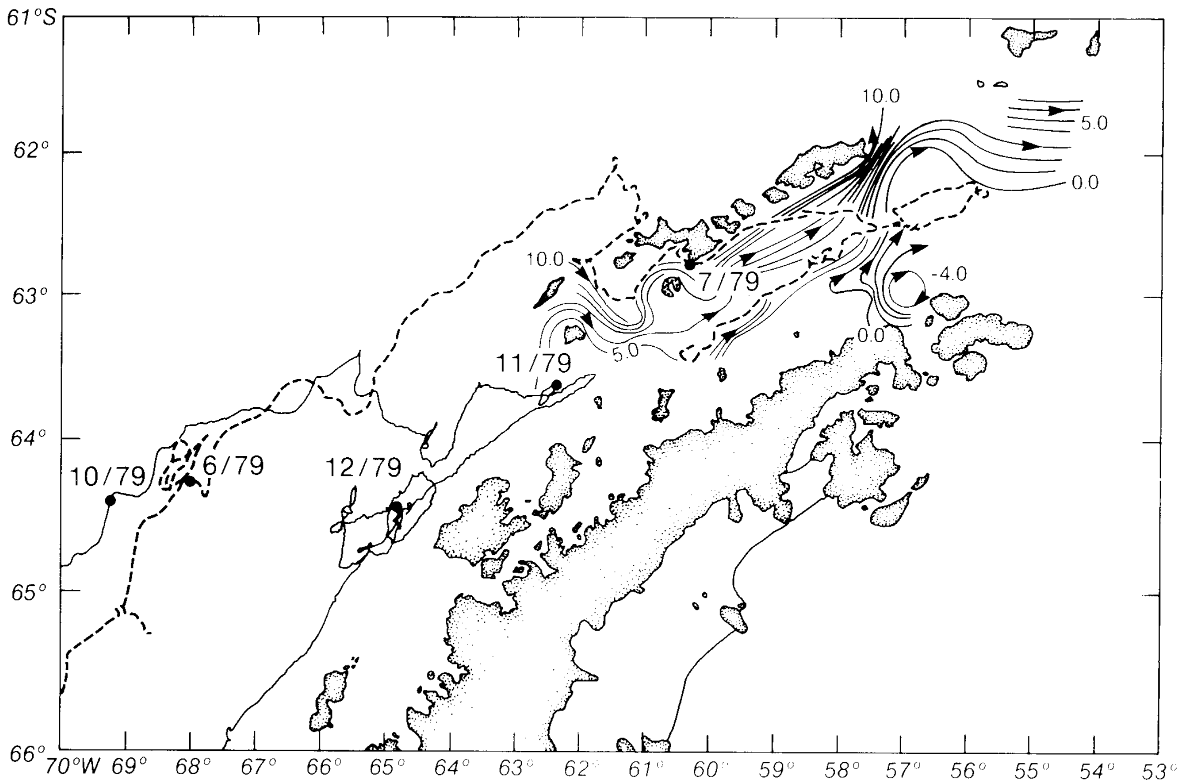

Figure 4. Path of two FGGE surface drifters that drifted through the eastern Bellingshausen Sea and the Bransfield Strait in 1979. The drifter tracks are overlaid on dynamic topography (dynamic cm/1800 decibars) contours that were computed by Clowes (1934). Figure from Capella (1989, PhD Dissertation, Texas A&M University).

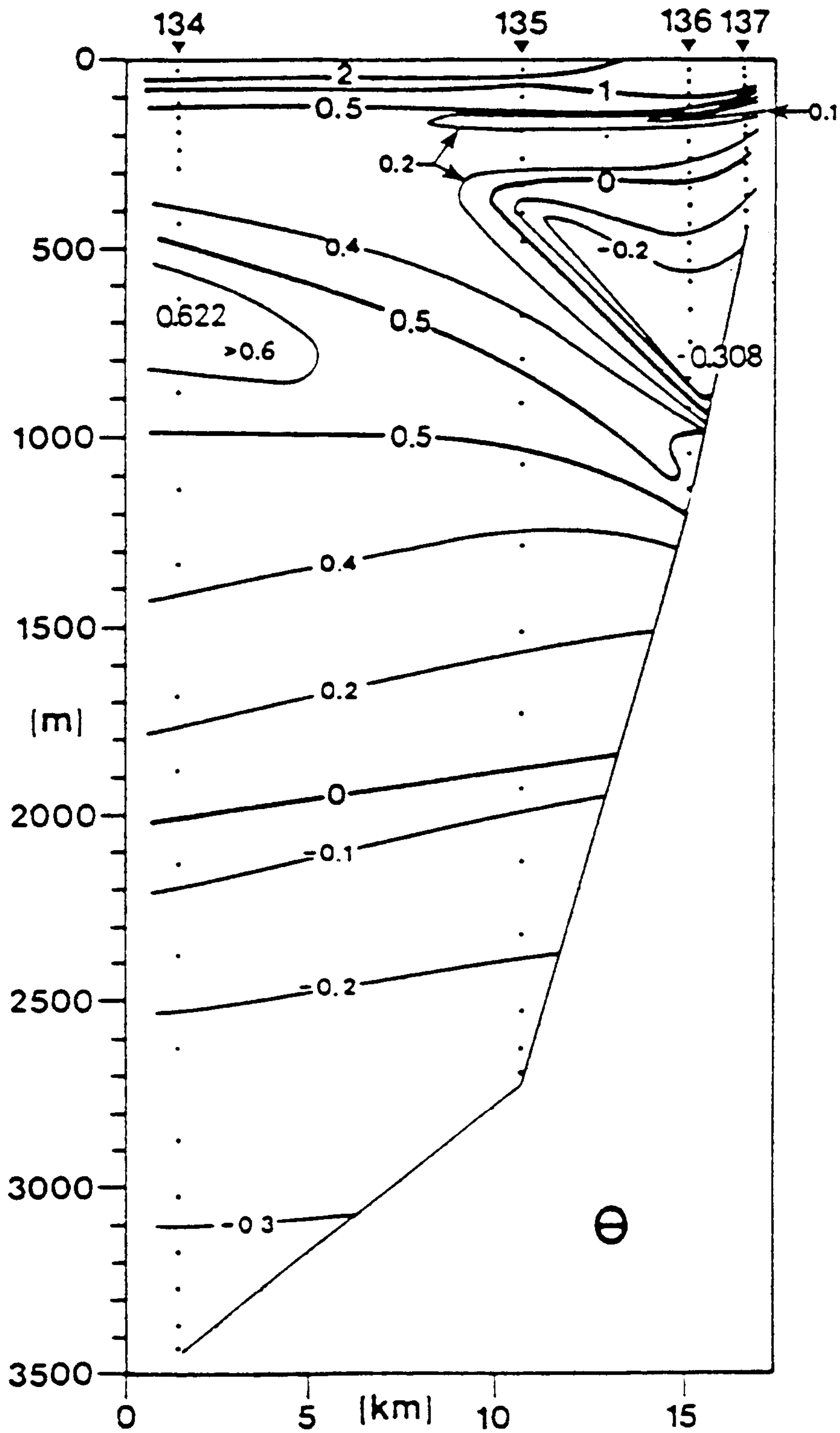

Figure 5. Temperature north of Elephant Island from a cruise in February 1984 (Nowlin and Zenk, 1988).

Clowes, A. I. J. 1934. Hydrology of the Bransfield Strait. Discovery Reports 9, 1-64.

Fu, L.-L., and D. B. Chelton. 1984. Temporal variability of the Antarctic Circumpolar Current observed from satellite altimetry. Science, 226, 343-346.

Gordon, A. L., E. Molinelli, and T. Baker. 1978. Large-scale relative dynamic topography of the Southern Ocean. J. Geophys. Res., 83, 3023-3032.

Gordon, A. L. and T. N. Baker. 1986. Southern Ocean Atlas Amerind Pub. Co. Pvt. Ltd., New Delhi, 31 pp.

Han, Y.-J, and S.-W. Lee. 1981 A new analysis of monthly mean wind stress over the global ocean. Rep. 26, Clim. Res. Inst., Oregon State U. 148 pp.

Hofmann, E. E. 1985. The large-scale horizontal structure of the Antarctic Circumpolar Current from FGGE Drifters. J. Geophys. Res,. 90, 7087-7097.

Hofmann, E. E., and T. Whitworth 111.1985. A synoptic description of the flow at Drake Passage from yearlong measurements. J. Geophys. Res., 90, 7177-7187.

Nowlin, W. D., Jr. and M. Clifford. 1982. The kinematic and thermohaline zonation of the Antarctic Circumpolar Current at Drake Passage. J. Mar. Res., 40(suppl), 481-507.

Nowlin, W. D., Jr. and J. M. Klinck. 1986. The physics of the Antarctic Circumpolar Current. Rev. Geophys. and Space Phys., 24, 469-491.

Nowlin, W. D., Jr. and W. Zenk. 1988. Westward bottom currents along the margin of the South Shetland Island Arc. Deep-Sea Res., 35, 269-301.

Peterson, R. G. and T. Whitworth III. 1989. The subantarctic and polar fronts in relation to deep water masses through the southwestern Atlantic. J. Geophys. Res., 94, 10,817-10,838.

Trenberth, K. E., J. G. Olson, W. G. Large. 1989. A Global Ocean Wind Stress Climatology Based on ECMWF Analyses National Center for Atmospheric Research, NCAR[FN-338+STR, 93pp.

van Loon, H. 1971. The half-yearly variation of the circumpolar surface drift in the southern hemisphere. Tellus, 23, 511-516.

Whitworth, T., 111.1979. Zonation of the Antarctic Circumpolar Current. Ph.D. dissertation, Texas A&M University 79pp.

Whitworth, T., 111.1983. Monitoring the transport of the Antarctic Circumpolar Current at Drake Passage. J. Phys. Oceanogr., 13, 2045-2057.

Whitworth, T., III, and R. G. Peterson. 1985. Volume transport of the Antarctic Circumpolar Current from bottom pressure measurements. J. Phys. Oceanogr., 15, 810-816.

Whitworth, T., III and W. D. Nowlin, Jr. 1987. Water masses and currents of the Southern Ocean at the Greenwich Meridian. J. Geophys. Res., 92, 6462-6476.

Zlotnicki, V., L.-L. Fu and W. Patzert. 1989. Seasonal variability in global sea level observed with Geosat altimetry. J. Geophys. Res., 94, 17,959-17, 1969.

6.6 Results from FRAM - the Fine Resolution Antarctic Model.

by D. J. Webb

6.6.1 Abstract

FRAM, the UK Fine Resolution Antarctic Model, is a high resolution ocean model of the whole of the Southern ocean south of 24°S. The results from the model show that the path of the Circumpolar Current is dominated by the deep topography of the ocean and that in some areas it has a braided structure. Eddy intense regions are found along the path of the main current. These are often most energetic near regions where the current is crossing the mid-ocean ridges.
At the latitude of the main westerlies, the flow in the surface layers of the ocean has a significant northward component due to the Ekman transport. This transport of dense surface water from the south to overlie less dense water to the north produces strong convection and is a factor in forming the strong fronts observed near the path of the Circumpolar Current.

6.6.2 Introduction

The UK Fine Resolution Antarctic Model, FRAM, is as an eddy resolving model of the Southern Ocean designed to investigate the role of eddies and other small scale features on the circulation, eddy structure, heat and momentum balances of the region. The experience gained from using the model should be useful in developing models for future climate research. The main run of the FRAM model lasted for 16 model years. During the first six model years the model was initialized, using a robust diagnostic method, to be as close as possible to the Levitus gridded temperature and salinity fields which are based on historical observations.

From six years onwards the model temperature, salinity and velocity fields evolved freely. Between year six and year ten a number of small changes were introduced into the model. The bottom friction term was reduced and changed to have a quadratic form. A bi-harmonic horizontal viscosity term was also added. By year ten a quasi-steady state had been reached, so the period starting at 10.0 years and ending at 16.0 years, was used to collect statistics on the flow. These data are now being used to study the primary physical processes occurring in the region.

6.6.3 Description of the model

The code of the PRAM model, like those of Bryan and Holland (1990) and Semtner and Chervin (1988) is based on that developed by Bryan (1969), Semtner (1974) and Cox (1984). The primary model variables are the ocean potential temperature, salinity and velocity. These continuous fields are represented in the model by a discrete set of values at the vertices of a three-dimensional grid. In the horizontal an Arakawa-B grid is used which offsets the position of the points at which velocity is defined from the points at which the variables affecting the density and pressure fields are defined.

The model covers the whole of the ocean south of 2408 with a resolution of 0.25 degrees in the north-south direction and 0.5 degrees in the east-west direction. This corresponds to 27 km in both directions at 6008. The model has 32 levels in the vertical. These range in thickness from 20.3 m near the surface to 233 m at depth.

The model uses an equation based on conservation of momentum to describe the evolution of the horizontal velocity field,

$$\frac{\partial \vec{u}}{\partial t} + \vec{u} \,.\, \nabla\vec{u} + \vec{f} \times \vec{u} = \frac{1}{\rho} \nabla\, p + A_m\, \nabla^2 \vec{u} + K_m \frac{\partial^2 \vec{u}}{\partial z^2} \qquad (1)$$

and advection-diffusion equations for the potential temperature and salinity fields,

$$\frac{\partial T}{\partial t} + (\vec{u}\,.\,\nabla)T = A_h\nabla^2 T + K_h\frac{\partial^2 T}{\partial z^2}, \qquad (2)$$

$$\frac{\partial S}{\partial t} + (\vec{u}\,.\,\nabla)S = A_h\nabla^2 S + K_h\frac{\partial^2 T}{\partial z^2} \qquad (3)$$

f is the vertical Coriolis vector, with magnitude 2ωsinϕ where ω is the angular velocity of the Earth and ϕ is the latitude. A_m and K_m are the horizontal and vertical diffusion coefficients of momentum and A_h and K_h are the corresponding diffusion coefficients of heat and salt. In the FRAM model, A_m equals 200 m^2s^{-1}, A_h 100 m^2s^{-1}, K_m 10^{-4} m^2s^{-1} and K_h 5 x 10^{-5} m^2s^{-1}. The linear bottom friction coefficient has a value of 0.001 m s^{-1}. (This was changed to quadratic friction later in the run). At the northern open boundary Am increases linearly to 2000 m^2s^{-1} over the last ten rows to prevent an instability developing at western boundary current inflow regions.

There is no equivalence to equation 1 for the vertical velocity. Instead it is calculated from the horizontal velocities using a conservation of volume equation. The pressure p at a depth z is given by,

$$p(z) = p_o + \int_o^z g\rho\, dz' \qquad (3)$$

where p_o is the pressure on the zero reference level, g is the acceleration due to gravity and p is density. To allow for the irregularities in the shape of the Earth, the reference level chosen is the geoid level about which the mean displacement z of the ocean surface is zero. These are related by the equation,

$$z = \frac{P_o}{g\rho} \qquad (4)$$

For computational efficiency the model ocean filters out surface gravity waves by imposing a rigid lid at the zero reference level. The effect of doing this on the large scale ocean circulation is negligible.

The equation of state used to calculate the density is the computationally efficient one of Semtner (1974). The model bathymetry is based on the US Navy DBDB5 bathymetric data set. This was first smoothed using a one by one degree median filter and then interpolated to the FRAM model grid. In a few regions with very large depth changes, some extra smoothing is used to prevent topographic instability (Killworth 1987).

The model was initialised to be as close as possible to the Levitus (1982) temperature and salinity data set. This is a gridded data set based on the best available historical data. The model could not be started directly using the Levitus fields, because small errors in the gridded data caused the model to become unstable. The errors probably arose from the interpolation that had to be done in data sparse regions.

Instead it was started from a state of rest in which the temperature throughout the ocean was at -2°C and the salinity was 36.69$^o/_{oo}$. The Levitus data was then assimilated into the model by adding the terms, $-(T-T_l)/\lambda$ and $-(S-S_l)/\lambda$ to equations 2a and 2b respectively, where T_l and S_l are the Levitus values of potential temperature and salinity. This scheme is the robust diagnostic method of Sarmiento and Bryan (1982). During the first 890 days of the model run, the time constant 1 had a value of 180 days in the top 5 layers of the model and 540 days in the lower layers. For the remainder of the assimilation period the time constant was 360 days in all layers.

6.6.4 Boundary conditions

The boundary condition used at the northern open boundary of the model is the one developed by Stevens (1990). This uses a Sverdrup balance for the barotropic part of the flow and a linear wave equation for the baroclinic part. At inflow points, the potential temperature and salinity fields are relaxed to the Levitus values along the northern boundary. During the initialization period the flux of heat and fresh water through the ocean surface was set to zero. The surface wind stress was initially also zero, but this was increased linearly during the third year of the run so that during the final three years it equaled the annual mean stress field of Hellerman and Rosenstein (1983).

6.6.5 Results

A model such as FRAM produces a large amount of data. Each archive data sets takes up the whole of a standard magnetic tape and during the run 500 such tapes have been filled. Early results based on analysis of the model at the end of the six year robust diagnostic period have been reported by the Fram Group (1991) and by Webb (1991).

The model recreates the strong fronts and jets associated with the Circumpolar Current, the slow circulation of the Weddell Sea gyre, the strong Agulhas current and its retroflection zone, the Agulhas Current eddies and the smaller scale eddies found along the path of the Circumpolar Current.

The transport in the model Circumpolar Current is 190 Sv (1 Sv = 10^6 m^3s^{-1}). This is higher than the measured values of 130 Sv (Whitworth *et al.*, 1982) but it agrees with the model values of Cox (1975) and Semtner and Chervin (1988). South of the Circumpolar Current, the main feature is the Weddell Gyre, with a total transport of 26 Sv. The model shows that it extends eastwards as far as the Kerguelen Plateau. The Ross Sea also forms a cyclonic gyre, with a transport of 7 Sv, extending from 160°E to 14°W. No gyre is found in the Bellingshausen Sea.

In the near surface layers, the major feature of the region is the strong northward Ekman transport produced at the latitudes of the band of westerlies. This transport is illustrated in Fig. 1 which shows the tracks of drifters in the surface layer over a period of 50 days. The corresponding tracks at 125 m (Fig. 2) show that below the surface layer the current has a much more zonal structure. The total Ekman transport at a latitude of 47°S is 30 Sv, dropping to 12 Sv at 60°S, the mid-latitude of Drake Passage. The return flow occurs mainly at depths between 1000 and 3000 m.

These figures also show that the Circumpolar Current to the west of Drake Passage is very broad and stable over the Amundsen Abyssal Plain. The model also shows little eddy activity in this region. (Although it does well in energetic eddy regions there is evidence that the model underestimates the eddy energy in quiescent regions.)

In marked contrast, in Drake Passage itself and to the east, the current forms narrow jets along its northern margin and the eastern boundaries of the Falkland Plateau and South Georgia. Similar jets are formed elsewhere around Antarctica in regions of strong topography. A very intensive jet is found at the Udintsev fracture zone in the South Pacific, where 100 Sv flows through a channel less than 130 km wide. The model shows a general eastward flow at all depths in Drake Passage. There are some exceptions, but they appear to be due to transient eddies and do not represent any systematic westward transport. The model forms the series of three fronts found in Drake Passage and a front between Weddell Sea water and the waters exiting Drake Passage. However it does not reproduce the very narrow southwestward running coastal current that has been reported in the

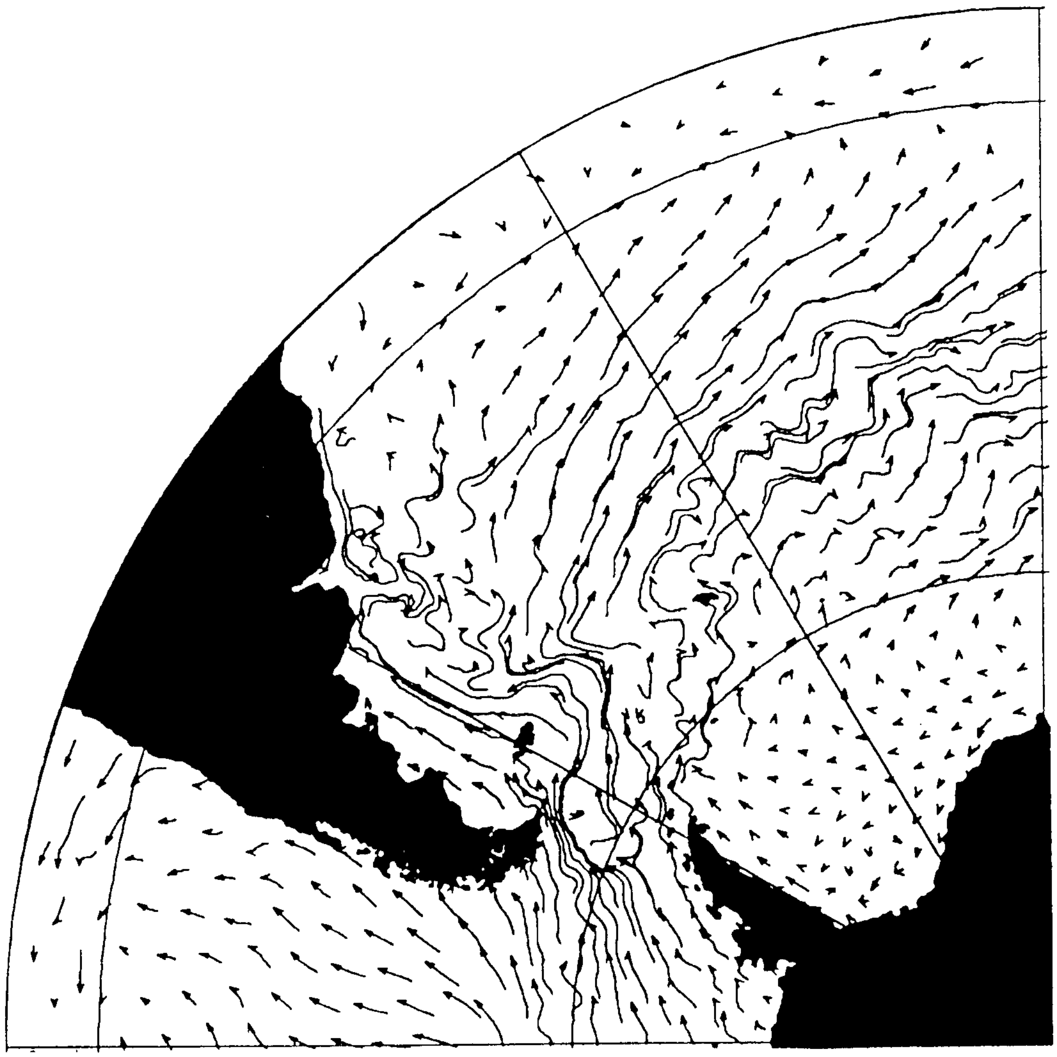

Figure 1. Tracks showing particle movements over a fifty day period in the surface layer of the FRAM model. The velocity data used to construct the tracks comes from the end of year 6 of the model run.

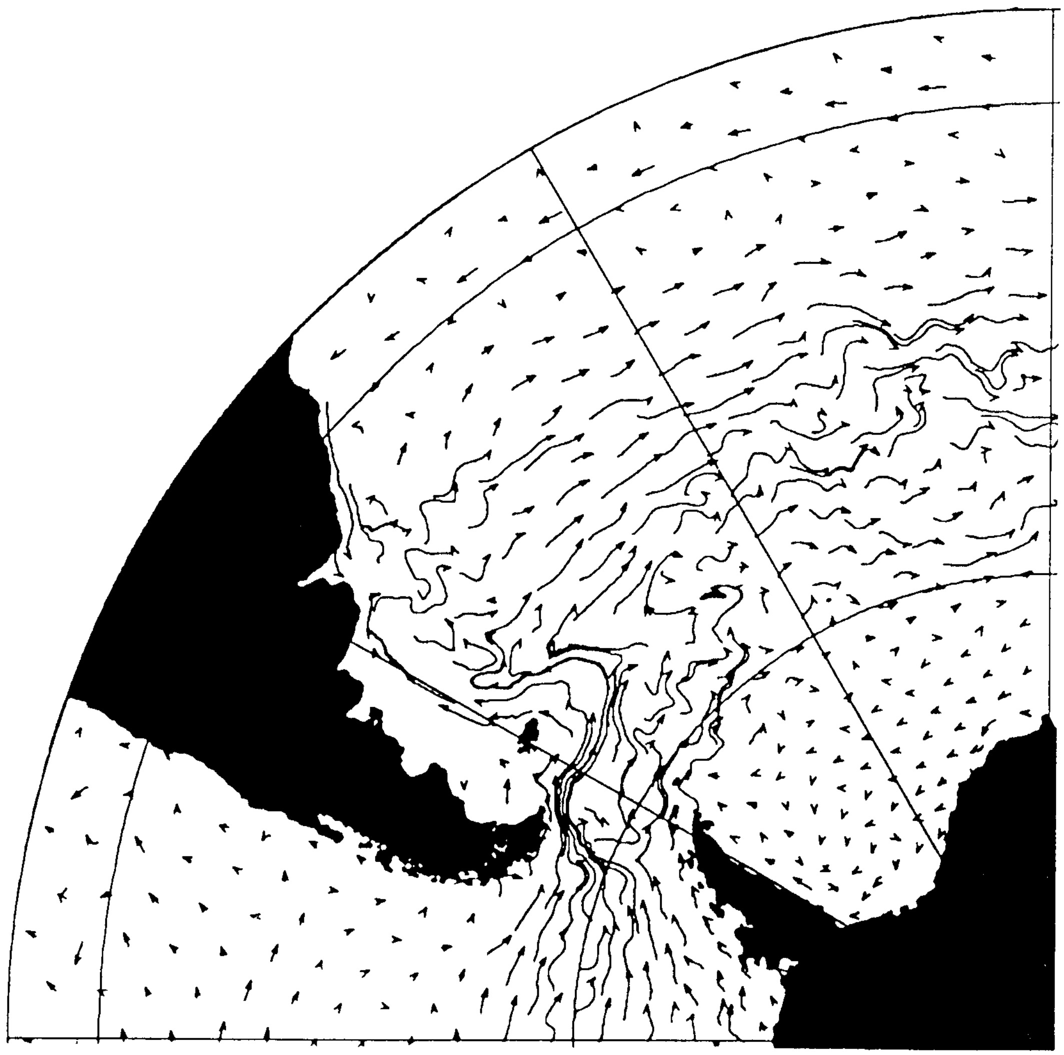

Figure 2. Tracks showing particle movements over a fifty day period at a depth of 120 m in the FRAM model. The velocity data used to construct the tracks comes from the end of year 6 of the model run.

Bransfield Strait. This may be because the resolution of the model is too coarse to represent the current.

6.6.6 Sea-ice

Problems in accessing good surface flux data sets meant that the main 16 year run of the FRAM model was carried out without a sea-ice model. However, starting from year 10.0 of the main run a run with sea-ice has been carried out lasting for 22 model months. We hope to continue this second run when computer resources are available.

The sea-ice run showed that the sea-ice field was very sensitive to the stratification and surface fluxes. If the fresh water stratification was too weak, the fresh water input too little or the evaporation too large then no ice formed. During the first year a series of bands of ice were formed as the increase in salinity in the surface layers caused them to mix with deeper layers. The entrained heat could then melt the ice that was formed. During the second year the effect was reduced.

6.6.7 Access to the model data

The model data set archived at the end of six model years (at the end of the robust diagnostic phase of the model run) is available in computer readable form from the British Oceanographic Data Centre, Bidston Observatory, Birkenhead, Merseyside L43 7RA, UK. They will also provide documentation. The data is in IEEE floating point format and is about 90 Mbytes long. Software for handling the data set is also available.

Other data sets from the PRAM model run will eventually be made available through the British Oceanographic Data Centre. End of month data sets have been archived for the whole fifteen years of the main run. Additional data sets, including mean, variance and cross-correlation fields, have been assembled for the period between ten and sixteen years when the model was in a quasi-steady state.

6.6.8 References

Bryan, F.O. and Holland, W.R. 1989. A high resolution simulation of the wind-and thermohaline-driven circulation of the North Atlantic Ocean. pp 99-115. In: P. Muller and D. Henderson (eds.), *Parameterization of Small-Scale Processes, Proceedings of the Hawaiian Winter Workshop, University of Hawaii, Manoa.*

Bryan, K. 1969. A numerical method for the study of the circulation of the world ocean. Journal of Computational Physics, 4, 347-376.

Cox, M.D. 1984. A primitive equation three-dimensional model of the ocean. *GFDL Ocean Group Technical Report No.1, GFDL/NOAA,* Princeton University, Princeton, 25Opp.

Cox, M.D. 1975. A baroclinic numerical model of the world ocean: preliminary results. In: R. 0. Reid, A. R. Robinson and K. Bryan (eds.), *Numerical Models of Ocean Circulation,* p 107-120. National Academy of Sciences, Washington D.C..

DBDB5 data set. U.S. Naval Oceanographic Office.

The FRAM Group (Webb, D.J. et al) 1991. An Eddy-Resolving Model of the Southern Ocean. Eos, Transactions, American Geophysical Union, 72, 15, 169 and 174-175.

Hellermann, S. and Rosenstein, M. 1983. Normal monthly wind stress over the world ocean with wind estimates. Journal of Physical Oceanography, 13, 1093-1104.

Killworth, P.D., 1987. Topographic instabilities in level models. Ocean Modeling, 75, 9.

Levitus, S. 1982. Climatological Atlas of the World Oceans. *NOAA professional Paper No.13.* U.S. Government Printing Office, Washington, D.C., 173pp.

Sarmiento, J. L. and Bryan, K. 1982. An ocean transport model for the North Atlantic. Journal of Geophysical Research, 87, 394-408.

Semtner, A.J. 1974. An oceanic general circulation model with bottom topography. *UCLA Department of Meteorology, Technical Report No.9.*, 99pp

Semtner, A.J. and Chervin, R.M. 1988. A simulation of the global ocean circulation with resolved eddies. Journal of Geophysical Research, 93, 15502-15522 and 15767-15775.

Stevens, D.P. 1990. On open boundary conditions for three dimensional primitive equation ocean circulation models. Geophysical and Astrophysical Fluid Dynamics. 51, 103.

Webb, D.J. 1990. FRAM - The Fine Resolution Antarctic Model. In: D. G. Farmer and M. J. Rycrost (eds.), *Proceedings of conference on 'Computer modeling in the Environmental Sciences'. Keyworth, April 1990.* pp.1-14, Clarendon Press, Oxford, pp 379.

Whitworth, T., Nowlin, W.D. and Worley, S.J. 1982. The net transport of the Antarctic Circumpolar Current through Drake Passage. Journal of Physical Oceanography, 12, 960.

6.7 Sea Ice Cover and Surface Temperature Trends in the 1980s

by Joey Comiso

6.7.1 Introduction

Because of the potential link with a possible global greenhouse warming, trends in the polar sea ice cover and surface temperature have been studied extensively in recent years (Kukla and Gabin, 1981; Zwally *et al.*, 1983; Gloersen and Campbell, 1988; Weatherly *et al.*, 1991). It has been suggested that early signals of a climate change will be first detected in the polar regions because of possible amplification of the signal due to various feedback mechanisms. Two of the key parameters associated with this feedback are the sea ice cover and polar temperatures. These two parameters are also closely linked with the ecology of the Antarctic region. Sea ice serves as a very large habitat of a large variety of organisms from microorganisms to mammals. The introduction of melt water during recession also stabilizes the vertical structure of the ocean and make it possible for phytoplankton to grow almost unhampered in ample light and nutrient rich environment. Surface temperature is also expected to largely influence population growth, survival, and (or) migration characteristics of many biological species in the ice and adjacent oceans.

The extent of the global sea ice cover has not been possible to quantify until the advent of satellite systems in the 1970s. Also it was very hard to monitor the ice cover with consistency when different types of satellite data are used for different periods. The launch of the scanning multichannel passive microwave radiometer (SMMR) in late October 1978 on board the Nimbus 7 satellite started a series of consistent measurements of ice extent and ice concentration up to August 1987. These measurements are continued to the present time and the foreseeable future with the launch of an operational system called Special Scanning Microwave Imager (SSMI) on board a Defense Meteorological Satellite Program (DMSP) in June 1987. Also, on board Nimbus 7 was the Temperature Humidity Infrared Radiometer (THIR) which provided thermal infrared data for about six years. Results from analysis of these data will be presented.

6.7.2 Sea Ice Cover

The southern ocean sea ice cover is one of the most variable parameters on the surface of the globe. It grows dramatically to about 20 x 10^6 km^2 in the winter and breaks up abruptly to about 4 x 10^6 km^2 in the summer (Zwally *et al.*, 1983, Comiso and Zwally, 1984). Compared to the Arctic, the environmental geographical background in the Antarctic is different. Land surrounds most of the southern limits of the Arctic ice cover while in the Antarctic there is no corresponding land boundary in the north. The lack of a northern land boundary makes the Antarctic ice cover more divergent since it is more vulnerable to dynamic forcing than the Arctic counterpart. Indeed, more open water and new ice formation within the ice pack is observed in this region than in the Arctic (Carsey, 1980; Cavalieri and Martin, 1985; Zwally *et al.*, 1986; Comiso and Gordon, 1987; Jacobs and Comiso, 1989). This is remarkable because heat and salinity fluxes increases considerably even with just a small increase in the fraction of open water. These fluxes are in turn closely linked with bottom water formation, ocean circulation, and ice/ocean/atmosphere interactions (Gordon, 1982, Gordon and Comiso, 1988).

The Antarctic sea ice cover over a seasonal cycle in 1984 is depicted by color coded monthly concentration maps shown in Fig. 1. Ice concentration is derived from the SMMR data using a technique described by Comiso and Sullivan (1986). Minimum extent usually occurs during late February while maximum extent occurs sometime in September. Sea ice grows very slowly during the months of March and April, and very rapidly in May and June. By July, maximum extent is almost achieved. The ice extent is then basically maintained until around November when the decay process starts. During December, except for a few places, like the western Weddell Sea and the Bellingshausen/Amundsen Seas, sea ice melts or retreats in practically everywhere. However, decreases in ice concentration usually commence in the coastal regions and in areas where there are

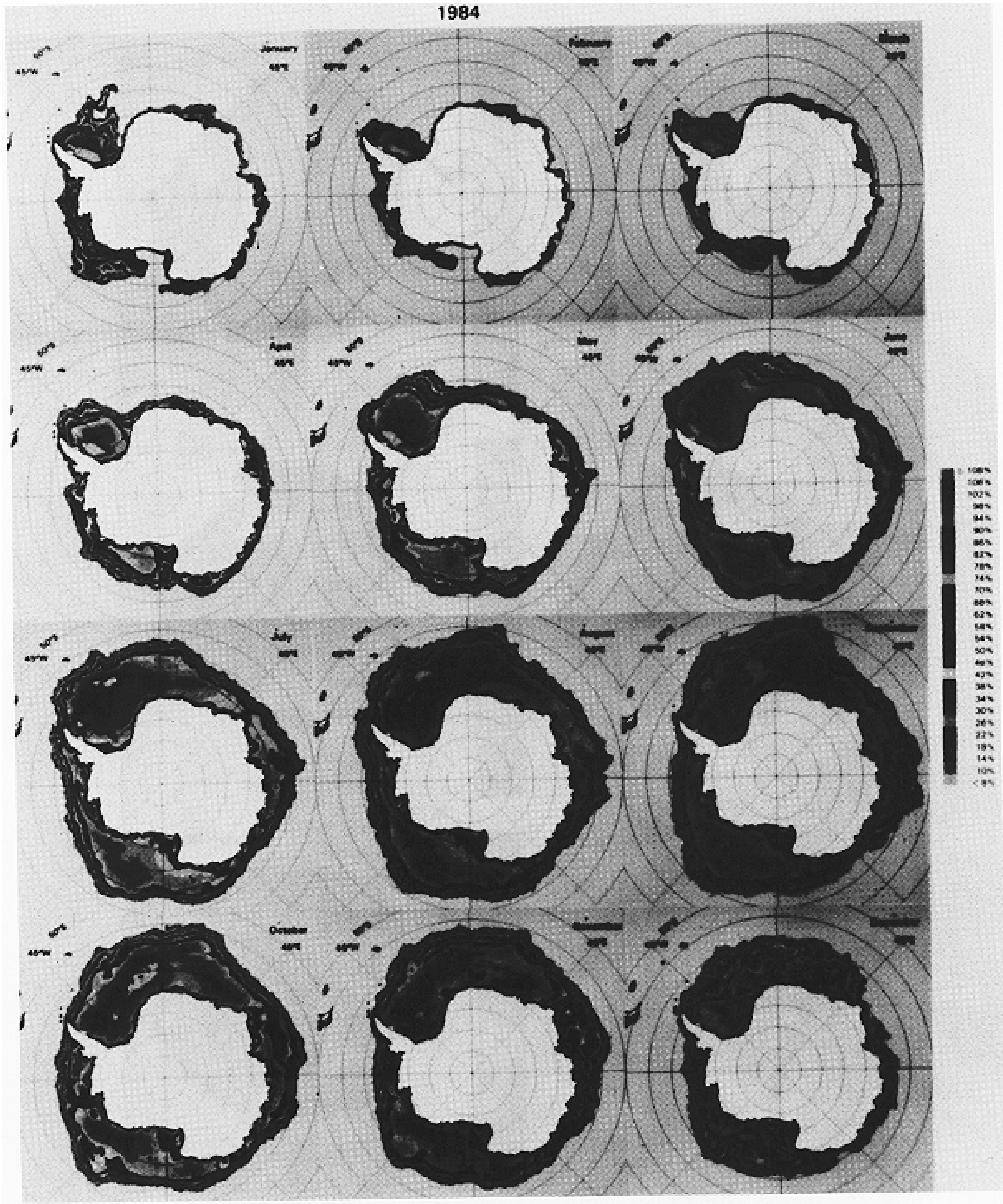

Figure 1. Color-coded monthly maps of ice concentration in 1984 derived from SMMR over a seasonal cycle. (Reproduced in black and white).

strong bottom topographical features.

The growth and decay as well as the spatial redistribution of the ice cover is strongly influenced by the direction and strength of the wind. The geostrophic wind follows generally the same pattern as the gyres around Antarctica with generally clockwise circulations in the Weddell Sea and the Ross Sea, westerlies along the coast and easterlies further north at the mid-latitudes. The easterlies along the coast are strengthened by katabatic flow from the continent, especially near glaciers (Weller, 1969). The latter is usually the site of the formation of coastal polynyas which act as ice factories on account of the persistence of these winds and therefore constant exposure of the ocean surface to cold air. From crude estimates of ice production, it has been postulated that a large fraction of the total ice cover originate from these coastal regions (Zwally *et al.*, 1986).

Fig. 2 shows difference maps of ice concentration during periods of growth and decay in 1980 through 1983. The images illustrate eastward movements of the ice cover during growth and basically follows the drift patterns shown by buoy data. During ice breakup or decay, there is no obvious preferential pattern except that ice breakups normally occur first in the interior as near the Maud rise region and the continental shelf region adjacent to Ross ice shelf. This pattern of decay suggests that the ocean and bathymetry plays an important role in the breakup of sea ice.

Ice concentration maps during several winters (September 1979-September 1986) are shown in Fig. 3. In this Figure, the ice cover shows large regional variability from one year to another. For example, the ice cover in the Indian Ocean was much more extensive (almost 5° further north) in 1979 than in 1981. Also, in the Bellingshausen/Amundsen Seas, the sharp corner and extensive sea ice near 150°W in 1985 was very much suppressed in 1980. A somewhat anomalous ice cover occurred in 1980, when the shape of the distribution of ice was approximately elliptical with the major axis parallel to 45°W. While the actual ice cover was not that much different during this year from other years, there are large areas covered by ice during this year that were not usually covered during other years (and vice versa). The cause and effect of this phenomena is still unknown.

A quantitative evaluation of the >10% ice extent, actual area, and open water area in the entire Antarctic region and in various sectors (as defined in Zwally *et al.*, 1983), are shown in Fig. 4. In Fig. 4a, the distributions for the entire region shows a relatively stable ice cover with no discernible interannual trend for either the maxima, minima, or average. Even the interannual variability is very slight. The distribution for the Indian Ocean sector (Fig. 4b) is very similar with again very little trend. The Pacific-Indian Ocean sector (Fig. 4c) show some interannual variability with enhancements in 1982 and 1983 but no interannual trend. The Ross Sea sector (Fig. 4d) show a dip in 1980 and enhanced values in 1983, 1984, and 1985. The Bellingshausen-Amundsen Seas sector (Fig. 4e) show a peak in 1979 and other years appear similar. Much of these interannual variabilities are associated with differences in dynamic forcing which causes the ice cover to have different shapes during different years. Because the interannual variations of total ice cover in the hemisphere is small, the impact of ice on the variability of the oceanography in the region may be small. Also, except for 1980, the regional variations do not seem to follow a definite pattern. Thus the overall impact to the oceanography of the interannual variations in the regions may not be very strong. From the ecological standpoint, however, such interannual variations may be very important during some years and in some regions. For example, in the Pacific-Indian Sector, at about 135°E, the distance from the continent to the ice edge during some winters is twice that of other years. The impact of such variability to some land animals who need to get to the ice edge for food could be tremendous.

6.7.3 Surface Temperatures

Despite obvious needs for more detailed surface temperature measurements in the polar regions, especially for climate studies, current data sets correspond only to those collected from stations and buoys which are sparsely distributed in these regions. A recent study by Weatherly *et al.* (1991) shows that there is good correlation of surface temperatures as measured from Antarctic continental stations with ice extent in adjacent regions. However, the location of the ice edge is usually several hundred kilometers from the coastal regions where the stations are located. Also, the station data might be influenced by local conditions (e.g. presence of katabatic winds, and altitude) and might

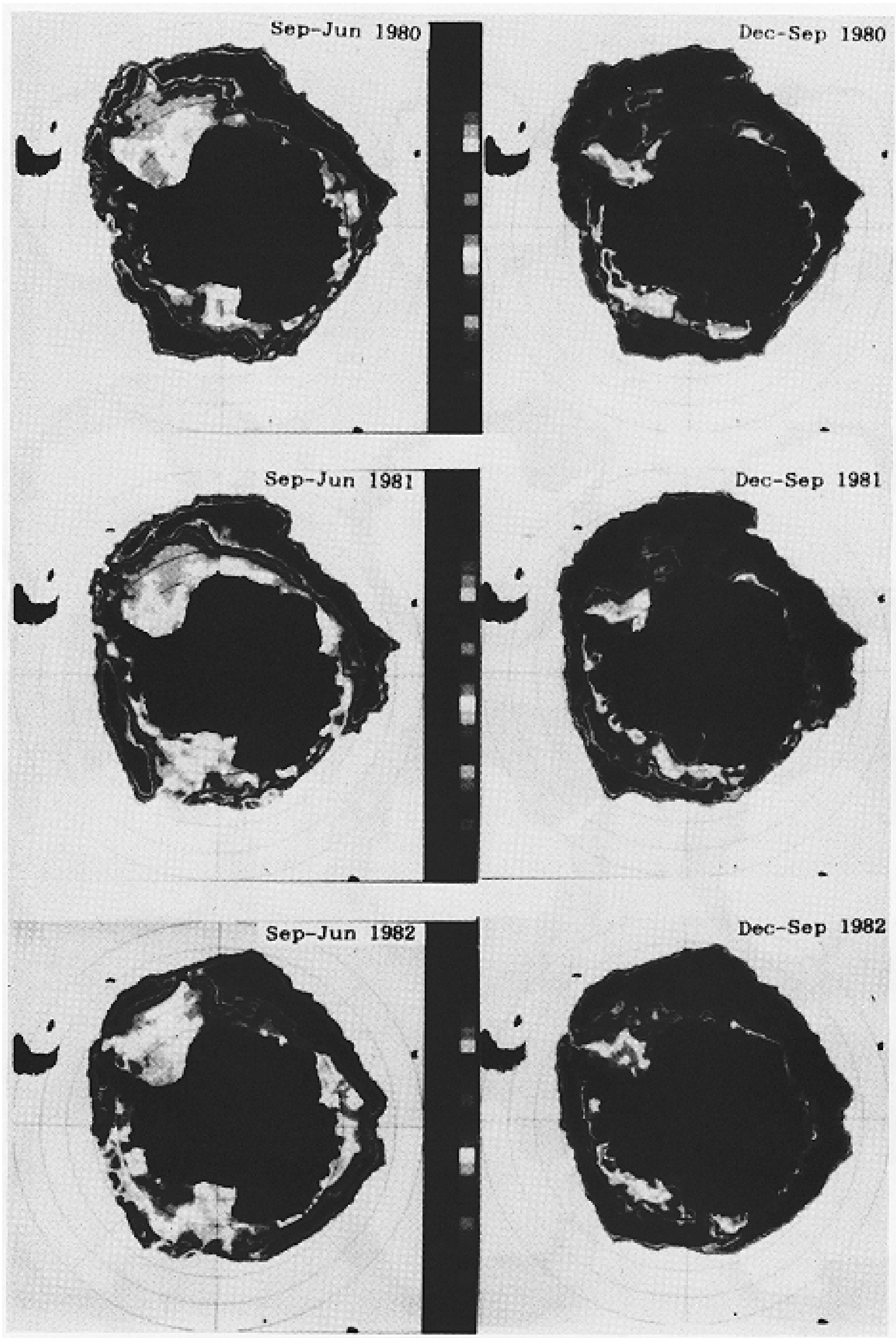

Figure 2. Ice concentration difference maps from fall to winter and from winter to spring in 1980, 1981, and 1982. (Reproduced in black and white).

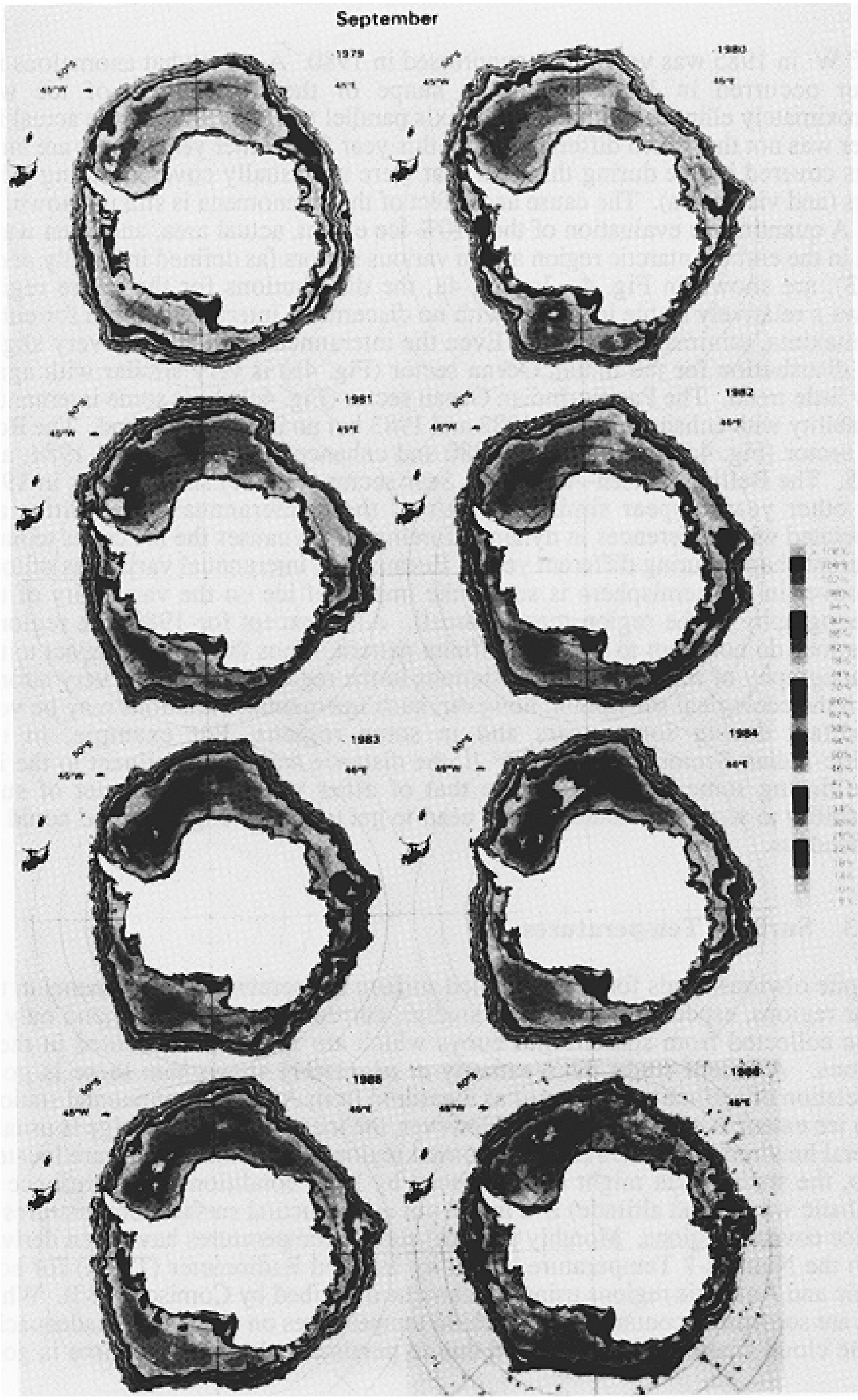

Figure 3. Color-coded monthly maps of ice concentration during the winters of 1979 through 1986. (Reproduced in black and white).

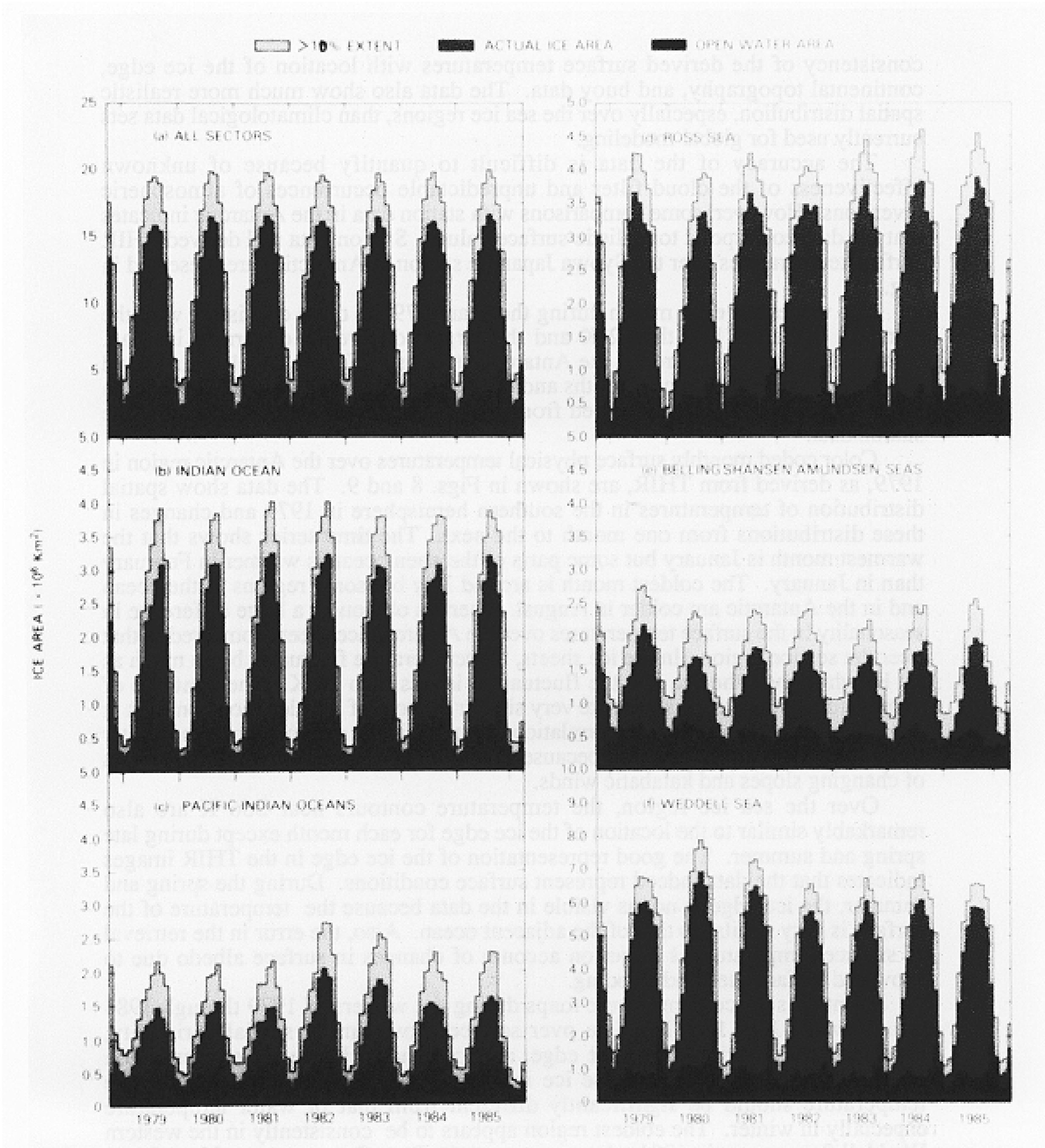

Figure 4. Distributions of monthly ice extent, actual ice area, and open water, from 1978 through 1986.

not reflect actual surface temperatures in the ice covered regions. Monthly physical surface temperatures have been derived from the Nimbus-7 Temperature Humidity Infrared Radiometer (THIR) for both Arctic and Antarctic regions using a technique described by Comiso (1983). While data are sometimes contaminated by cloud temperatures on account of inadequacies in the cloud filtering procedure and due to persistent cloud cover, there is good consistency of the derived surface temperatures with location of the ice edge, continental topography, and buoy data. The data also show much more realistic spatial distribution, especially over the sea ice regions, than climatological data sets currently used for global modeling.

The accuracy of the data is difficult to quantify because of unknown effectiveness of the cloud filter and unpredictable occurrences of atmospheric inversions. However, some comparisons with station data in the Antarctic indicates that the data correspond to realistic surface values. Station data and derived THIR surface temperatures over the Syowa Japanese station in Antarctica are presented in Fig. 5.

The values for each month during the year 1979 are quite consistent with the standard deviation less than 2°K and the largest difference occurring in May. Similar data were compared at the Antarctic stations in Ferrell, Meeley, and Byrd for both winter and summer months and the results are shown in Figs. 6 and 7. In all cases, temperature data derived from THIR appears to be consistent with the station data.

Color coded monthly surface physical temperatures over the Antarctic region in 1979, as derived from THIR, are shown in Figs. 8 and 9. The data show spatial distribution of temperatures in the southern hemisphere in 1979 and changes in these distributions from one month to the next. The time series shows that the warmest month is January but some parts of the open ocean is warmer in February than in January. The coldest month is around July but some regions in the ocean and in the Antarctic are colder in August. There is obviously a large difference in seasonality in the surface temperatures over the Antarctic ice sheets compared to that over the sea ice region. In the ice sheets, the temperature fluctuates by as much as 40°K, while over the sea ice, the fluctuation is less than 20°K. The contours of temperatures over the ice sheets are very similar to those of the elevation contours in the region with the best overall correlation occurring in the summer while the winter values are not as well correlated because of modifications on account of the effects of changing slopes and katabatic winds.

Over the sea ice region, the temperature contours near 266°K are also remarkably similar to the location of the ice edge for each month except during late spring and summer. The good representation of the ice edge in the THIR images indicates that the data indeed represent surface conditions. During the spring and summer, the ice edge is not as visible in the data because the temperature of the surface is very similar to that of the adjacent ocean. Also, the error in the retrieval of surface temperature is larger on account of changes in surface albedo due to snow and surface melt and flooding.

Monthly surface temperature maps during the winters of 1979 through 1984 are shown in Fig. 10. The data over sea ice show similar spatial variability, especially the location of the ice edge, as those shown in the ice concentration maps. This is expected because ice is such a good insulator and the surface temperature should be significantly different from that of water temperature especially in winter. The coldest region appears to be consistently in the western Weddell Sea except in 1981 when areas near the Ross Sea appears colder. Some relatively warm areas also appear near the coastal regions where winter coastal polynyas are located.

In the interior of the continent, the coldest winter appears to have occurred in 1983 while the warmest winter was in 1980. It is not apparent that there was a significant influence of surface temperature on the ice cover during these years. The aforementioned anomaly in the shape of the ice cover in 1980 may thus be associated to factors other than surface temperature. Furthermore, there is no obvious trend in surface temperature. During the time period when data were available, the temperatures in 1979, 1983 and 1984 in east Antarctica appeared to be lower by about 40 than in other years. While the surface temperatures were significantly warmer during 1980, 1981, and 1982, the extent and size of the ice cover during these years do not appear significantly different. This result suggests that short term effects to the ice extent of a surface warming of the order of a few degrees may not be easy to infer from global climate models. Since the change in temperature

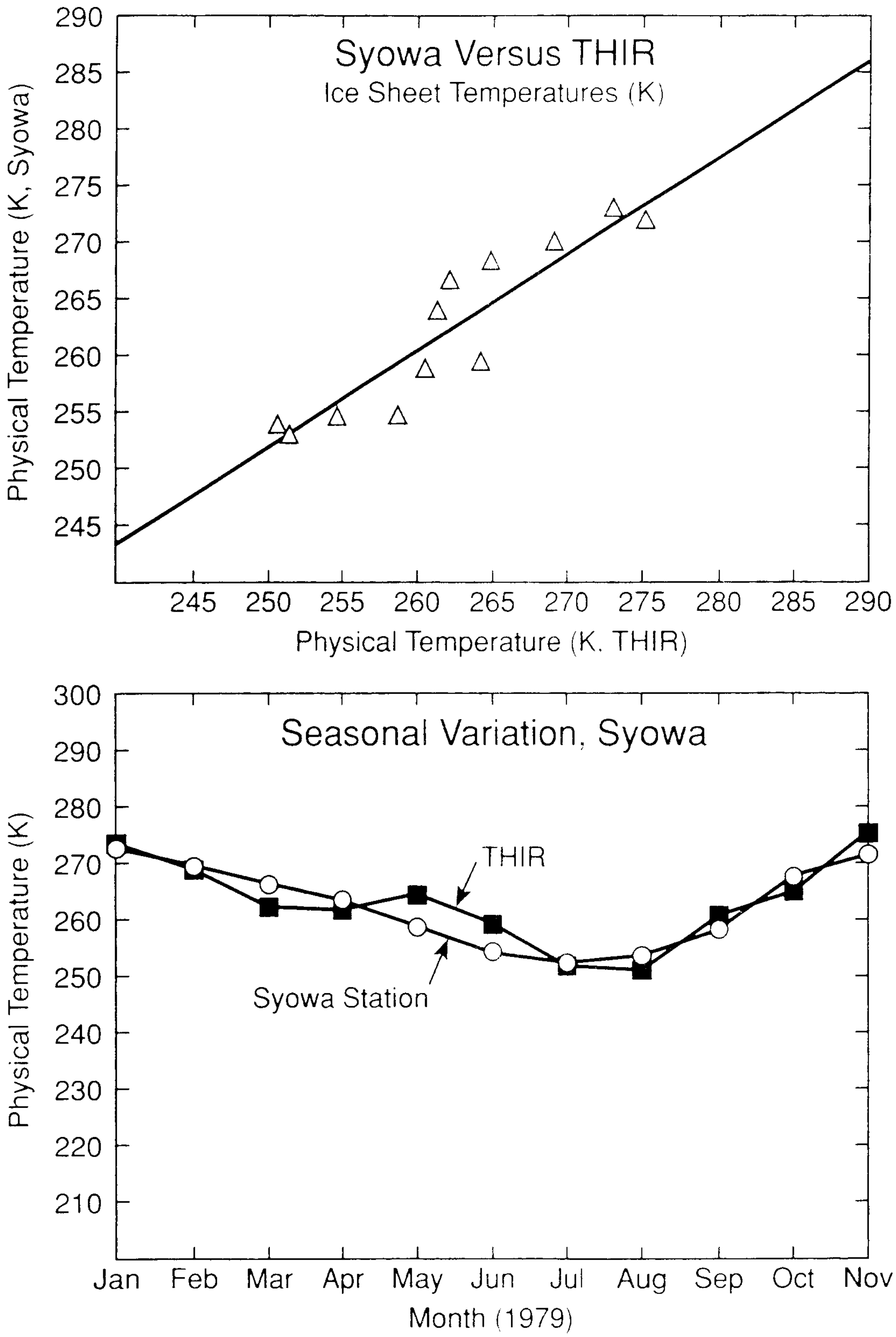

Figure 5. Syowa station surface physical temperature data compared with THIR data for each month in 1979.

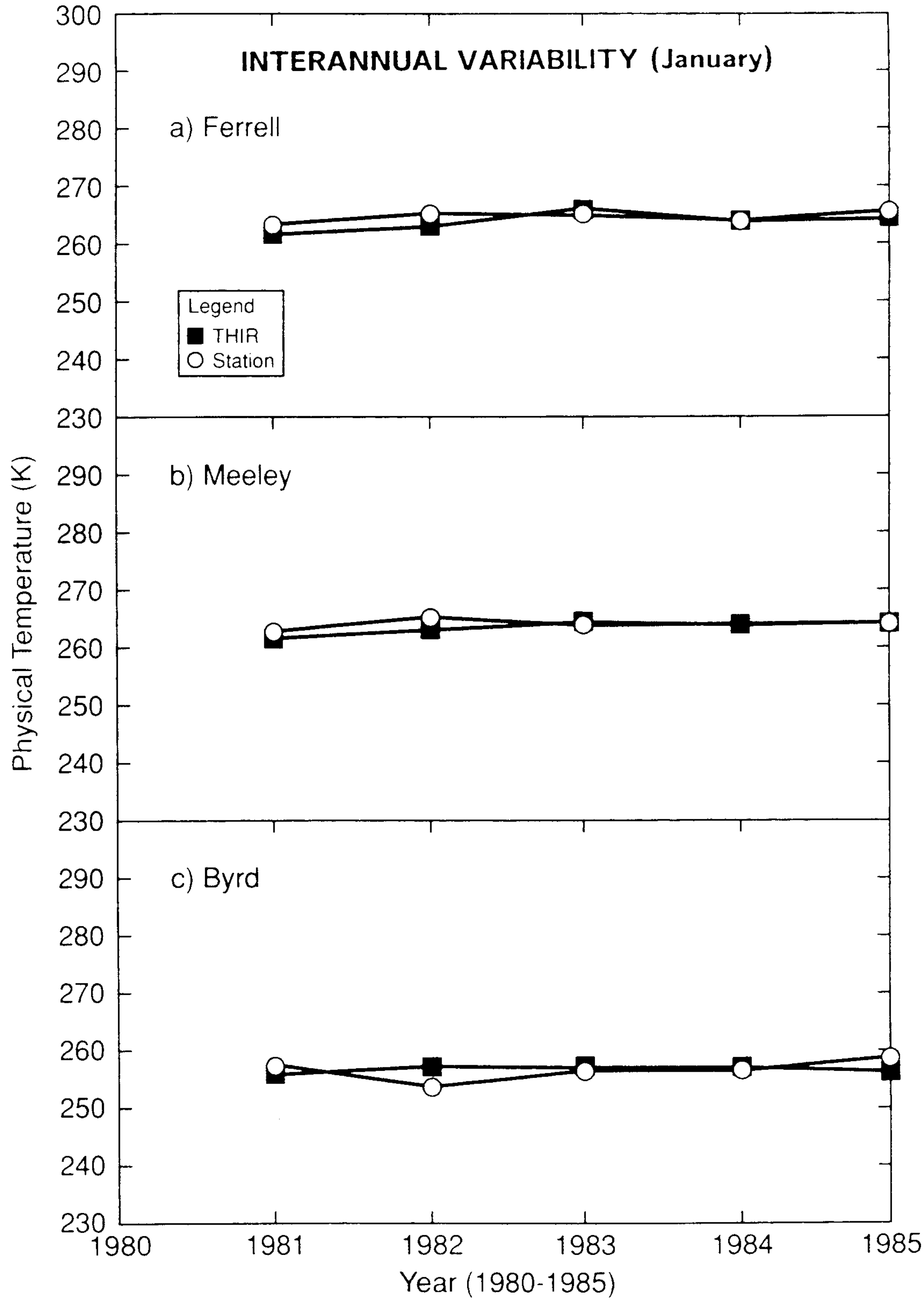

Figure 6. Ferrell, Meeley, and Byrd station surface physical temperature data compared with THIR data during several summers.

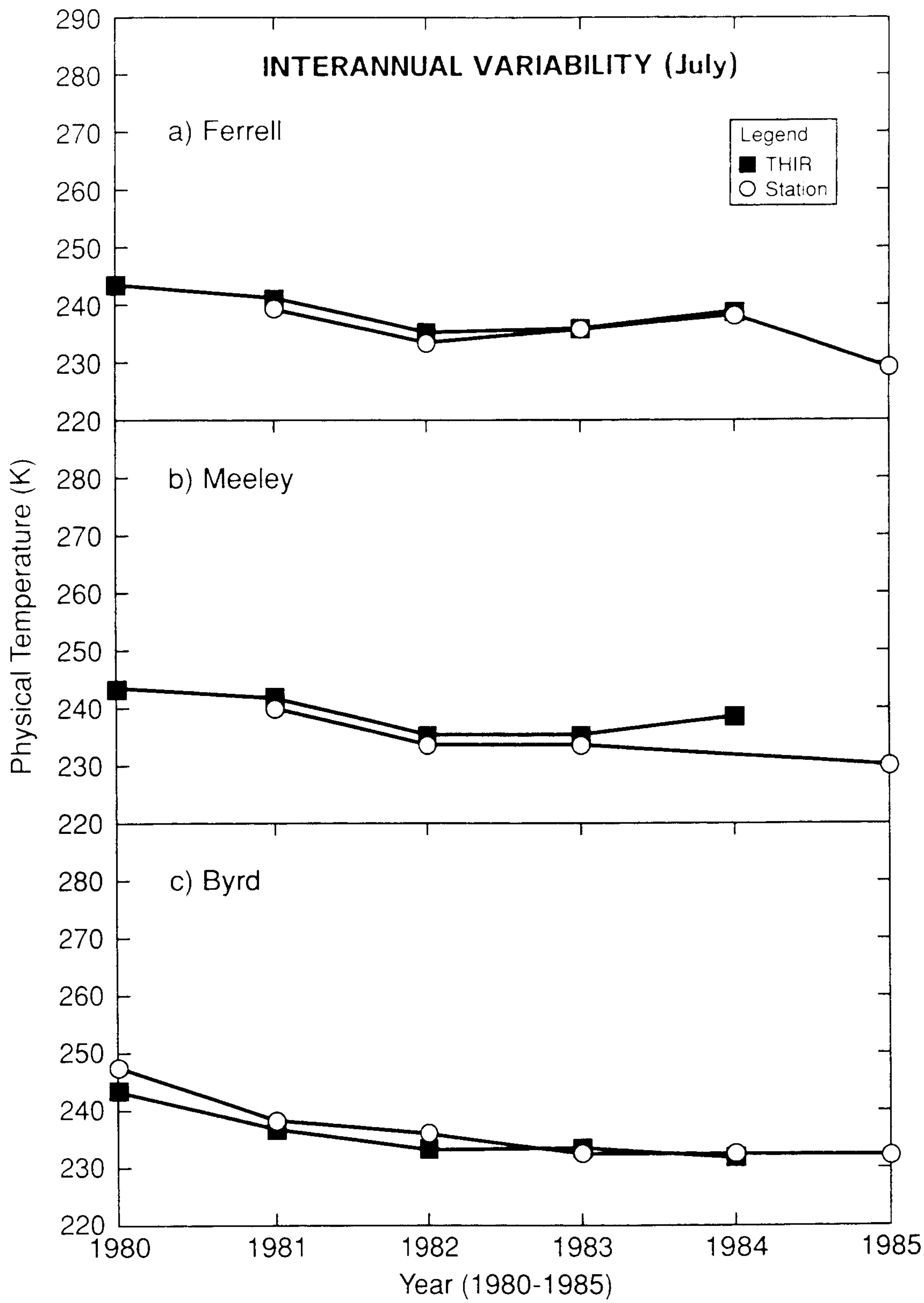

Figure 7. Ferrell, Meeley, and Byrd station surface physical temperature data compared with THIR data during several winters.

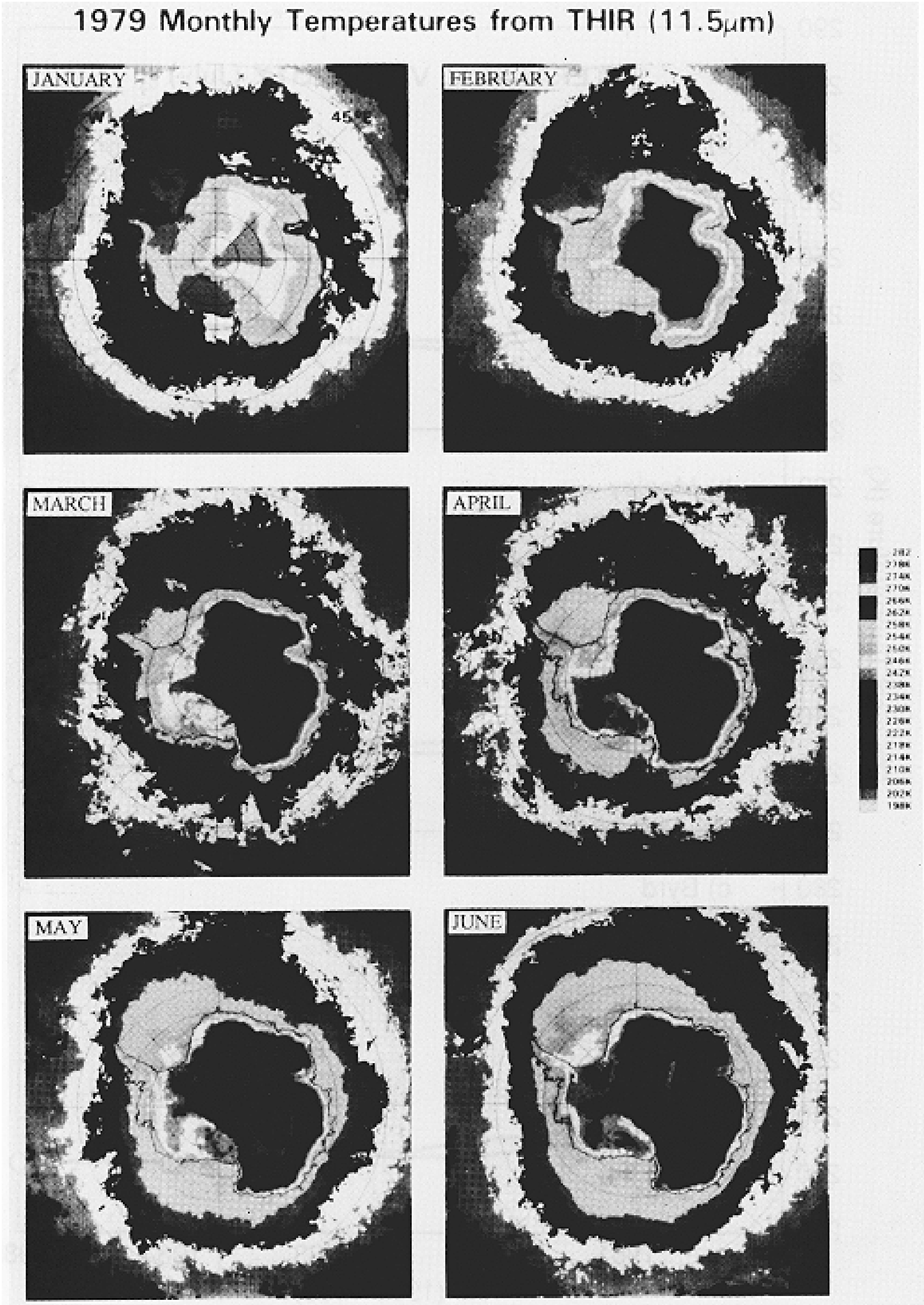

Figure 8. Color-coded monthly surface physical temperatures from January to June 1979. (Reproduced in black and white).

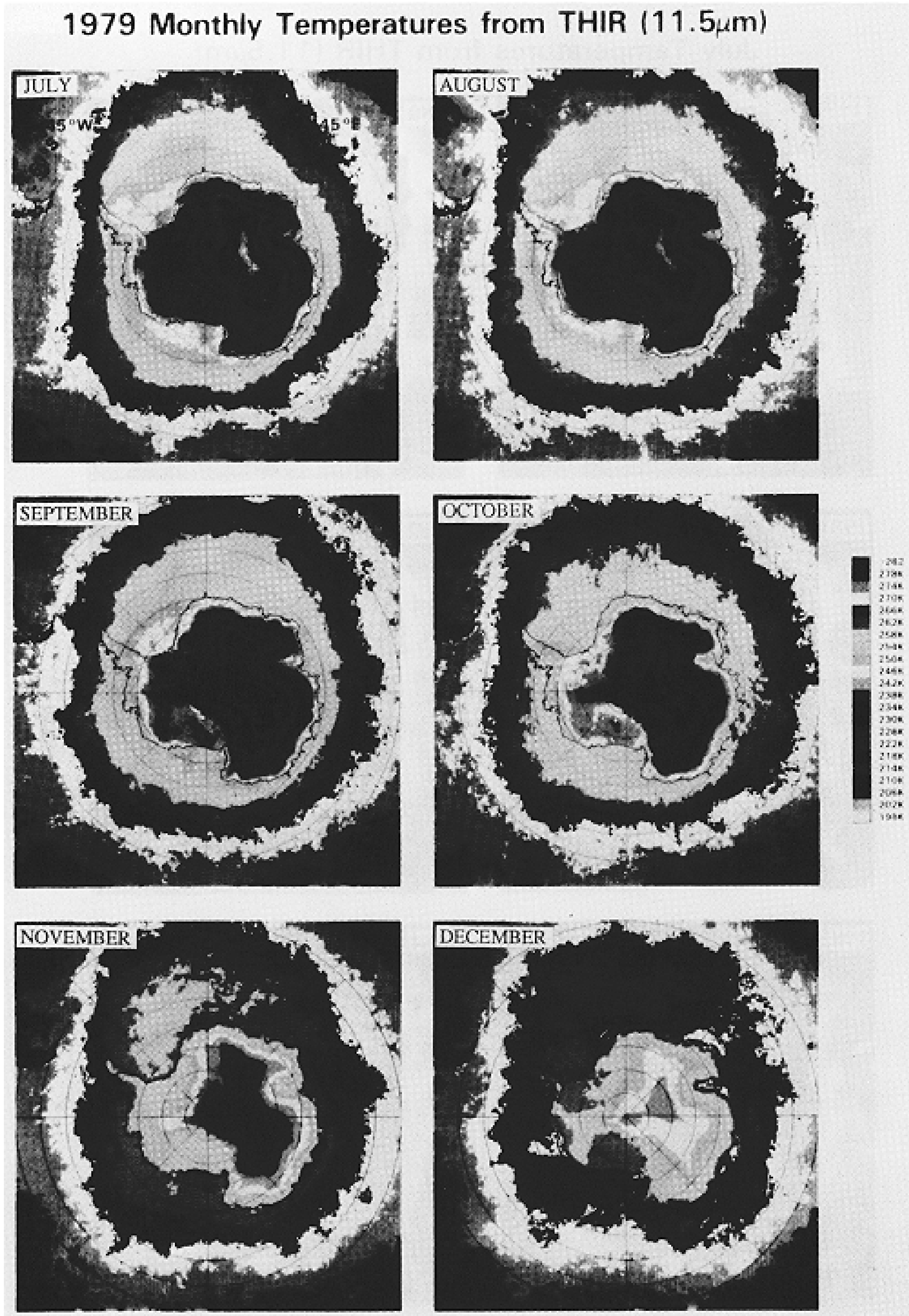

Figure 9. Color-coded monthly surface physical temperatures from July to December 1979. (Reproduced in black and white).

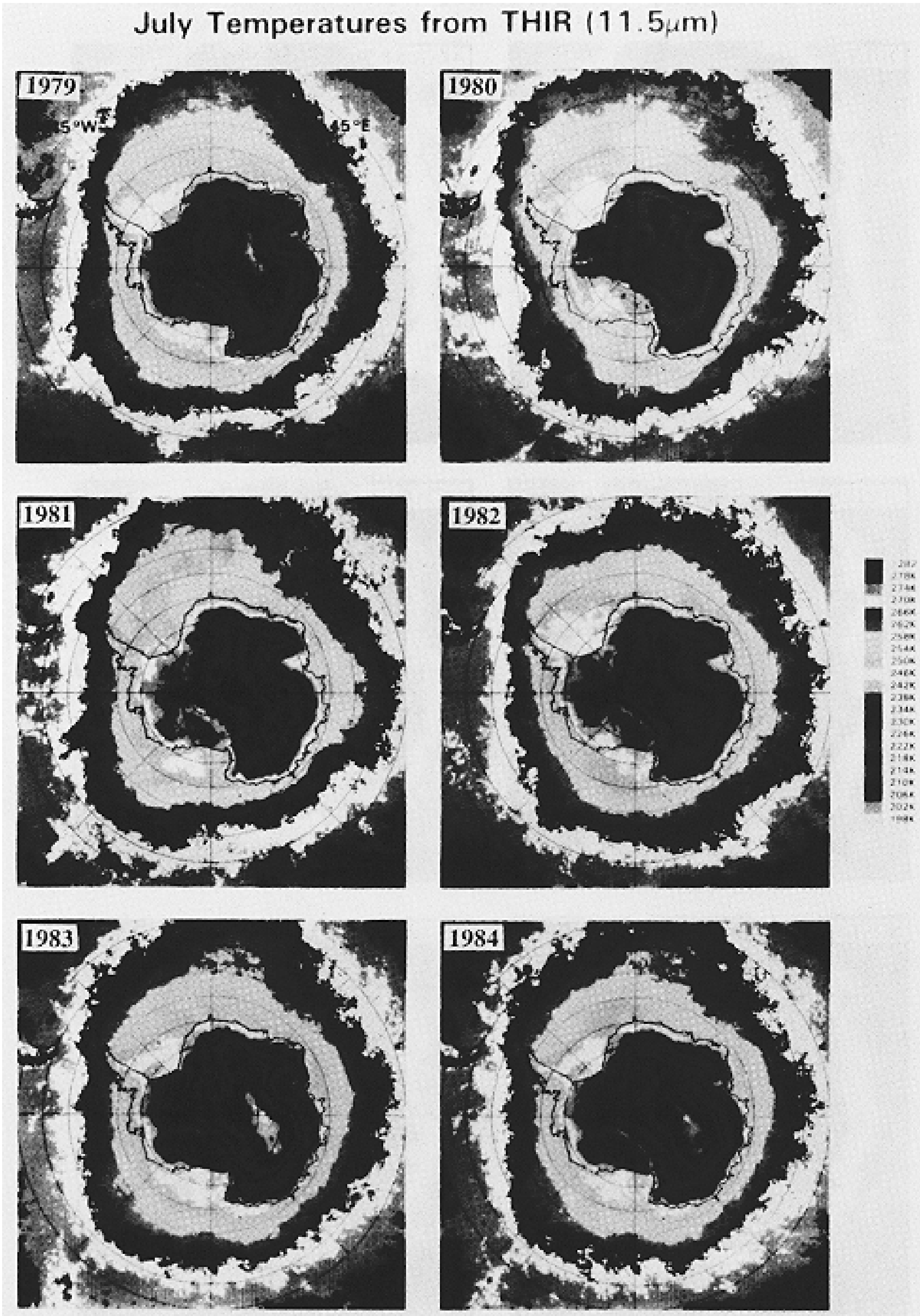

Figure 10. Color-coded monthly surface physical temperatures during several winters. (Reproduced in black and white).

is primarily in the interior of the continent and is only slightly reflected in the sea ice region, further study is needed to better evaluate these results.

6.7.4 Discussion and Conclusions

During the period 1979 through 1986, the extents and total ice areas vary by a factor of five from summer to winter in the southern hemisphere but no interannual trend is apparent. There was also no significant trend in surface temperature during this period. However, there are considerable regional variabilities during the period. In 1980, the ice cover was anomalously different in that the shape of the ice edge was almost elliptical, the western Weddell Sea had a lot of ice while at the opposite end in the Indian/Pacific Ocean region, there was very little ice. The location, size, and shapes of coastal polynyas also vary from one year to the next. Distances from shore to the ice edge could at times vary by a factor of two. The surface temperatures also follow the same patterns as the sea ice cover with the ice edge basically replicated in the temperature maps. The coldest regions over sea ice in winter is usually over the western Weddell Sea while those for the Antarctic ice sheet is over the highest elevations. The coldest temperatures occurred in 1979, 1983, and 1984 when the minimum temperature was at least 4°K colder than during other years. However, such drop in temperature was not reflected in the ice cover during these years. The lack of correlation suggests that changes in surface physical temperature of the order of a few degrees may not necessarily mean immediate changes in the extent and size of the sea ice cover.

6.7.5 References

Carsey, F., Microwave observation of the Weddell polynya. 1980. Mon. Weather Rev. 108, 2032-2044.

Cavalieri, D.J., and S. Martin, 1986. A passive microwave study of polynyas along the Antarctic Wilkes Land Coast. In: S. Jacobs (ed.), *Oceanology of the Antarctic Continental Shelf, Antarctic Research Series,* 43, pp.227-252, AGU, Washington, DC, *1985.*

Comiso, J.C. 1983. Sea ice microwave emissivities from satellite passive microwave and infrared observations. J. Geophys. Res. 88, 7686-7704.

Comiso, J.C. and A.L. Gordon. 1987. Recurring Polynyas over the Cosmonaut Sea and the Maud Rise. J. Geophys. Res. 92, C3, 2819-283.

Comiso, J.C. and C.W. Sullivan. 1986. Satellite microwave and in situ observations of the Weddell Sea ice cover and its marginal ice zone. J. Geophys. Res. 91, 9663-9681.

Comiso, J. C., and H. J. Zwally. 1984. Concentration Gradients and Growth/Decay characteristics of the Seasonal Sea Ice Cover. J. Geophys. Res. 89, CS, 8081-8103.

Gloersen P. and W.J. Campbell. 1988. Variations in the Arctic, Antarctic, and Global sea ice covers during 1978-1987 as observed with the Nimbus 7 scanning multichannel microwave radiometer, J. Geophys. Res., 93, 10666-10674.

Gordon, A.L. Weddell deep water. 1982. J. Mar. Res. 40, 199-217.

Gordon A. and J.C. Comiso. 1988. Polynyas in the southern ocean. Scientific American 256(6), 89-96.

Jacobs, S.S., and J. C. Comiso. 1989. Satellite passive microwave sea ice observations and oceanic processes in the Ross Sea, Antarctica. J. Geophys. Res.94, 18195-18211.

Kukia, G. and J. Gavin. Summer ice and carbon dioxide. Science 214, 497-503.

Weatherly, J.W., J.E. Walsh, and H.J. Zwally. 1991. Antarctic sea ice variations and seasonal air temperature relationships. J. Geophys. Res. 96, 15119-15130.

Weller, G. A meridional surface wind speed profile in Mac Robertson Land, Antarctica. Pure Appl. Geophys., 77, 193-200.

Zwally, H.J., J.C. Comiso, and A.L. Gordon. 1986. Antarctic offshore leads and polynyas and oceanographic effects. In: S. Jacobs (ed.), *Oceanology of the Antarctic Continental Shelf, Antarctic Research Series*, 43, 203-226.

Zwally, H.J., C.L. Parkinson, and J.C. Comiso. 1983. Variability of Antarctic Sea Ice and changes in carbon dioxide. Science 220, 1005-1012.

7 WORKING GROUP REPORTS

7.1 Zooplankton/Krill Working Group Report

Chairman: Mark Huntley

Rapporteur: Steve Nicol

Members:

Charles Greene
Tsutomu Ikeda
Victor Marin
Langdon Quetin
Robin Ross
Suzanne Razouls
Sigrid Schiel
Jon Watkins
Stanislaw Rakusa-Suszczewski

7.1.1 Site selection

The group recommends the consideration of two sites for field studies: (1) the Bellingshausen Sea, and (2) an area directly west of the Ross Sea, bounded by the continent to the south, 65°S, and 140° to 160°E. Most of the discussion which follows refers to the Bellingshausen Sea site in particular, but applies in general to both sites.

7.1.2 Climate change context

Both sites provide an opportunity to assess the role of sea ice in the life cycle and habitat of Antarctic krill, *Euphausia superba.* Climate change might be expected to alter: (1) the areal extent of seasonal ice cover, (2) the thickness of ice, (3) the rate of formation and retreat, (4) and the percentage of open water within the pack. Furthermore, both sites afford the opportunity to observe the effects of glacial meltwater on physical stability, circulation patterns, and their effects on ecosystem structure and dynamics. Both areas have been subject to significant fisheries for krill, so there exists the possibility for examining fisheries/climate change interactions.

7.1.3 Target species

Krill *(Euphausia superba)* is designated as a target species due to its clear importance from an ecological and economic viewpoint. Furthermore, there exist abundant historical data on the species.
The following species were also indicated as important species:

** *Salpa thompsoni*
* *Euphausia crystallorophias*
* *Calanoides acutus*
* *Calanus propinquus*
Themisto gaudichaudi
Metridia gerlachei
Rhincalanus gigas
Thysanoessa macrura
Sagitta gazellae

Salpa thompsoni is designated as especially worthy of consideration due to its propensity to dominate in years and locations where *E. superba* are scarce. *Euphausia crystallorophias* is a high Antarctic, neritic euphausiid, particularly associated with the pack ice. *Calanoides acutus* and *Calanus propinquus* represent important copepod species with contrasting life cycles: *C. acutus* exhibits seasonal, ontogenetic vertical migration, whereas *C. propinquus* does not.

7.1.4 Definable populations

The gyral circulation of the Bellingshausen Sea is thought to contain a functional population of *E. superba* and, by inference, of other significant holozooplankton species. Similarly, the 150°E study site is known to have supported a consistent krill fishery in a restricted area along the continental shelf break. However, the details of the regional circulation in these areas are not well known, and are expected to benefit from a combination of WOCE and GLOBEC field studies.

7.1.5 Population dynamics

Understanding the population dynamics of the key species in these two areas will require two separate types of cruises: (1) quasi-synoptic demographic surveys and (2) process-oriented cruises. Particular attention will be paid to the analysis of demographic parameters during the winter season and their influence on the size of populations during the productive summer season. Recommendations regarding the measurement of population dynamics parameters are made below *(Recommended Research Strategy).*

7.1.6 Focus on processes and mechanisms

The working group identified key gaps in our knowledge regarding the life cycle of Antarctic krill and other holozooplankton. Particular amongst these problems is the question of overwintering strategies, encompassing under-ice behavior, potential benthic interactions, and physiological adaptations to the winter environment. The group characterized certain critical processes with respect to their temporal/spatial scales (Table 1).

TABLE 1

PROCESS	TIME SCALE	SPATIAL SCALE
Reproduction	days-months	1-10 km (H) 1000 m (100 m resolution)
Migration (H)	days-weeks	10-100 km
Migration (V)	hours-seasonal	300 m
Swarming	hours-weeks	10 m - 10 km
Mortality		
a) "natural"	weeks	microscale-gyre scale
b) predation	seconds-months	
Growth	days-weeks	
Life cycle	2-3 years (hatch-hatch)	gyre scale

*Note: Sample to 1000 m for copepods

7.1.7 Historical database

The group acknowledged that, while meager, data do exist for both study regions, particularly in regard to krill in the Bellingshausen Sea study area. Relevant data have been reported from the work of the BIOMASS program, V. Siegel, the Discovery expeditions, the Eltanin expeditions, and a variety of Polish and Russian expeditions.

7.1.8 Modeling

The group recommends the development of coupled biological-physical models for holozooplankton populations in the study areas. These models should include the parameters of sea ice formation and retreat and its effect on stability of the water column.

7.1.9 New technology

New developments in remote sensing technology were encouraged. These might include moored sensing systems which would provide long-term Eulerian data, complementing shorter-term Lagrangian information available from research cruises. Satellite and aircraft-based observing technologies were also endorsed.

7.1.10 Relation to other programs

It was noted that other programs and scientific activities in the Bellingshausen Sea in the near future would include BOFS (JGOFS), WOCE, the US LTER (a ten-year ecosystem study in Palmer Basin), RACER, AMLR, and a *Polarstern* cruise to the BellingshausenAmundsen Seas in 1993-94. In addition, shore-based laboratories in the Antarctic Peninsula region, as well as Rothera (Adelaide Is.) would provide facilities for laboratorybased process studies and long-term continuous observations.

7.1.11 Recommended research strategy

It is recommended that the field research program include three principal activities: (1) Quasi-synoptic survey cruises, (2) Process-oriented cruises, and (3) Remote sensing.

The quasi-synoptic survey cruises should take place at approximately monthly intervals for a minimum period of three years, in order to resolve the full life cycle of *E superba* and other key species. These cruises should encompass shelf, slope and oceanic environments (Fig. 1), with the aim of resolving mesoscale features in both the biotic and dynamic physical environments.

Process cruises should focus on the processes and mechanisms identified above, and should be directed on a phenomenological basis from information arising from results of the survey cruises.

Remote sensing aspects of the program should incorporate new and existing technologies capable of yielding synoptic data over long time scales.

In general, the working group recommends that this project could feasibly begin by 1996-97. It would involve multiple ships from different nations, and would require that a common quasi-synoptic survey grid be occupied at different times by all participants.

It was noted that sampling strategies may differ depending upon the species being investigated. For example, while the 200 m depth horizon may be adequate for a study of juvenile and adult krill, the 1000 m depth horizon may be more appropriate for copepods and early larval stages of krill.

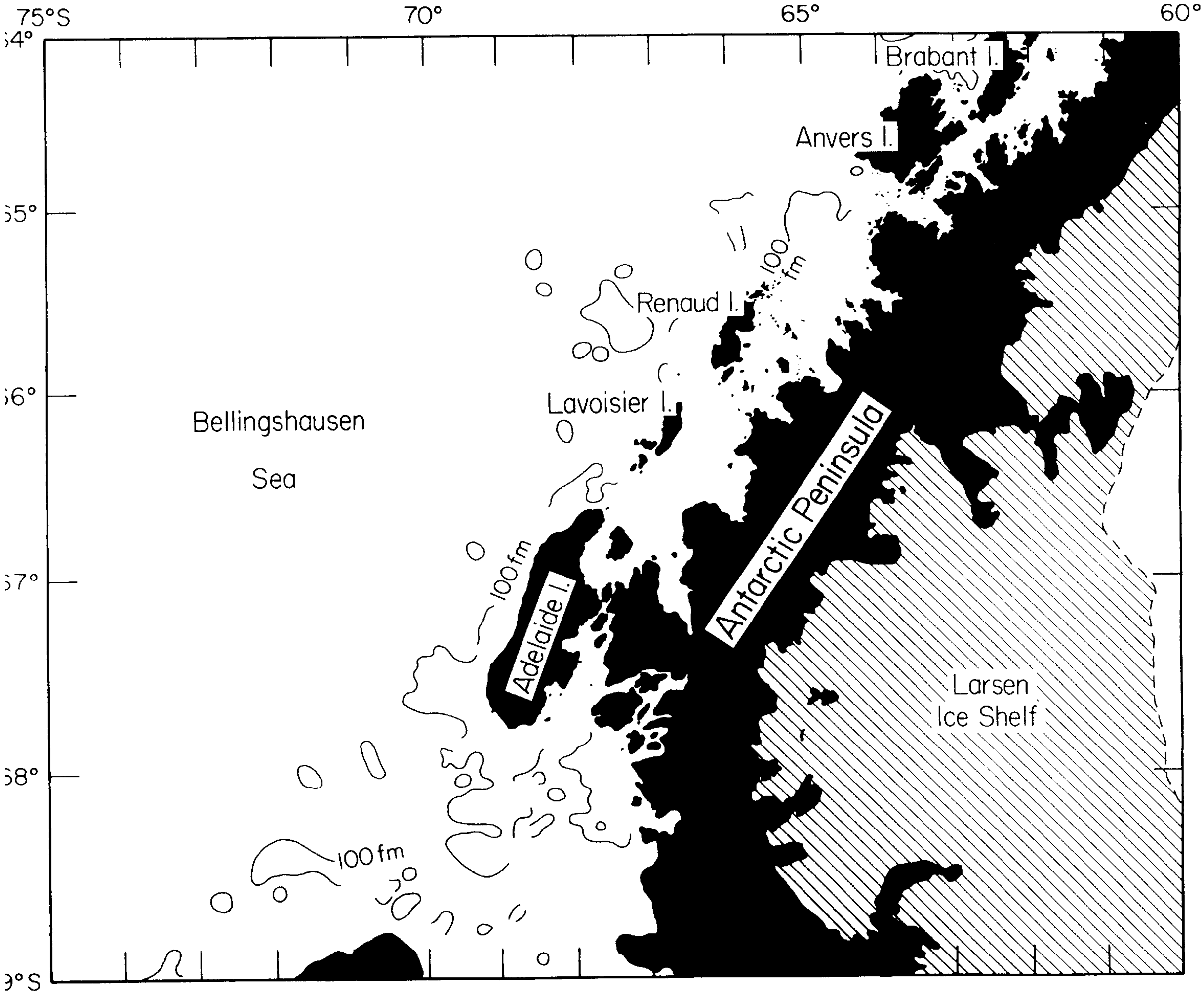

Figure 1. Proposed study area for GLOBEC operations in the Bellingshausen Sea.

7.2 Benthic Working Group Report

Chairman: Donal Manahan

Rapporteur: Jackie Grebmeier

Members:

Wolf Arntz
Jim Barry
Ulrich Bathmann
Paul Dayton
Rennie Holt
Ken Smith
Bill Stockton
Martin White

In the context of GLOBEC, the benthic working group discussed process-oriented objectives that would be investigated at various shallow and deep water sites surrounding Antarctica to be occupied by various international scientific programs. The objective at these sites would be to investigate effects of climate change on the benthos by studies of community composition, population dynamics and energy flow.

7.2.1 Site selection criteria

Selection of research sites was based on historical long-term data records, logistical constraints (ship, field station availability), and the location of high and low Antarctic sites and species for latitudinal comparisons. The group selected the following 5 sites surrounding Antarctica:

1. Ross Sea/McMurdo Sound: high Antarctic (USA)
2. South Orkney/South Shetland Islands: low Antarctic (e.g., UK, POL, D)
3. SE Weddell Sea: high Antarctic (D)
4. Davis Sea: high Antarctic (AUS)
5. Antarctic Peninsula: low Antarctic (various countries)

7.2.2 Climate change context

Benthic structures in the Antarctic are notable for their persistence, which is a valuable characteristic to investigate the effects of climate change. The benthos holds a long-term record of ecological processes both within the fauna and sediments. Within the global climate change context, variation is likely to be measurable as latitudinal changes in community structure and in benthic dynamics, both surrounding islands as well as the main land mass. In particular, Antarctic benthic fauna appear to have higher temperature sensitivity than temperate species, often with Q_{10}'s >10, indicating they may be critical indicators of small temperature changes due to a climatic shift. A second major variable influenced by climatic change is likely to be a shift in organic carbon supply and food chain disruption, resulting in changes in the benthic structure.

A. Criteria for Selection

Five characteristics were identified as criteria for selection of target species, including:

1. Measurable growth parameters
2. Abundant
3. Wide or restricted distribution (either group will react to climate change differently)
4. Known life history
5. Amenable for reproductive studies

B. Species (pelagic and nonpelagic larvae)

Three groups of benthic fauna were selected as potential target species. Examples are presented for each, inclusive of both wide ranging species with pelagic (p) larvae and restricted fauna, often characterized by brooders (b).

1. Bivalves, e.g. *Adamussium* (p), *Laternula* (p), *Mysella* (b), *Gamardia* (b)

2. Echinoderms, e.g. *Odontaster* (p), *Sterechinus* (p), *Ophionotus* (p), *Diplasteria* (b)

3. Crustaceans, e.g. *Notocrangon* (p), *Chorismus* (p), *Glyptonotus* (p)

7.2.4 Definable populations

The group agreed that selected benthic populations were very tractable using genetic techniques in addition to current data bases on populations. Populations with well-known interactions with other species within the community and known fluctuations, would be desirable.

7.2.5 Population dynamics and physical processes

Coincident measurements of benthic population dynamics (e.g. recruitment, life history strategies, production) with physical processes (e.g. ice cover, temperature, salinity, currents) are essential for determination of key variables influenced by climatic change. Currently standard population dynamic studies of various target species are underway in McMurdo Sound (USA) and areas of the Weddell and Scotia Seas (Germany, U.K.).

7.2.6 A. Processes and mechanisms inducing change

Six major processes were identified that could presently be investigated as mechanisms indicative of global change. These include:

1. carbon flux
2. ice conditions
3. current flow
4. temperature and salinity
5. light regimes
6. redox profiles in sediments.

B. Effects resulting from climate change

Based on input information from physical processes and the mechanisms that could induce changes in the benthos, the group discussed tractable measures in the benthos that could result from climatic perturbations. Four major areas of studies were determined, which include:

1. energy flow
2. physiology
3. population dynamics
4. community studies.

The energy flow studies are the major area for coordination with JGOFS, which proposes to undertake studies of carbon flux, carbon mineralization in the sediments, and bioturbation. The remaining three areas of study are specific to benthic faunal structure specifically in line with GLOBEC directives. Physiological studies of target species would provide essential information on rates and processes, e.g. the effects of temperature and carbon supply fluctuations on both larval and adult fauna. Population dynamics would include studies of recruitment, production and reproduction. Community studies would include measurements of species composition, abundance and biomass.

7.2.7 Historical database

The group identified the importance of background studies utilizing the large database available from the support and use of Antarctic field stations as well as past offshore benthic studies.

7.2.8 Modeling input

A modeling effort of the population dynamics for target species would be undertaken as the data sets become available. Input from the carbon/energy flow studies would be valuable.

7.2.9 New technology

(to be discussed in another workshop group)

7.2.10 Relation to other programs

GLOBEC will benefit from close cooperation between JGOFS (energy flow), CCAMLR (resource interactions), WOCE (circulation), and FRAM (modeling).

7.2.11 Research strategies

The benthic working group agreed that the selection of permanent stations along designated transects that crossed from the shallow shelf to the deep offshore areas were essential to adequately investigate possible climatic changes to benthic structure. Sampling at these stations would include recruitment and reproductive output measurements, along with visual observations of the sediments by both still camera/video and by SCUBA. Measurements would include physical, biological and sediment coring. Interaction experiments (short-term) would be undertaken both at permanent stations and land-based field stations. Long-term measurements at permanent stations would also occur on the designated transects on a ship-ofopportunity basis during maintenance of field stations. Studies of the historical record in the sediments (e.g. radioisotope methods of dating, stable isotope measurements of bivalves, foraminifera) and sea level change information recorded in raised beaches would be valuable.

7.3 Top Predators Working Group Report

Chairman: Inigo Everson

Rapporteur: Valerie Loeb

Members: William Fraser
Adolf Kellermann
Tony Koslow
Richard Veit

7.3.1 Approach

This section, originally intended to concern only fishes, has been expanded to include penguins, other seabirds and seals. This modification was made due to the important coupling between these predators and nekton in the southern ocean food web (Croxall *et al.*, 1988). These birds and seals, like fishes, are directly or indirectly dependent on krill as a food source (Laws, *1985)* and are likely to be sensitive indicators of environmental change.

The reproductive success of Southern Ocean birds and seals has been shown to depend on interannual variations in prey abundance (Croxall *et al.*, 1988); their long term fluctuations in abundance have been related to changing sea ice conditions (Fraser *et al.*, in press). Therefore these higher predators are especially valuable to a program designed to detect the biological effects of global warming.

There are other practical reasons for their inclusion. Birds and seals can be more easily and inexpensively surveyed than other pelagic animals. While foraging, they perform spatially and temporally integrated "sampling regime" over a substantial area. Lengthy time series already exist on the reproduction and abundance of several of the numerically dominant species (e.g. Adélie and chinstrap penguins, fur and crabeater seals) in various locales (Palmer Station, King George Island, Signy Island and South Georgia). Furthermore, the recently established CCAMLR Ecosystem Monitoring Program (CEMP) which involves studies on selected bird and seal species. The results of this program have direct relevance to GLOBEC. Studies focused on fishes and higher predators will provide information on the relationships between predator-prey and their environment which is critical to understanding variability in the Southern Ocean ecosystem. Such studies may also provide the bases for monitoring the effects of man-induced perturbations.

The group agreed that in order to detect changes in fish and higher predators induced by climatic change it is essential to establish long term base line monitoring. These studies are dependent on having good information from field studies and modeling exercises identifying critical processes.

7.3.2 Site selection

We suggest that the Atlantic sector, including the Antarctic Peninsula, South Georgia and the South Orkney Islands, is the most appropriate study region because of its known sensitivity to variation in the Antarctic Circumpolar Current and its existing historical data bases. Within this area, the Weddell and Bellingshausen Seas are considered important and contrasting sea ice zones worthy of study; South Georgia is an open water area with considerable commercial fishing activity (krill and finfish), a historical data base and ongoing monitoring programs; the South Orkneys are within the Weddell-Scotia Confluence and experience commercial fishery activity (especially summertime krill harvesting). The wide latitudinal range was felt to be important for assessing larger scale ecological changes which would be associated with climate change.

7.3.3 Target species

We have selected a relatively long list of target species with the justification that ecological changes among groups of species across the broad study area are more likely to reveal compelling evidence of climatically related change. The target fish species all have broad distributional ranges and represent commercially harvested forms, abundant non-harvested holopelagic forms and accessible shallow water species.

Commercially harvested species:
Champsocephalus gunnari
Notothenia larseni (by-catch)
Electrona carlsbergi

Non-harvested holopelagic species:
Pleuragramma antarctica
Electrona antarctica

Non-harvested nearshore species:
Notothenia neglecta
Trematomus hansoni
Harpagifer sp.

The commercial species are fished primarily in the northern areas of the Atlantic sector and are included in CCAMLR monitoring operations. The icefish *Champsocephalus gunnari* is an important fisheries resource and has a long term CCAMLR data base; *Notothenia larseni* is an abundant by-catch in fisheries operations; *Electrona carlsbergi*, a myctophid, is the basis of a developing open ocean commercial fishery. The non-harvested holopelagic species *Pleuragramma antarctica* and *Electrona antarctica* are abundant and important in food webs in high Atlantic waters and represent contrasting ecological patterns. *Notothenia neglecta, Trematomus hansoni* and *Harpagifer* may be conveniently collected at the shore stations.

The target penguin and seabird species are primarily krill predators considered important by CEMP: Adélie, chinstrap, macaroni and gentoo penguins; cape and Antarctic petrels; Black browed albatross. Because of their different feeding activities we also feel it would be useful to include the grey headed albatross (fish and squid prey) and South Polar skua (which feeds on *Pleuragramma antarctica)* as target species. The mammalian target species are crabeater and Antarctic fur seals. Both are dependent on krill, but occupy different habitats analogous to those of Adélie and chinstrap penguins.

7.3.4 Definable populations

We are uncertain whether various populations can be distinguished at the present time. The CCAMLR subareas under consideration are felt to be reasonable management units for the commercial fish species. Some bird and seal species show distributional differences which may represent distinct populations. For these species populations could probably be distinguished using mitochondrial DNA or other molecular techniques.

7.3.5 Population dynamics

The commercial fish stocks are monitored and analyzed annually by CCAMLR and cohort analyses have been performed on the South Georgia stocks. Through traditional fisheries techniques, spawning stock biomass for these and the other finfishes can be established through ongoing base line studies of growth and reproduction. Continuing national and CEMP bird and seal programs are monitoring growth rates, breeding success and cohort survival.

7.3.6 Focus on processes and mechanisms

Included are studies providing data important for understanding population dynamics relative to direct and indirect effects of environmental change.

Direct effects include:

(1) The effect of temperature on growth and development rates of different ontogenetic stages of fishes:

(2) Overwintering studies of higher predators to gain knowledge of a critical mortality period;

(3) The possible effects of increased UV radiation on near surface fish eggs and larvae.

Indirect effects include:

(4) Hydrographic conditions and dispersal of pelagic early life stages of fishes:

(5) The importance of food (e.g. krill) availability on fish condition, reproductive behavior (e.g. gonadal development, timing of spawning);

(6) Foraging dynamics of higher predators in relation to prey abundance and aggregation behavior.

7.3.7 Historical database

Historical data bases on the commercial fish species have been established by CCAMLR and are being augmented by national programs. CCAMLR has catch statistics and has undertaken cohort analyses of the major commercial species. The BIOMASS program also established a data base on both commercial and non-harvested fish species as well as bird and mammal species. National programs in the U.S., U.K., Germany, France, Australia, New Zealand and South Africa have also provided data on a variety of fish and bird species. Long term data bases have been established for Adelie and chinstrap penguins, crabeater and Antarctic fur seals, various other seal species, and ca. 15 sea bird species nesting on South Georgia and the South Orkneys. Predator populations have been monitored at Palmer station since 1977, King George Island since 1976, the South Orkneys since 1953 and South Georgia since 1962.

7.3.8 Modeling

Specific suggested models based on data resulting from the focused studies and historic bases include:

(1) Physical oceanography (e.g. temperature, water column stability, dynamics) and resulting effects on food supply, growth and development rates, survivorship, and dispersal during early life stages of fish;

(2) A standard population dynamics model for seabirds, integrating physiological data and environmental variables;

(3) Movement and dispersal of foraging predators (based on behavioral data) relative to acoustically detected prey target distributions to determine how seabirds and seals locate food patches.

(4) Fisheries vs. climate related effects on harvested species.

(5) Trophodynamic models of multispecies interactions between fish and higher predators and their prey.

7.3.9 Technology

Technological improvements or developments which would be useful in the suggested studies of fish, sea birds and seals include the following:

(1) Improved acoustics hardware and software for the location, identification and quantification of fish;

(2) Underwater visual systems for assessing prey (krill, pelagic fish) distribution;

(3) Improved satellite tracking and time depth recording devices for predators;

(4) Improved finer-scale resolution in remote sensing of sea ice coverage with differentiation of sea ice condition and other hydrographic conditions;

(5) Improved finer-scale resolution of sea ice conditions through aircraft observations;

(6) Biochemical methods for evaluating fish condition factors;

(7) Genetic markers for determining stock identity;

(8) Increased usage of Lagrangian drifters for assessment of current transport and advection.

7.3.10 Relation to other programs

The goals of this research are related to those of CCAMLR with respect to the effects of commercial fisheries operations and also to CEMP. Information derived from the JGOFS, WOCE, and FRAM programs are directly applicable to our studies. The research of relevant groups within SCAR is also relevant. The focused interest on fisheries dynamics and potential impact of climatic change in the Southern Ocean is shared with CSIRO which is developing a project to examine the trophodynamics of fish stocks along the continental slope of southern Australia.

7.3.11 References

Croxall, J. P., T. S. McCann, P. A. Prince and P. Rothery. 1988. Reproductive performance of seabirds and seals at South Georgia and Signy Island, South Orkney Islands, 1976-1987: Implications for Southern Ocean monitoring studies. In: D. Sahrhage (ed.), *Antarctic Ocean and Resources Variability,* Springer-Verlag, Berlin, 261-285.

Fraser, W. R., W. Z. Trivelpiece, D. G. Ainley and S. G. Trivelpiece. Increases in Antarctic penguin populations: Reduced competition with whales or a loss of sea ice due to environmental warming. Polar Biology, in press.

Laws, R. M. 1985. The ecology of the Southern Ocean. Am. Sci. 73, 26-40.

7.4 Physics/Climate Working Group Report

Chairman: Eileen Hofmann

Rapporteur: David Webb

Members: Joey Comiso
Jian-Hwa Hu
John Klinck
Peter Niiler

7.4.1 Overview

The Working Group's discussions focused on three broad categories of physical environments in the Southern Ocean that potentially could be affected by climate change which in turn could have effects on associated ecosystems. The first of these is the large scale circulation of the Southern Ocean. This was thought to be least known from a biological perspective and the one that may show the least effect of climate change. However, the large-scale system is one that is well represented in models and therefore climate change effects due to changes in circulation patterns could be investigated with modeling studies. The second, the sea-ice region, was considered to be an important environment and one in which climate change may have a noticeable effect. Observations of changes in sea ice can be made routinely with satellites and enough of an historical data base now exists to begin analysis and correlative studies of interannual variations in sea-ice cover. The final environment is that of the coastal ocean. This was considered to be the least studied of the three environments and the one that potentially may show the most effect of climate change.

7.4.2 Climate change

Possible climate change scenarios have recently been reviewed by the International Panel on Climate Change. Work by a number of researchers indicates mean temperature increases, at the Earth's surface, of 4°C are to be expected by 2150. Flux changes at the sea-surface will be of the order of 2 W m^{-2} (compared to a total flux of a few hundred W m^{-2}). The percent of interannual variability in the heat flux is much larger than the expected climate change

The accuracy of present climate predictions is limited by the relatively coarse (300 km grid) atmospheric and oceanic models used for climate research. However, the models indicate that in sea-ice regions the increase in summer temperatures will be substantially smaller than the global mean. Global warming will be delayed over the oceans with the greatest delay occurring in the Antarctic Ocean, just south of the belt of minimum westerlies.

The present models predict a reduced temperature contrast in the atmosphere between the equator and the poles. This will result in a reduced strength of the westerlies and a corresponding change in the strength of the Antarctic Circumpolar Current.

Finally, the models predict increases in the cloudiness of the atmosphere (resulting from increased evaporation). As the Southern Ocean is cloud covered, typically 80% of the time, even small increases in cloud cover could result in large changes in the biological productivity of the region.

7.4.3 Large-scale system

The large scale structure of the circulation in the Southern Ocean is controlled largely by the surface wind stress and the shape of the ocean bottom. The wind stress, in general terms, controls the strength (total transport) of the Antarctic Circumpolar Current. The bathymetry, on the other hand, controls the location of the current. In particular, the ACC is constrained to flow through Drake Passage, north of the Kerguelen Plateau, south of the Campbell Plateau and through the Eltanin Fracture in the East Pacific Rise. These gateways for the ACC determine its path through the Southern Ocean. The location of the atmospheric Westerlies would have to shift by ten or more degrees of latitude in order to have any major effect on the structure of the circulation in the Southern Ocean.

The polar gyres near the Antarctic Continent may be different from the large-scale structure. The location of the Weddell gyre is strongly influenced by the Antarctic Peninsula. The other, suspected, gyres (e.g. in the Ross Sea) may become much more evident if the Easterlies along the continent became stronger. These gyres might also extend farther into the Southern Ocean if the winds were to change.

Within the large scale, Antarctic Circumpolar Current, there are narrow (about 50 km in width) high speed current jets that are associated with density fronts. These jets are separated by relatively low speed zones of about 100 km width. A study of surface drifters shows that these fronts are associated with a secondary circulation that leads to flow convergence at the surface (surface drifters tend to collect over the fronts). The strength and importance of this secondary circulation has not been investigated nor has its effect on biological processes.

The high speed, narrow currents in the ACC are subject to flow instability which leads to mesoscale eddies. This eddy variability is evident in satellite altimetric observations, specifically in the measures of the time variation of the height of the sea surface. In fact, the ACC stands out in the Southern Ocean as a band of large flow variation. There is also measurable flow variation near the Antarctic Continent but it is not clear how much of this is due to the presence of ice.

Within the band of high variability associated with the ACC, areas of even higher variations exist. The largest magnitude of the eddy kinetic energy occurs in the Agulhas Retroflection and near the collision of the Brazil Current and the Falkland Current. Lesser hot spots are over the Kerguelen Plateau, the Macquarie Ridge, the Campbell Plateau, the East Pacific Rise and the Scotia Arc. The implication of this observation is that mesoscale variability is driven to some extent by the interaction of flow in the Southern Ocean (which penetrates to the bottom with only slightly diminished speed) with relatively shallow (less than 1 km) parts of the Southern Ocean.

A comparison of phytoplankton maps from CZCS and bathymetry reveals a striking necessary condition: high phytoplankton occurs in regions of large bottom slope. However, not every region of strong bottom slope is associated with high phytoplankton concentrations. Some of the regions of high phytoplankton are also areas of high flow variability, but not all. The relationship among flow variability, bathymetry and high phytoplankton concentration is not clear at this time.

7.4.4 Sea-ice region

Sea ice in Antarctica is one of the most seasonal parameters on the surface of the earth. In winter, it is a very extensive habitat, covering an area about 20 x 10^6 km^2 and a large percentage of the Southern Ocean south of 50°S. In summer, only 20% of the winter ice cover remains. The immediate effect of the large seasonality is to cause seasonal modifications in the vertical structure of the underlying ocean. During growth, in fall and winter (about 9 months), the formation of ice causes the ejection of salt thereby decreasing stability of the mixed layer. During spring and summer, the retreat of the ice causes the introduction of large amounts of low salinity melt water to the surface providing vertical stability in the water column. It has been postulated that the presence of melt water is a key factor leading to phytoplankton blooms near ice edges. Melt water provides vertical stability in the water column and allows phytoplankton to grow in high-light high-nutrient environments.

During winter, the presence of leads and polynyas are also significant factors affecting the environment. Their presence is known to cause a considerable change in heat fluxes between the ocean and the atmosphere and salinity fluxes between the ice and ocean. Leads are linear and random features of open water (or new ice) in the ice pack and are known to constitute less than 10% of the ice cover. Polynyas are more rounded features and have been classified as either sensible heat polynyas or latent heat polynyas. The sensible heat polynyas which are usually in the deep ocean and can cover large areas are believed to be caused primarily by upwelling over topographical features (e.g. the Maud Rise). Latent heat polynyas are usually located along the coast and are formed by katabatic (or synoptic) winds. Biological populations have been observed to be considerably enhanced in lead and polynya regions. A careful monitoring of these features is therefore important.

Consistent records of ice extent from satellite observations have indicated no significant change in ice cover during the past seventeen years. However, there have been large regional variations. Large polynyas in 1974 through 1976 were observed in the Weddell Sea, but not in other regions. In 1980, the ice cover in the Weddell Sea was *15%* larger than normal. This was compensated by smaller than average sea ice extents in other regions such as the Ross Sea and the Indian Ocean during this period. Long term effects of global warming would reduce the seasonality of sea ice and perhaps result in the eventual absence of summer ice. However, on the short term, the effect is not too obvious because of the complex feed backs that exist between ice, ocean, and the atmosphere.

7.4.5 Coastal circulation

Much of the physical oceanography research that had been done in the Antarctic has focused on the processes associated with the large-scale flow of the Antarctic Circumpolar Current or on processes that contribute to bottom water formation. With few exceptions, the regional and coastal circulation of the Antarctic has been ignored.

The historical hydrographic and current measurements that exist for the Antarctic are primarily concentrated in the Bransfield Strait-South Shetland Island region. These data reveal that the coastal flow in this region consists of complex circulation patterns that exhibit seasonal variability in strength and direction, in response to changes in wind stress and ice cover. The coastal currents are relatively narrow, being on the order of a few kilometers in width, but having large horizontal extent. For example the narrow westward flowing current on the north of the South Shetland Islands is thought to be circumpolar in nature. The coastal currents are influenced by bottom topography and coastal geometry, which can result in small scale variability.

Coastal regions such as the Bransfield Strait are areas where different water masses meet. This results in the formation of small scale frontal regions that can and do exhibit considerable variability in space and time. It is also likely that coastal flows are influenced by the amount of melt water from ice shelves and glaciers that is introduced each year.

Climate change effects could potentially affect the coastal circulation in the Antarctic through such processes as reduced inputs of melt water and/or changes in solar radiation. Either of these processes could alter water column stability, which would affect the intensity of vertical mixing in coastal regions. Also, changes in the wind stress field would alter the intensity of the seasonal surface circulation.

7.4.6 Recommendations

The Working Group recommended that:

There is a need for assembly and analysis of historical information. In particular the observations from shore-based stations in the Antarctic should be put into a standard format and made available. Such data sets would help in filling in the lack of long term observations of environmental parameters in the Antarctic.

Understanding the processes associated with sea-ice extent and variability are an important part of determining what (if any) effect climate change will have on the Antarctic,

Understanding of coastal circulation is a necessary component of addressing questions that relate to marine population fluctuations. Many species, such as krill, spawn on or near the continental shelf where their larval forms are dispersed by the coastal currents. Thus, understanding the factors that result in the successful recruitment of these species requires first a knowledge of the coastal current systems. The existence of shore-based laboratories makes coastal programs logistically feasible for the Antarctic.

There is a need for consistent and synoptic observations of sea ice and currents in the Antarctic. Attention should focus on designing measurement programs that use satellites, moored instrumentation and drifters.

7.5 Modeling Working Group Report

Chairman: Eileen Hofmann

Rapporteur: Victor Marin

Members: Joey Comiso
Jian-Hwa Hu
Tony Koslow
Dick Veit
David Webb

7.5.1 Overview

The Working Group's initial discussions focused on several broad issues that dealt with general aspects of modeling marine systems. Many of these general issues are already treated in the GLOBEC document on theory and modeling (GLOBEC, 1990). The Working Group suggests that interested individuals refer to this document for a discussion of the general modeling philosophy and issues that are relevant to the GLOBEC program. Issues that pertain to the development of models specifically for animal populations in the Southern Ocean were discussed by the Working Group. One area that needs development is that of sea ice models. Many of the marine populations in the Antarctic depend on sea ice during some or all of their life history. Hence, correct representation of interannual variability in the extent of sea ice cover and/or its effect on these populations in models is important. It was also recognized that the results of large scale circulation models, such as FRAM, are a valuable resource. The Working Group discussed how the output from this type of model can be combined with finer scale regional models. The need for development of models that simulate the aggregation behavior of animals such as that observed for krill and its predators was noted. Much of the mortality of krill populations is due to predators such as penguins and seals. The inclusion of higher predators, that are decoupled from flow fields, in planktonic models was discussed by the Working Group. Furthermore, animals such as krill also decouple from the circulation field in the latter part of their life cycle. The Working Group discussed the approaches that could be taken to address this type of model. Expanded discussions of these points is given in the following sections.

7.5.2 Modeling issues

7.5.2.1 Modeling with uncertainties

For many of the zooplankton species of interest in the Southern Ocean there is incomplete knowledge of their life cycle. This presents problems in designing a model to investigate the biology/ecology of the species. Consequently, an approach would be to focus on those species for which most complete information exists (e.g. *Euphausia superba, Calanoides acutus).* A second approach is to focus on more conceptual models of life strategies, for example seasonal migrating and non-migrating species. These models should incorporate active migration as well as passive dispersal.

7.5.2.2 Matching fine and coarse scale resolution models

Any program undertaken in the Antarctic as part of the GLOBEC initiative most likely will have a regional focus (i.e., Bellingshausen Sea). However, even for a regional focus circulation models will need to include larger scale circulation effects. One way to incorporate these effects is to imbed a high resolution regional circulation model in a coarser resolution large scale model. A second way is to use a coarse large scale circulation model to provide the boundary forcing for the regional model. The techniques for matching solutions between different scale models are not well developed and this is an area of research that needs attention.

7.5.2.3 Compatible space and time scales between physical and biological processes

Biological processes encompass a large range of spatial and temporal scales. Often the scales of importance are not resolved adequately in circulation models. In particular, the vertical resolution of circulation models is often inadequate for considering biological processes. On the other hand, high vertical resolution is necessary to correctly represent air-sea exchange processes that are expected to occur due to climate change.

7.5.2.4 Sea-ice models

Thermodynamic models of sea ice are reasonably well developed. These models describe the growth and melting of a uniform ice field over the course of a year. Schemes for incorporating thermodynamic sea ice models into general circulation ocean models have also been developed. The simplest is essentially to advect the ice with the local current field and more complicated models treat ice as a plastic medium.

The present models do not realistically predict the ridging of sea ice or the formation of caverns by the rafting of sea ice. Such models need development. The present models also do not attempt to describe the details of the flow field below the sea ice. However, this may be possible using a general circulation model with high resolution in the top 200 m.

7.5.2.5 Models for recruitment

There is a critical need to use Lagrangian calculations to look at the dispersal of holoplanktonic species and the planktonic stages of benthic, micronektonic, and nektonic species. This requires proper circulation models and also measurements of growth and the migration pattern. These calculations are relatively inexpensive and yield considerable insight on the dispersal and distribution of the species.

7.5.3 Recommendations

1. Preliminary modeling efforts should be undertaken before field studies to ensure collection of optimal data sets. This part of the modeling would be based upon existing data and scientific intuition and where available incorporate historical time series data.

2. Models of biological processes should be based upon physiological principles and basic biology. This is a basic premise of the GLOBEC modeling philosophy.

3. The group strongly recommends the use of existing models especially mixed layer models, general circulation models, regional circulation models and sea ice models. The results of these models should be interfaced with biological models to investigate the role of physical and biological processes in determining biological distributions.

4. There is a critical need to invest resources in developing sea ice models to give a realization of the circulation associated with the sea ice field.

5. The group detected a need to transfer aggregation theories developed in terrestrial ecology to marine populations. This is of particular importance for models developed to study the swarming behavior of krill and models that treat the aggregation of predators in response to the swarms/patches of krill.

6. Physiological and basic principles models require measurements on rates and

processes. This in turn requires close cooperation between modelers and experimentalists.

7. Biological models should explicitly incorporate large-scale variability in the physical environment.

8. A comprehensive model should be constructed in the end to integrate the aforementioned results.

7.5.4 References

Theory and Modeling in GLOBEC: A First Step, Report to the GLOBEC Steering Committee from the Working Group on Theory and Modeling, February 1990, 9 pp.

7.6 Physiological Rates Working Group Report

Chairman: Sigrid Schiel

Rapporteur: Langdon Quetin

Members: Tsutomu Ikeda
Donal Manahan
Stanislaw Rakusa-Suszczewski
Robin Ross
Martin White

7.6.1 Needed physiological investigations

I. Determinations of physiological state

A. Considered GLOBEC Report Number 3 "Biotechnology Applications to Field Studies of Zooplankton" very important in regard to the need to investigate the following:

1. Metabolism and locomotory ability
2. Morbidity
3. Diapause
4. Egg production rates
5. Growth rates
6. Developmental stages
7. Age
8. Feeding rates and diet

[The group felt that GLOBEC Report Number 3 covered many important issues well. We sought not to duplicate the effort of that workshop, but raise some new issues and/or those specific to antarctic work.]

B. Determinations need to reflect different time intervals in the physiology of the animal, i.e., long term versus short term changes in the state of the animal.

C. Need to consider all of the approaches in Report Number 3 and work toward

1. Reducing the number of measurements required
2. Simplifying measurement techniques

D. Special importance should be given to resolving the debate about temperature compensation in antarctic species. Need to emphasize techniques to help address this issue. Need to contrast different life stages and organisms from different biotopes (new for Antarctic GLOBEC).

II. Seasonal studies need to be emphasized regarding

A. Environmental triggers of behavioral and metabolic events - in polar environments very small changes (i.e. 0.5°C) may trigger change.

B. Comparisons of metabolic responses between extremes in the environment, e.g. summer versus winter. Most organisms investigated show seasonal cycles in metabolic activity.

C. May need new resources for station/ocean work throughout the year.

III. Physiological "plasticity" needs to be considered. especially to understand the capacity of antarctic animals to respond to environmental change (new to antarctic work)

A. Need detailed laboratory experiments to interpret simpler shipboard measurements in the context of an animal's metabolic history and consequences to its future.

B. Need to measure physiological responses by the target organism to conditions outside the normal environmental range normally encountered.

1. Consideration given to likely environmental changes based on model predictions for effects of global change
2. Identify possible changes in temperature, salinity, food, and ultraviolet radiation
3. Vary environmental parameters in small increments because of high Q_{10}'s found to date in invertebrates

C. Need to understand physiological ontogeny of the organism, or how different developmental stages respond to variables in the environment

1. Priority should be given to the early stages of development since their survival may be particularly sensitive to environmental conditions, concept of critical period during early life history

D. Need more effort toward understanding physiological state of the target organism in reference to environmental processes

E. Important to explore the idea of the ability of Antarctic species to procrastinate a physiological decision, especially whether it is a generality for Antarctic species

IV. Additional specific questions

A. Krill and salps do not generally occur together. Is this separation in part due to physiological differences between the two species, or primarily due to physical conditions in the environment?

B. What physiological parameters should be measured during the life cycle or at specific stages of the target organism that would most likely be an index of processes affecting population dynamics?

V. Target species

A. Attention should be given to not only studying a few species in detail, but also to studying a greater number of species in less detail.

1. Detailed studies on a few species are important to evaluate which measurements are the most appropriate to emphasize.

2. Studies on a broad range of species should illustrate the generality of results from detailed measurements on a particular species, i.e., using the chosen parameters

B. Logistical selection criteria for detailed studies

1. Is a particular species suitable for experimentation?
2. Is it possible to obtain all life stages?
3. Is there historical data?

C. Target species for detailed study

1. Plankton
    a. Euphausiids, recommend *Euphausia superba*
    b. Copepods, recommend *Calanoides acutus*
    c. *Salpa thompsoni,* because it generally appears to be found in the absence of krill

2. Benthos
    a. Echinoderms, *Sterechinus* sp.
    b. Crustaceans, *Notocrangon antarcticus*

3. Fish

    a. Pelagic

    Pleuragramma antarcticum (high latitude) or

    Nototheniops larseni (lower latitude)

    b. Demersal (near shore)

    Harpagifer or

    (larvae spend less time in water column, restricted distribution close to shore)

    Trematomus hansoni

    (near McMurdo Station, pelagic larvae, widely distributed over shelf)

4. Seabirds
    a. Adélie penguin
    b. chinstrap penguin

The above outline was agreed upon by all of the participants in the workshop, or at least it was clearly written on a chalk board and no strong objections were voiced. The following is the rapporteur's abbreviated account of notes taken during discussion. These notes may not be the consensus of the group, but are added at this point for further information.

The complexity of the benthos is greater than the planktonic community. For the benthos site selection should consider historical long term records, logistical constraints, and high and low latitude sites. The Ross Sea, McMurdo Sound and the South Orkney Islands should be considered possible sites. In the context of climate change the persistence of the benthic structure, the long term faunal and sediment record, and the ecological community structure should be considered. Some of the criteria for selection of target species should be their abundance, whether they have a wide or restricted distribution, and whether measurable growth parameters exist.

The group discussed the merits of looking at a few species in detail or many species in less detail. The detailed approach was favored, but with a note that a broader range of species needs investigation at some level. For the detailed approach we need to consider how an organism responds to different carbon inputs, determine the physiological state of the organism and have the laboratory data to understand the implications. Ground truthing of physiological measurements and how different environmental variables affect the physiology of an organism is essential if we are to use these measures as assessments of the physiological state of an organism in the field (Fig. 1). Possible measurements included metabolic rate, growth, and (particularly for larvae) enzyme activity, amount of total protein and the pattern of synthesis of specific proteins. Concern was expressed about whether techniques were too sophisticated for field use and that they would not be

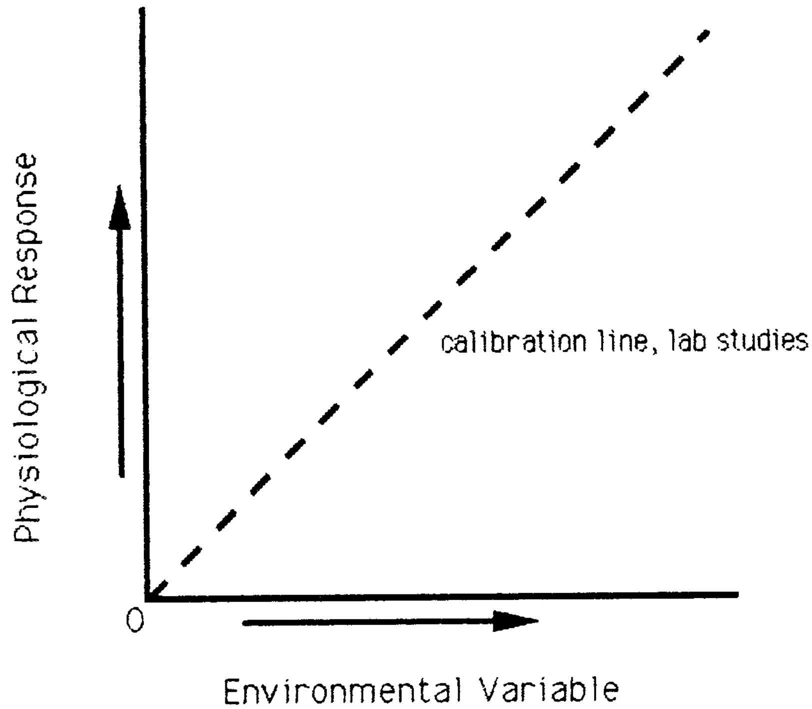

Figure 1. Schematic representation of the effect of environmental variables on physiological response. Dashed line represents input from laboratory experiments.

something that "everyone" could do. Citrate synthase activity was suggested as an example of a useful and appropriate assay since the assay is simple, material needs to be frozen only at -80°C, and citrase synthase is thought to be a good index of metabolism.

It may also be useful to better understand an organism's maximum potential versus what we actually see in the field. Growth rates would be a good example. Another question mentioned was how do we relate physiology to birth and death rates? or How do we relate physiological status to light, temperature, salinity and other abiotic factors? What followed was a general discussion of what to measure. Krill in Prydz Bay experience a constant low temperature compared to those west of the Antarctic Peninsula that encounter a 4-5°C range in temperature. The same species from different areas may show different physiological responses that may make "physiological state" difficult to interpret. It was mentioned again that growth was a good integrator of recent past environmental events. A combination of the biochemical and physiological approaches may be most suitable for GLOBEC. However, we need to be aware of potential problems. One example mentioned was the contribution of enzymatic activity from bacterial enzymes in krill stomachs to any analysis of krill.

Physiological rates should be evaluated in terms of their relevance to population dynamics. In addition, the relative importance of stages to measure since the work load may need to be prioritized. It was also emphasized that there should be a thorough review about what we know of particular species important to the study, and a critical evaluation of past research.

7.7 Population Dynamics Working Group Report

Chairman: Jarl-Ove Stromberg

Rapporteur: Adolf Kellermann

Members: Wulf Arntz, William Fraser, Jacqueline Grebmeier, Mark Huntley, Tony Koslow, Suzanne Razouls, William Stockton

The group felt that much of the parameters and processes relevant to study the dynamics of populations have already been tackled in the format I working groups. The apparent paucity of information needed to define populations of benthic, planktonic and warm-blooded organisms was acknowledged. As a pragmatic approach, it was agreed that spawning units may be identified in certain species which for a first attempt may be regarded as populations although exchange between them is documented but yet unresolved. The primary task for the group was then agreed as to identify the key gaps in the array of demographic parameters for the various taxonomic groups, and what variables influence population dynamics of these groups that may be sensitive to climate change. It was pointed out that even small water temperature changes may have significant impacts on growth and developmental rates, and hence on parameters relevant to population dynamics.

The potential study areas were the Bellingshausen Sea and adjacent waters to the east, but it was felt that because of logistic constraints of national ongoing and planned projects, other areas such as the Weddell Sea or Prydz Bay should be taken into consideration. These may also be utilized to look at a given target species under different latitudinal regimes, or the shipborne work in the primary study areas may be complemented by shore-based studies in different regions on e.g. rates and processes. In general, the group acknowledged that the most striking and important gap is the lack of data from the winter months for all taxonomic and ecological groups.

7.7.1 Benthos

Shipborne sampling periods are limited to the austral summer months. This may be improved by the use of ice-strengthened research vessels, and by future and present establishment of shore-based research. In analyzing length frequency data, the apparent longevity of many benthic organisms may obscure patterns that are useful for age and growth estimated. An apparent feature with respect to early life history seems to be the decrease of species having meroplanktic larvae 1) with latitude, and 2) with bottom depth. Another feature is the long developmental times of embryos which may contribute to circumantarctic distribution patterns, but may also be interpreted as waiting stage for favorable environmental conditions during larval drift. Field studies indicate that recruitment may be sporadic and irregular. Colonization should be studied in areas which are exposed after major ice shelf calving. Similarly, re-colonization and the succession of species may be studied in areas of high iceberg grounding frequency.

7.7.2 Fish

Although the shortcomings of traditional fishing methods were recognized, it was understood that there are no new techniques readily available. In recent years, population dynamics of the commercially harvested species has been studied in detail. It was agreed that stock assessment should not be the main objective in the study areas, although there is at present no commercial fisheries going on. Instead, the existing gaps are the proper assessment of larval and juvenile growth and developmental rates as related to biotic and physical environments. Key events in the life history such as hatching, settlement and first maturity have to be determined.

7.7.3 Zooplankton

The group reiterated the gaps that were identified by the Zooplankton and Krill WG format I, i.e., the need for both quasi-synoptic demographic surveys and process-oriented cruises. Among particular processes, reference was made to the processes identified by that group.

7.7.4 Higher level predators

Populations in sea birds can be clearly identified and followed. Marking and tracking is feasible in sea birds. The bottleneck is apparently the winter months, especially with respect to foraging dynamics, i.e., food consumption, distribution relative to prey. Since more than 90% of the bird biomass consists of penguins, study efforts should focus on these. Adelie and chinstrap populations in the Antarctic Peninsula area have shown a decrease and increase in population size, respectively, over the past 40 years, which may well be related to changing degrees of pack-ice cover. Environmental conditions for these species seem to vary more in the Weddell Sea than in the Bellingshausen Sea. Some seal species may be regarded as ecological equivalents of these penguin species, e.g. the crabeater and fur seals.

7.7.5 Techniques

Standardized techniques have to be agreed upon in order to make comparisons in space and time possible.

7.7.5.1 Benthos

Both semiquantitative and quantitative sampling gears should be used. The first includes Agassiz-trawl (4 mm mesh) and video-systems, while quantitative gear comprise box cores, multiple corers and meiofauna corers. For the megafauna, video-systems and cameras can be considered as being quantitative. The minimum mesh size for sieving is 0.5 mm. Aging methods need to be developed, such as the use of hard parts in sea urchins or appendices in crustaceans, and these estimates need to be validated. Rearing experiments have not shown to hold great potential for this due to the lack of growth in some species in captivity.

7.7.5.2 Zooplankton

A continuous recording device is the Optical Plankton Counter (OPC) which is towed at 8-10 knots with a depth range of 300-0 m, and which is now commercially available. Net sampling has to be vertically stratified down to 2000 m with desirable fine scale sampling within strata of 100 m. Multiple opening-closing nets should be used with mesh sizes around 250 µm. These may be complemented by acoustic doppler systems and moorings. Under ice studies may be performed by SCUBA diving or hand operated horizontal tows through holes in ice floes or fast ice.

7.7.5.3 Fish

Early life stages should be obtained with the RMT 1+8, but also the international young cod net was recommended. For adult fish, standard 100-300 feet bottom trawls, and benthopelagic, high fishing nets should be used. Rearing experiments provide insights into the capacity of otoliths as recorders of past growth and environmental histories of fish.

7.7.5.4 Higher level predators

The techniques used are internationally standardized (CCAMLR). All data are considered quantitative. Tracking devices should be developed and utilized. Studies of the microstructure of seal teeth have revealed important insights into foraging patterns and success of fur seals, providing indicators of unfavorable conditions and environmental disturbances. Similar techniques should be tested for possible application in other seal species.

Table 1: Summary of technologies now available (*), under development (**), or desirable but requiring development (***), for Southern Ocean GLOBEC investigations.

SENSOR	INSTRUMENTATION	DEPLOYMENT PLATFORMS
Mobile survey cruises		
Acoustics	Low-frequency acoustic array, for school detection or tracking**	towed
	Multi-frequency surface acoustics (existing), dual-, split-beam* (**)	towed body, hull mounted
	Multi-frequency remote acoustics (prototype), dual-, split-beam**	multiple nets, towed bodies and vehicles
	Acoustic Doppler Current Profiler (ADCP)*	hull mounted
Optics	Optical particle counter**	nets and towed bodies
	Video camera systems* (**)	towed bodies, vehicles and benthic sledges
Sampling	Automated sample processing	multiple and high-speed trawls
Process oriented cruises		
Acoustics	Acoustic volume imaging systems**	ROV's, profilers, submersibles
	Side-scan sonar (others from above)*	
Optics	TV and still cameras, still* and video photogrammetry**	Profilers, ROV's, divers
Fixed location experiments		
Acoustics	Low-frequency acoustic array**	
	Acoustic volume imaging**	
	Acoustic transponder and receiving arrays for predator-prey studies**	
Optics	Micro video cameras for predator-prey studies (High definition)*(**)	
Moorings		
Acoustics	Multi-frequency acoustics*(**) ADCP's*(**)	vertical profiling arrays
Optics	Longterm cameras* and videos	cameras such as Bathysnap
Sampling	Bottom landers for growth and physiology***	

7.8 New Technology Working Group Report

Chairman: Jon Watkins

Rapporteur: Ken Smith

Members: Ulrich Bathmann, Inigo Everson, Charles Greene, John Klinck, Valerie Loeb, Stanislaw Rakusa-Suszczewski

In view of the large amount of discussion devoted to new technology in previous GLOBEC meetings (see Initial Science Plan, 1991; GLOBEC; North Atlantic Program 1991, Workshop on Biotechnology applications to field studies of zooplankton, 1991) the working group concentrated on developments necessary due to the unique physical environment of the Southern Ocean or specific requirements of target species that may not have been addressed elsewhere. Key areas identified were the effect of working in and under the ice and the problems associated with studying krill and salps. A summary of existing, developing and desirable new technology will be found in Table 1.

7.8.1 Physical oceanography and meteorology

a) Ice position, thickness and quality: there are many developments under way for obtaining this information through remote sensing by satellites and instrumentation on aircraft (see for instance Comiso, this report). The group recognized that there was a need for real time data on small spatial scales e.g. to investigate the local environment surrounding a ship. Potentially such information (e.g. at a scale of 1 - 100 km) could be collected from aircraft, balloons, drones and drogues. There was no expertise within the present group to assess the recent developments in remote measurements of ice quality. This was considered to be a very important parameter and therefore should be addressed.

Recommendation: aircraft logistic support for operations coupled with real time satellite data would be necessary. Satellite receiving stations capable of collecting such data either on ship or on adjacent bases would be necessary.

b) Local weather and sea surface conditions: data such as wind speed/direction are available from WOCE meteorological buoys in addition to local and large scale surface circulation.

Recommendation: there should be close coordination between GLOBEC and WOCE concerning meteorological and physical oceanographic data for study areas.

c) Structure of water column: in general it was thought that systems used or being developed by oceanographers for use in other areas were likely to be suitable for studies in a Southern Ocean GLOBEC (although see constraints under 2.a). The Group stressed that it was most important that oceanographic and biological measurements were coordinated and were measured over the same scales. Frequently the oceanography was determined at larger scales than those applicable to biological processes, especially those implicated in the swarming of krill.

Recommendations: physical oceanography for small scale phenomenon - on the scale of meters to centimeters - would need to be accorded high priority. Relevant temporal and spatial scales of study for oceanography, phytoplankton, krill and predator dynamics are discussed in detail in Murray *et al.* (1988; see especially Fig. 8). A general treatment of scale-related issues for zooplankton is discussed in Marine Zooplankton Colloquium 1(1988).

d) Bathymetry: An understanding of this is vital because of the effect on currents.

Recommendations: bathymetry of the study region should be well defined with multi-beam echosounders (such as SeaBeam) and side scan sonar.

7.8.2 Ice biology

a) Distribution and abundance of organisms: the presence of ice presents extra sampling problems in comparison to other areas. Once in the ice, ships are effectively stationary or cause much disturbance if steaming is attempted. Therefore remote sensing techniques must be developed further. Development of remotely operated or autonomous vehicles would allow under-ice surveys. In addition ice islands and ice-anchored drifting buoys could be used to provide extra information. Under-ice profiling could be carried out from moored arrays which could contain instrumentation such as transmissometers, fluorometers, ADCP, sediment traps, multifrequency acoustic profiling instruments. It is stressed that deployment of such equipment under the ice is not a simple case of using techniques and equipment developed elsewhere due to the remote location of the study sites and the inaccessibility of the equipment for much of the year. The development of equipment to make *in situ* observations on animals living within the ice was also thought to be necessary.

Recommendation: non-invasive techniques to observe krill and zooplankton distribution, abundance and behavior in both ice-free and ice-covered areas should be accorded high priority (e.g. use of optical holography, multifrequency acoustics, etc.).

Recommendation: close coordination with the Sea Ice Working Group of SCAR and with SO-JGOFS should be established concerning the biological data for sea ice, under ice and water biota of the Southern Ocean.

b) Physiology: It was felt that equipment capable of making *in situ* measurements of respiration, growth, etc. would be beneficial for benthic animals and the under-ice environment. It was pointed out that use of captive populations in large tanks (see Price *et al.* 1987 for use of such a tank in Canada) or in enclosures in sheltered bays would provide valuable information on behavior and physiology (see Foote *et al.* 1989 for use of rafts and cages at South Georgia).

Recommendation: large enclosures need to be developed further to simulate natural conditions for physiological studies of krill and other organisms. For example, enclosures in Admiralty Bay could be more cost effective than building large scale laboratory facilities ashore.

7.8.3. Species specific problems

a) Antarctic krill *Euphausia superba:* krill are frequently found at or near the sea surface (0-10 m). This depth range is particularly poorly sampled by nets and acoustics (see for example Everson and Bone, 1986a, on results from an upward-looking echo-sounder). Moored upward-looking acoustic arrays could be capable of distinguishing water movement and acoustic backscatter from targets in the upper 5-10 m in both ice-free and ice-covered areas. The effect of high sea states on the distribution of krill and other zooplankton/micronekton in surface waters was discussed. While this creates problems for all observation techniques it may not be severe because of the downward migration of animals under these conditions.

Recommendation: instrumentation be improved or developed to examine the upper 10 m of the water column and the undersurface of the ice.

Many animals and krill in particular have been shown to avoid nets (see for instance Everson and Bone, 1986b). It was agreed that for krill, stealth nets capable of sampling with minimum avoidance at relatively high speed were desirable. The Group recognized the need for the development of non-invasive sampling techniques but stressed that these should be validated at the earliest opportunity. There was good evidence that krill were able to avoid divers, submerged cameras and other "non-invasive" systems.

Recommendation: evaluate avoidance/attraction effects of measuring devices and deployment platforms on krill behavior.

b) Salps: in addition to krill, salps must be adequately studied. Because of the delicate nature of salp aggregates, it is important to use a combination of nets and video systems to quantify them and distinguish aggregation sizes.

Recommendation: improve large volume sampling techniques to determine abundance, biomass and distribution of salps with minimal disturbance to aggregates. It was suggested that a large volume water sampler monitored by video camera for triggering at appropriate times might be developed. It is important that sampling devices for both krill and salps are routinely available to take advantage of the alternate occurrence of these two species.

c) Copepods: the Group did not discuss instrumentation specifically for copepod studies. It is likely that techniques mentioned in the North Atlantic proposal and under-ice biology would form the core of new developments.

7.8.4 Data management

The Group recognized that this was not the best forum to discuss data management but that a number of points should be highlighted at this time. Timely interchange of data, data access, data entry protocols and validation were all areas that could cause problems. A number of other international programmes have experience in setting up and administering databases (e.g. BIOMASS, WOCE).

Recommendation: data management must be considered early in the development of GLOBEC in concert with other existing international programs.

7.8.5 References

Everson, I. and D. G. Bone. 1986a. Detection of krill *(Euphausia superba)* near the sea surface: preliminary results using a towed upward-looking echo-sounder. British Antarctic Survey Bulletin 72: 61-70.

Everson, I. and D. G. Bone. 1986b. Effectiveness of the RMT-8 system for sampling krill *(Euphausia superba)* swarms. Polar Biology 6: 83-90.

Foote, K. G., I. Everson, J. L. Watkins and D. G. Bone. 1990. Target strengths of Antarctic krill *(Euphausia superba)* 38 and 120 kHz. Journal of Acoustic Society of America 87:16-24.

Marine Zooplankton Colloquium 1, 1989. Future marine zooplankton research - a perspective. Marine Ecology Progress Series 55:197-206.

Murphy, E. J., D. J. Morris, J. L. Watkins and J. Priddle. 1988. Scales of interaction between Antarctic krill and the environment. In: D. Sahrhage (ed.), *Antarctic Ocean and Resources Variability, pp 120-130-* Springer, Berlin.

Price, H. J. 1989. Swimming behavior of krill in response to algal patches: a mesocosm study. Limnology and Oceanography 34: 649-659

8 LIST OF ACRONYMS

ACC	Antarctic Circumpolar Current
ADCP	Acoustic Doppler Current Profiler
AMERIEZ	Antarctic Marine Ecosystem Research at the Ice-Edge Zone
AMLR	Antarctic Marine Living Resources
BIOMASS	Biological Investigations of Marine Antarctic Systems and Stocks
BOFS	Biogeochemical Ocean Flux Study
CCAMLR	Convention for the Conservation of Antarctic Marine Living Resources
CEMP	CCAMLR Ecosystem Monitoring Programme
CSIRO	Commonwealth Scientific and Industrial Research Organization
CTD	Conductivity, Temperature, Depth probe
CZCS	Coastal Zone Color Scanner
ENSO	El Niño-Southern Oscillation
EPOS	European Polarstern Study
FGGE	First GARP Global Experiment
FIBEX	First International Biomass Experiment
FRAM	Fine Resolution Antarctic Model
GLOBEC	GLOBal ocean ECosystems dynamics
IOC	Intergovernmental Oceanographic Commission
JGOFS	Joint Global Ocean Flux Study
LTER	Long Term Ecological Research Study
MOCNESS	Multiple Open and Closing Net and Environmental Sensing System
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
OPC	Optical Plankton Counter
RACER	Research on Antarctic Coastal Ecosystem Rates
ROV	Remotely Operated Vehicle
SCAR	Scientific Committee on Antarctic Research
SCOR	Scientific Committee on Oceanic Research
SCUBA	Self-contained Underwater Breathing Apparatus
SIBEX	Second International Biomass Experiment
WOCE	World Ocean Circulation Experiment
XBT	Expendable Bathythermograph

9 PARTICIPANTS

Wolf Arntz
Alfred Wegener Institut für Polar und Meeresforschung
Columbusstrasse
D-2850 Bremerhaven
GERMANY

Ulrich Bathmann
Alfred Wegener Institut fur Polar und Meeresforschung
Columbusstrasse
D-2850 Bremerhaven
GERMANY

Edward Brinton
Scripps Institution of Oceanography
0201
La Jolla, CA 92093-0201

Joey Comiso
Laboratory for Hydrospheric Processes
Code 971
Goddard Space Flight Center
Greenbelt, MD 20771

Paul Dayton
Scripps Institution of Oceanography
0201
La Jolla, CA 92093-0201

Inigo Everson
British Antarctic Survey
High Cross
Madingley Road
Cambridge CB3 OET
UNITED KINGDOM

Bill Fraser
830 Hunt Farm Road
Long Lake, MN 55356

Jackie Grebmeier
108 Hoskins Hall
Department of Ecology
University of Tennessee, Knoxville
Knoxville, TN 37996-1191

Charles Greene
Ecology and Systematics
Corson Hall
Cornell University
Ithaca, NY 14853

Eileen Hofmann
Department of Oceanography
Crittenton Hall
Old Dominion University
Norfolk, VA 23529

Rennie Holt
NOAA
Southwest Fisheries Center
P.O. Box 271
La Jolla, CA 92038

Jian-Hwa Hu
National Taiwan Ocean University
2 Pei Ning Road
Keelung 20224
Taiwan
REPUBLIC OF CHINA

Mark Huntley
Scripps Institution of Oceanography
0202
La Jolla, CA 92093-0202

Tsutomu Ikeda
Japan Sea National Fisheries Research Institute
5939-22, Suido-cho 1 chome, Nigata-shi
Nigata 951, JAPAN

Adolf Kellerman
Alfred Wegener Institut fiir Polar und Meeresforschung
Columbusstrasse
D-2850 Bremerhaven
GERMANY

James Kennett
Marine Science Institute
University of California, Santa Barbara
Santa Barbara, CA 93106

John Klinck
Department of Oceanography
Old Dominion University
Norfolk, VA 23529

Tony Koslow
CSIRO Department of Fisheries and Oceanography
Antarctic Division
Channel Highway
Kingston, Tasmania 7150
AUSTRALIA

Valerie Loeb
Moss Landing Marine Laboratories
Moss Landing, CA 95039

Donal Manahan
Department of Biological Sciences
University of Southern California
Los Angeles, CA 90089-0371

Victor Marin
Depto. de Ciencias Marinas
Facultad de Ciencias
Universidad de Chile
Casilla 653
Santiago
CHILE

Steve Nicol
CSIRO Department of Fisheries and Oceanography
Antarctic Division
Channel Highway
Kingston, Tasmania 7150
AUSTRALIA

Peter Niiler
Scripps Institution of Oceanography 0230
La Jolla, CA 92093-0230

Gustav-Adolf Paffenhöfer
National Science Foundation
Ocean Sciences, Room 609
1800 G Street, NW
Washington, DC 20550

Polly Penhale
Division of Polar Programs, Room 624
National Science Foundation
1800 G Street, NW
Washington, DC 20550

Langdon Quetin
Marine Science Institute
University of California, Santa Barbara
Santa Barbara, CA 93106

Stanislaw Rakusa-Suszczewski
Department of Polar Ecology
Institute of Ecology
Polish Academy of Sciences
Dziekanow Lesny
05-150 Lomianki Waszawa
POLAND

Suzanne Razouls
Université Pierre et Marie Curie
Observatoire Oceanographique de Banyuls
Laboratoire ARAGO
66650 Banyuls-sur-Mer
FRANCE

Robin Ross
Institute of Marine Science
University of California, Santa Barbara
Santa Barbara, CA 93106

Sigrid Schiel
Alfred Wegener Institut für Polar und Meeresforschung
Columbusstrasse
D-2850 Bremerhaven
GERMANY

Kenneth L. Smith
Scripps Institution of Oceanography 0202
La Jolla, CA 92093-0202

Jarl-Ove Stromberg
Kristine Marine Biological Station
Kristineberg 2130
S-450 34 Fiskebackskil
SWEDEN

Cornelius W. Sullivan
Department of Biological Sciences
University of Southern California
University Park
Los Angeles, CA 90089-0373

Richard Veit
Zoology Department, WB-10
University of Washington
Seatde, WA 98195

Jon Watkins
British Antarctic Survey
High Cross
Madingley Road
Cambridge CB3 OET
UNITED KINGDOM

David Webb
Institute of Oceanographic Sciences
Deacon Laboratory -- Brook Road
Wormiey, Godalming
Surrey GU8 5UB
UNITED KINGDOM

Martin G. White
British Antarctic Survey
High Cross
Madingley Road
Cambridge CB3 OET
UNITED KINGDOM