Journal of the Korean Society of Oceanography
Vol. 33, No. 3, pp. 123—135, September 1998

Current Status of Antarctic Environments and Resources

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Cooperative scientific research in Antarctic has been successful since the International Geophysical Year 1957/1958. Presently, 43 nations have joined the Antarctic Treaty as consultative parties or acceding states, and other treaties and agreements have evolved to conserve the integrity and to manage the resources of the Antarctic ecosystem. Although yet to be designated, tourism areas in Antarctica are under consideration. Due to its remoteness and vast magnitude, Antarctica's science is slowly emerging. Satellite technology has enabled observation of the progression of the ozone hole above Antarctica. Mineral exploitation has yet to take place, as has the transport of Antarctic icebergs to some arid nations. On the other hand, both seal and whale exploitations have occurred, devastating these populations. The lessons learned from past human greed are used to design krill and squid fisheries, though the life histories of these organisms are yet to be adequately understood. An ecosystem approach to managing Antarctic resource exploitation is essential. Procuring the needed logistics to do so is daunting, requiring the highest degree of international cooperation and educational outreach to nurture the needed effective scientific and engineering talent, both natural and social.

INTRODUCTION

For more than a century since it was discovered in the early 19th century, Antarctica was regarded as a remote and useless land mass. Only sealers and whalers explored hunting sites there, and some adventurers considered it a conquerable object. Though pioneering western countries such as the United Kingdom, France and Norway continued to support exploration and scientific activities in Antarctica for the expansion of territory and preemption of natural resources, Antarctica was considered too remote to be realistic for ordinary people. Recently, however, environmental problems in and around Antarctica have rapidly surfaced. Serious destruction of the ozone layer over Antarctica, which is detrimental to the survival of life forms within, is now thought to be linked to the uncontrolled anthropogenic emission of chlorofluorocarbon (CFC). Climatic changes and the recent warming trend of Earth caused by the emission of greenhouse gases are becoming scientific and societal issues for Antarctica and all of Earth. For instance, inadvertent total melting of the Antarctic ice sheet could raise the global sea level by more than 60 m (USNSF, 1997).

Further, humanity now realizes the possibilities of exploiting Antarctic resources. As is the case with other continents, mineral and petroleum resources may exist under the Antarctic continent and the surrounding continental shelf area since it is theorized that Antarctica was in the temperate zone 180 million years ago as part of the ancient supercontinent Gondwanaland. In the Southern Ocean around Antarctica, the vast krill population supports fisheries as well as the Antarctic marine ecosystem. If the harvesting of Antarctic krill is economically feasible, its commercial exploitation could start anytime. Some fish resources already have been diminished in the Southern Ocean due to overfishing, and many scientists believe that any restoration of resources or the ecosystem of Antarctic waters may take longer than restoration in temperate areas. Since Antarctica is an integral part of Earth's environment, and since mineral exploitation in Antarctica is yet to occur and fishery exploitation may increase, the time to establish adequate environmental safeguards is now, before further exploitation.

The age and stability of Antarctica's marine environment have encouraged the evolution of Southern Ocean communities of endemic organisms with specialized relations among themselves and their abiotic environment. This is particularly true in the shallow waters of the continental margin and Antarctic islands. Phytoplankton populations in the Antarctic region are dominated by diatoms. In fact, nearly 100 species are found in Southern Ocean waters. Antarctic krill, *Euphausia superba*, a shrimp-like herbivorous planktonic crustacean, forms the principal link in Antarctica's food web. Most primary production of Antarctic waters is channeled through this herbivore alone and, either directly or indirectly, krill supports all of Antarctica's higher species, which include at least five species of whale, three species of seal, twenty fish species, three types of squid, and numerous bird species. We consider birds living south of the Antarctic Convergence an important part of the marine ecosystem. The population of birds in this area is estimated at 350 million, weighing over 0.4 million metric tons; it is greater than the combined weight of Antarctic seals and whales (USNSF, 1997). In comparison, we quote that the 6 billion people now on Earth weigh approximately 300 million metric tons in total. Maritime Antarctica is home to at least 150 species of lichen, 75 mosses, 22 macrofungi, and many species of algae (Smith, 1984). Particularly hospitable to this vegetation, meltwater in the area helps support an herb species. The Antarctic mainland plays host to a number of microscopic plants, which are found mainly in crevices and cavities of exposed rock. Even the poorly developed soil of Antarctica harbors bacteria, algae, yeast and other fungi, lichens, and even moss spores; they usually are dormant.

The increasing interest in krill fishing, along with other possible exploitation of living resources in the Antarctic region, is attributed to the establishment in the 1960s of 200-nautical-mile-wide resource management zones around coastal nations. These exclusive economic zones (EEZs) have driven fishing industries to look for other areas such as the Southern Ocean and open ocean to make up for lost catch. In the 1970s and 1980s, concern grew over the loosely regulated exploitation occurring in the Southern Ocean in the absence of any formal, effective management scheme for the protection of Antarctic environments and resources, and Antarctic Treaty member nations since this time have considered establishing an international agreement to provide for Antarctica's protection. With the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR) of 1982 and the Protocol on Environmental Protection to the Antarctic Treaty, (so-called Madrid Protocol), which was signed in Madrid, Spain, on 4 October 1991 and became effective in January 1998, Antarctic environments and resources may be managed more prudently, though a fatal flaw of these agreements is that all decisions must be unanimous.

ANTARCTIC TREATY SYSTEM TO PROTECT THE AREA

The Antarctic Treaty arose out of the success of activities in the International Geophysical Year (IGY), 1 July 1957—31 December 1958, when Antarctica was a focal point of coordinated international scientific research. The treaty, which applies to the area south of 60°S latitude, essentially extended the terms of the IGY, recognizing such an initiative as having common interest to humanity. The treaty's fourteen articles were agreed upon by twelve nations. The treaty was signed on 1 December 1959, and entered into force on 23 June 1961 with the aim of preserving Antarctica as an international laboratory dedicated to peaceful scientific research, and a place where scientific investigation, international scientific cooperation and the free flow of information are supreme. The treaty deemed Antarctica a demilitarized continent—the only one in the world—and according to the treaty's spirit, Antarctica is to continue forever to be used exclusively for peaceful purposes and not to become the scene or object of international discord. Presently, 43 nations have joined the Antarctic Treaty as consultative parties or acceding states (Table 1). Consultative meetings of treaty states are held annually (before 1991, meetings were held every two years), at which time issues and recommendations concerning Antarctica are presented and discussed.

Flaws of the treaty include its failure to resolve the territorial claims of seven nations: Argentina, Australia, Britain, Chile, France, New Zealand and Norway (Fig. 1). The sovereignty question was aggravated by the establishment of 200-nautical-mile wide EEZs bordering coastal nations, and growing interest in Antarctica's potential mineral resources has not helped the lack of agreement on either the extent or existence of national territorial claims. Nonetheless, the Treaty deserves credit for the over 30 years of peaceful international cooperation in scientific activities in the region since it took

Table 1. Antarctic treaty contracting parties in chronological order of ratification of the treaty by the original signatories, and the dates of accession or succession by other states (OS=original signatory, CP=consultative party, AS=acceding state)

	Nation	Date	Status
1	United Kingdom	May 1960	OS/CP
2	South Africa	June 1960	OS/CP
3	Belgium	July 1960	OS/CP
4	Japan	August 1960	OS/CP
5	United States of America	August 1960	OS/CP
6	Norway	August 1960	OS/CP
7	France	September 1960	OS/CP
8	New Zealand	November 1960	OS/CP
9	Russian Federation[3]	November 1960	OS/CP
10	Poland[1]	June 1961	AS/CP
11	Argentina	June 1961	OS/CP
12	Australia	June 1961	OS/CP
13	Chile	June 1961	OS/CP
14	Czech[4]	June 1962	AS
15	Slovakia[4]	June 1962	AS
16	Denmark	May 1965	AS
17	Netherlands[1]	March 1967	AS/CP
18	Romania	September 1971	AS
19	Brazil[1]	May 1975	AS/CP
20	Bulgaria	September 1978	AS
21	Germany[5]	February 1979	AS/CP
22	Uruguay[1]	January 1980	AS/CP
23	Papua New Guinea[2]	March 1981	AS
24	Italy[1]	March 1981	AS/CP
25	Peru[1]	April 1981	AS/CP
26	Spain[1]	March 1982	AS/CP
27	People's Republic of China[1]	June 1983	AS/CP
28	India[1]	August 1983	AS/CP
29	Hungary	January 1984	AS
30	Sweden[1]	April 1984	AS/CP
31	Finland[1]	May 1984	AS/CP
32	Cuba	August 1984	AS
33	Republic of Korea[1]	November 1986	AS/CP
34	Greece	January 1987	AS
35	Democratic People's Republic of Korea	January 1987	AS
36	Austria	August 1987	AS
37	Ecuador[1]	September 1987	AS/CP
38	Canada	May 1988	AS
39	Colombia	January 1989	AS
40	Swiss	November 1990	AS
41	Guatemala	July 1991	AS
42	Ukraine	October 1992	AS
43	Turkey	January 1996	AS

[1]These Acceding States became Consultative Parties on the following years: Poland, 1977; Federal Republic of Germany, 1981; Brazil and India, 1983; People's Republic of China and Uruguay, 1985; German Democratic Republic and Italy, 1987; Sweden and Spain, 1988; Finland, Peru and Republic of Korea, 1989; Netherlands and Ecuador, 1990.
[2]Papua New Guinea succeeded to the Treaty after becoming independent of Australia.
[3]Russia succeeded the status of Soviet Union in 1992.
[4]These states became independent from Czechoslovakia.
[5]The German Democratic Republic had acceded to the Federal Republic of Germany in 1990, and is referred to as Germany thereafter. Federal Republic of Germany and German Democratic Republic acceded to the Treaty on February 1979 and November 1974, and became Consultative Parties in 1981 and 1987, respectively.

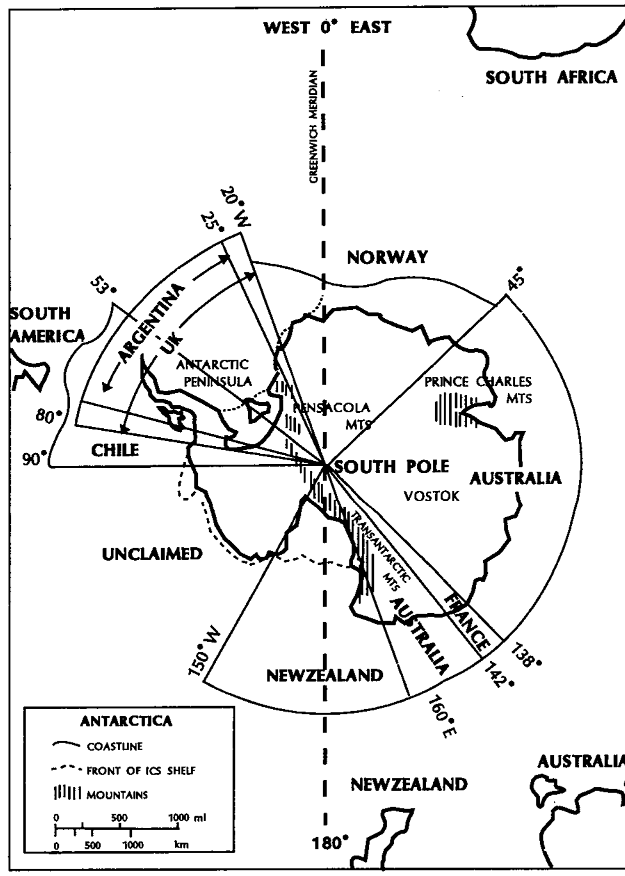


Fig. 1. Territorial claims in Antarctica.

effect, and research concerning environmental protection has been the focus of Antarctic studies.

In response to the Antarctic Treaty's encouragement to preserve and conserve Antarctica, the "Agreed Measures for the Conservation of Antarctica's Fauna and Flora" were adopted in 1964 ("Agreed Measures"), recognizing Antarctica as a special conservation area. This convention was the first internationally agreed-upon system to monitor human impact on the Antarctic ecosystem. One of the more important sections designates as specially protected certain native species of Antarctic fauna and flora (Article VI). Article VII stipulates that all governments must minimize any potential interference with natural habitat conditions in areas of prominent scientific interest, known as Specially Protected Areas (SPAs), and regulations on the introduction of non-indigenous species are contained in Article IX. Within the framework of the Agreed Measures, Antarctic Treaty nations in 1972 expanded the application of SPAs to include marine areas, and proposed the designation of Sites of Special Scientific Interest (SSSI), which solicit a lesser degree of protection and facilitate scientific research.

In 1985, provision was made to further expand the Agreed Measures, calling for the designation of Areas of Special Tourist Interest (ASTI). Currently, no ASTI have been designated. The objective of setting aside such areas is to contain the stress inflicted by tourism. Ungoverned tourism can greatly disrupt natural communities, such as penguins, which may forego taking up a nesting site, or abandon one already established, as a result of intemperate human presence. The presence of tourists can also upset scientists and their work in Antarctica. The increased traffic of people and transport that comes with a tourist industry brings the increased chance of related accidents, and attending to such an occurrence draws away from the limited human and material resources of research communities. Although the only incident of its kind, the crash of an Air New Zealand flight in which 257 people died disrupted nearly all work at Scott Base and McMurdo Sound during the 1979/1980 season.

In the years leading to 1980, CCAMLR was developed to promote the protection, scientific research and environmentally sound management of the living marine resources in the Southern Ocean. The agreement was signed in 1980 and entered into force on 21 April 1982. Its preamble stresses the importance of research to increase knowledge of Antarctica and its ecosystem. It applies to the entire marine region within the Antarctic Convergence. The CCAMLR is holistic in its approach. Guided by the principle that the rational use of resources should be based on ecosystem management, it introduced the concept of precautionary catch limits that regulate fish catches in order to ensure their active reproduction at maintained population sizes. The accord also aims to maintain ecological relationships between harvested and dependent species, and addresses the direct and indirect impacts of harvesting and of species introduction. The scientific committee of CCAMLR seeks and analyzes data on how much of each resource may safely be harvested, makes recommendations concerning conservation measures, and generally facilitates Antarctic marine research.

A most promising development in Antarctica's protection is the establishment of the Madrid Protocol. The Convention on the Regulation of Antarctic Mineral Resource Activities, concluded in Wellington, New Zealand, on 2 June 1988 after six years of negotiation, was not entered into force. The Madrid Protocol, which became effective in January 1998, replaced it, however, and bans all mineral resource exploitation activities except for scientific research. The basic approach of the Madrid Protocol, toward questions of Antarctic environmental protection is prevention, rather than cure. In addition to the ban on mineral exploitation, it promotes the protection of the Antarctic environment and its dependent and associated ecosystems. Annex V to the Madrid Protocol designates "Antarctic Specially Protected Areas" (ASPAs), the areas earlier designated by the Agreed Measures as SPAs and SCSI, and the Protocol prohibits entry into an ASPA except in accordance with a permit issued under Article VII of the Protocol. Also, any area, including any marine area, where activities are or will be conducted, may be designated as an Antarctic Specially Managed Area (ASTHMA). The Protocol does not require any permit for entry into an ASTHMA (Anonymous, 1994).

CHARACTERISTICS OF ANTARCTIC ENVIRONMENTS

Spreading out over the southernmost region of Earth, Antarctica covers an area of 14×106 km^2, which is 10% of the world's land surface or about the combined land area of Europe and the United States. The continent is almost entirely within the Antarctic Circle at 66°30'S. It is the most remote of Earth's land masses, with Cape Horn, at distance of 990 km, its closest neighbor. The continent is roughly divided by the Transantarctic Mountains, with Greater Antarctica to the east and Lesser Antarctica to the west. Antarctica ranges in height from about sea level to more than 4000 m; its mean altitude exceeds 2000 m (Fig. 2). Older geologically, Greater Antarctica is mountainous, with many peaks above 4000 m. Antarctica's highest point is Mount Vinson Massif at 5140 m, while its central lake basins are 2500 m below sea level. Without ice cover, Lesser Antarctica would be exposed as a series of insular islands. As it stands, the area features a series of isolated inland peaks that protrude the ice—nunatuks—and the Antarctic Peninsula, which extends toward southernmost South America. Antarctica's few lakes and ponds have become saline over the past 100 000 years, with some saltier than seawater. Their basins, however, are largely filled with perennial ice, and are only

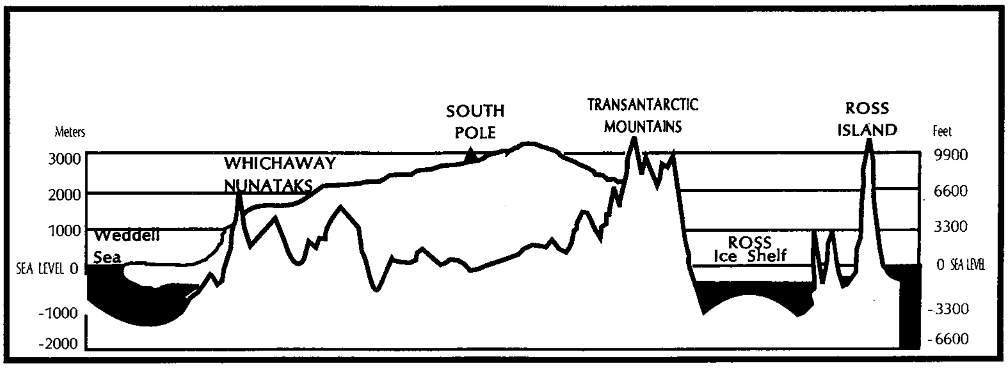


Fig. 2. Section through Antarctica showing land and ice cap. The weight of the ice cap has literally squashed the Antarctic land mass by an average of 600 meters. As a result, much of the land beneath the ice is below sea level, and much of the continental shelf is over 500 meters below the sea surface.

sometimes fringed with open water during the austral summer.

Antarctica's climate is that of a cold desert. During austral winter, little or no daylight reaches the continent. The sun sits below the horizon for the entire six months of 21 March to 21 September. During July, the coastal temperature averages −20°C, and the interior ice sheet −65°C. Surface temperature varies by elevation and therefore reflects topography. Temperature decreases slightly with latitude—by approximately 0.66°C with each degree. Because temperature depends strongly on elevation, however, the lowest temperature normally occurs in the most elevated area of the continent—the pole of low temperature, at Vostok, Antarctica—rather than at the South Pole (Fig. 1). Mean temperature at the pole of low temperature is −49°C, and at Vostok in July 1983, a very low temperature of −89.6°C was recorded. In contrast, the summer sun can sufficiently warm the continent' s surface to raise the temperature of exposed areas to a depth of 30 cm, and in coastal areas where there are considerable exposed rocks, temperature sometimes exceeds +9°C during Antarctica's summer.

Precipitation over continental Antarctica is less than that of most deserts. The annual range of precipitation measured in liquid form is approximately 3 cm in the interior to between 20 and 30 cm on the continental margin. Only about 7 cm of snow accumulates yearly at the South Pole. Continental blizzards, due to the aridity, are mainly snow blown from place to place rather than fresh snowfall. Antarctica's temperature is so low and the air so dry that sublimation of ice and snow is more typical than melting. As a result, there is little runoff and are few streams. Mass balance, or the difference between the accumulation and ablations of mass on the ice sheet or shelf, is one method of precipitation measure. For most of Antarctica, the annual balance is less than 10 g/cm^2. Within this region, there is an area of about 2×106 km^2 where the balance is less than 5 g/cm^2.

Ninety-eight percent of Antarctica's surface is covered with ice, constituting 24×10^6 km^3, 90% of the world's fresh water; and 90% of its ice cover averages 2000 m in thickness. Approximately 2% of the continent that remains exposed is mostly rock. Permanent ice shelves—seaborne portions of the huge ice cap overlying the continent—have formed in may areas along the coast. The Ross Sea ice shelf is as large as France. There is a steady flow of ice into the surrounding sea by these ice shelves as streams from Lesser Antarctica gradually move the glacial ice seaward at a rate of about 800 m per annum. At shelf outlet points, large tabular icebergs are released.

Nearly all parts of the continent experience persistent winds as cold air from the interior blows down and outward over the ice slope to the coast. These katabatic, or gravity type winds, often exceed 300 km an hour. Variable pressure gradients at about 60°S off the coast of Greater Antarctica and 70°S off the coast of Lesser Antarctica, together with the strong oceanic gradient from 35°S to 60°S, largely determine the average wind speeds for the seas around Antarctica. Wind strength in coastal areas may be due either to changes in katabatic wind strength, local pressure gradients, or both. Mean annual wind speed for a four-year period observed at Cape Denson and Port Martin was 18.5 m/s, the highest average wind speed near sea level anywhere on Earth. A distinction of these surface winds is how abruptly they change speed, falling and rising from calm to 50 m/s in a few minutes. The changes in speed are accompanied by variations in surface pressure, temperature, humidity, and snow drifting, a pattern known as Loewe's phenomenon. Just off the coast, winds decrease, although there may be winds of 50 m/s or more in certain areas due to the passage of depressions. Winds of the continental interior are calmer, and the maximum speed recorded for the South Pole is 24 m/s.

Central to the issue of ozone and Antarctica is the hole in the stratospheric layer of ozone, located specifically in the region of 20—25 km above the continent. Its increasingly long presence over Antarctica has triggered intense questioning of its cause and consequences. The hole itself is held responsible for a 50% decrease every austral spring in the amount of total ozone above the continent relative to its yearly average. Previously present only from September until November, since 1985 the hole has lingered into December each year. Observations as early as 1957 discovered depletion of ozone over Antarctica, but the recent advent of satellite and computer technology has enabled researchers to precisely ascertain changes in the extent and magnitude of the ozone hole. The process of ozone depletion involves certain gases, including nitrous oxides, water vapor, chloroform, methane and CFCs, which when broken in the stratosphere by solar radiation, destroy ozone. The meteorologic conditions of Antarctica encourage this breakdown. No significant changes in the amount of total ozone had been identified on a global level before the early 1980s (Fig. 3a). The global average of total ozone above Antarctica seems to have decreased since the mid-1980s, however, and local concentrations over Halley Bay decreased rapidly through the 1980s (Fig. 3b).

Ozone acts as a buffer for Earth, filtering out 70—90% of solar radiation and preventing the penetration of some of the more hazardous rays. Its depletion in the stratosphere thus allows increased radiation to reach the Earth's surface, including the shorter and particularly harmful UV-B and UV-C rays, in 4—320 nm in wavelength. The biologically injurious consequences of exposure to the harsher rays include damage to DNA and weakening of the immune system, and large doses can be fatal. Phytoplanktonic organisms, which are fundamental to the Antarctic food web, make their principal habitat the surface area of the marine environment to a depth of about 1 m, and are especially vulnerable to the incidence of radiation. Injury inflicted on these primary producers will weaken the base of Antarctica's simple food web and have repercussions throughout the aquatic environment.

The size of the Southern Ocean changes significantly by season. The continent including sea-ice cover doubles in size each winter as pack ice stretches 800—1600 km from the coast (Fig. 4). By September each year, the sea ice surrounding Antarctica covers an area greater than that of the continent itself. Using the Greenwich meridian to measure its diameter, Antarctica spreads 5400 km across during the austral winter compared to 3600 km during summer months. The total area of sea-ice cover is least between February and March, at about 3×106 km^2, and swells to its maximum cover of 19×106 km^2 in September. Although it is yet little understood, Antarctica's climate has a profound effect on Southern Hemispheric weather systems.

The East Wind Drift near the continental margin and the West Wind Drift at a distance of several hundred kilometers from the continent, between 40°S and 60°S, comprise one aspect of the dynamics

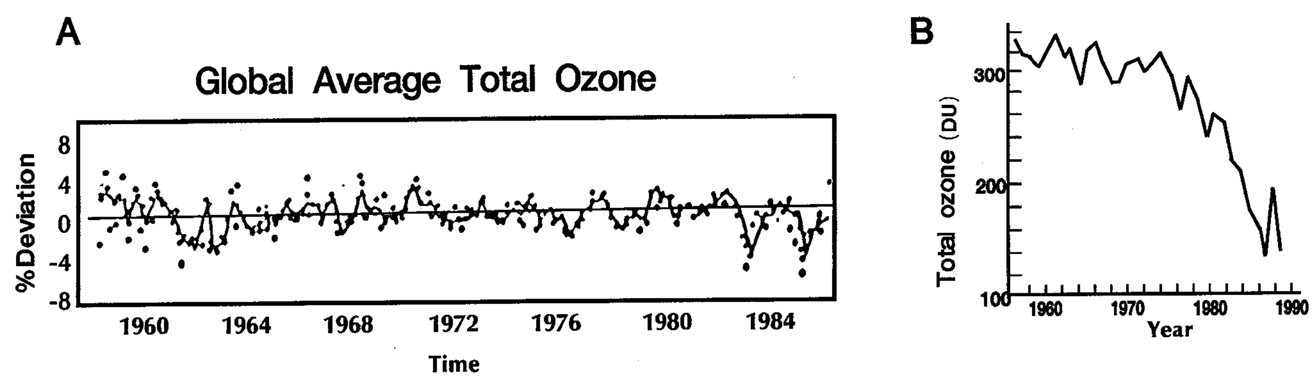


Fig. 3. Changes in ozone concentration with time: **(a)** global average of total ozone, and **(b)** monthly means of total zone over Halley Bay, Antarctica (Kang *et al.*, 1993). DU=Dobson unit.

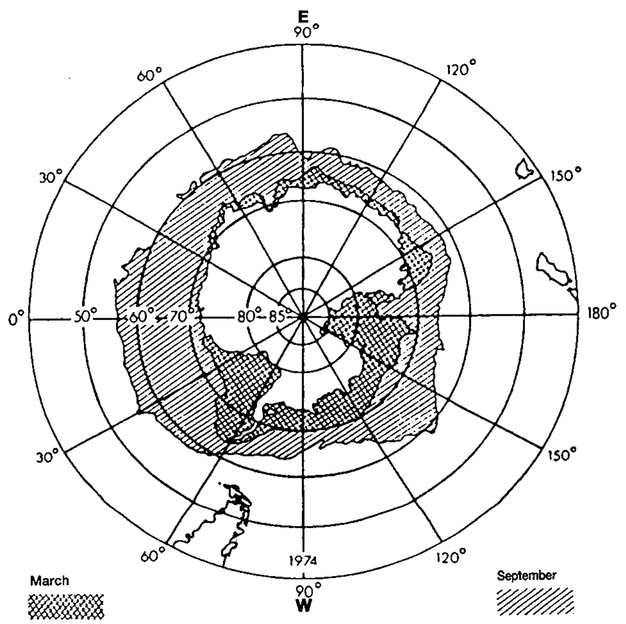
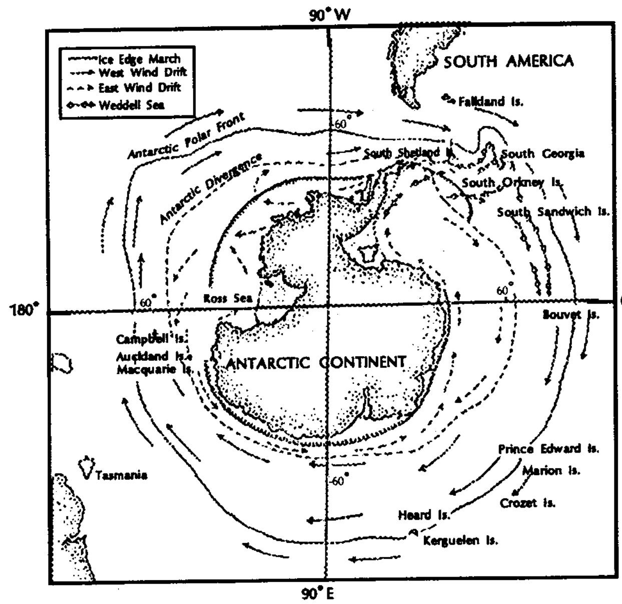


Fig. 4. Mean maximum (September) and minimum (March) distribution of Antarctic pack-ice.

of Antarctica's waters (Fig. 5a). In the extremities of the West Wind Drift, cold Antarctic surface water sinks beneath the less dense sub-Antarctic surface water and constitutes the polar frontal zone or Antarctic Convergence (Fig. 5b). The Wind Drifts, together with the Antarctic Convergence and other circulation patterns, give rise to the unique marine environment of the Southern Ocean. Steep temperature gradients in the Convergence zone are the source of the rich productive marine ecosystem south of the Convergence due to an increase of plant nutrients swept southward with the warmer sub-Antarctic waters. The position of the Convergence varies with changing temperature, pack ice conditions, and currents, shifting between 47°S and 62°S. It demarcates the natural boundary of Antarctic waters, and the area within its domain is twice as great as the area of Antarctica's land mass.

Deeper in the Southern Ocean, another circulation pattern exists. At the edge of the continent, cold water sinks to form the cold Antarctic Bottom Water (AABW) that flows northward over the seafloor in the South Atlantic, South Pacific, and Indian Oceans (Fig. 5b). Above AABW, the warmer, nutrient-rich and more saline circumpolar deep water flows southward. At the continent's edge, these water masses collide. In the zone of upwelling thus created, nutrient-rich water is thrust to the surface promoting the growth of phytoplankton and



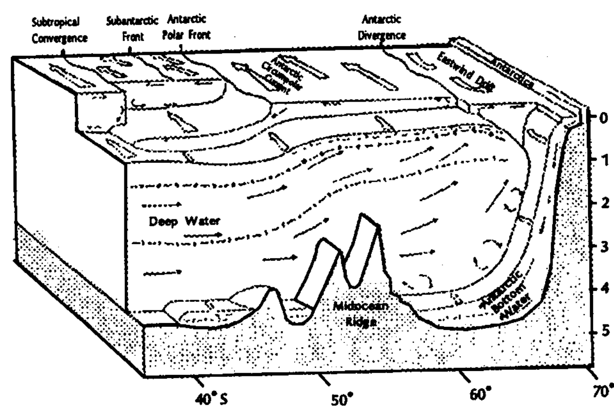


Fig. 5. Current system and water masses in the Southern Ocean: (**a**) surface circulation, and (**b**) schematic representation of the vertical structure.

phytoplankton-dependent marine life.

Along with AABW sinking to the seafloor around Antarctica, man-made pollutants are swept downward and northward into the three major oceans. The residence time of AABW is several hundred years. Already some traces of man-made excess CO_2 are found in AABW. In the short term, the waste-carrying capacity of the deep ocean is a blessing, since it cleanses our atmosphere. The long-range ramifications of this event need to be elucidated, however. Off New Zealand, already some CFC compounds are detected at 1200 m deep. Long-term monitoring of Antarctic environmental factors is essential to understanding such changes in and around the continent.

NON-LIVING RESOURCES

Of the 2% of Antarctica's surface that is ice-free, only 10% has been mapped, and only 1% has been explored for minerals. In fact, the area of Antarctica so far charted equates to the U.S. State of Delaware relative to the whole of the United States and Mexico. Most of the discussion concerning Antarctica's non-living resources, therefore, is based on circumstantial evidence rather than hard data. Specifically, the Gondwanaland hypothesis supports speculation that mineral resources exist in Antarctica, theorizing that the continent's makeup is similar to that of the land masses with which the theory supposes Antarctica was earlier united, and that Antarctica thus possesses similar resources.

A case in point is the Transantarctic Mountain range that is believed to have been continuous with Tasmania and eastern Australia in the neighborhood of 200 million years ago, during the early Mesozoic, according to the theory that all land masses were then conjoined and formed the supercontinent Gondwana. Commercial grade deposits of lead, zinc, tungsten, copper, tin, silver and gold exist in the Australian areas and are therefore postulated to exist in Antarctica's Transantarctic Mountains. Tracking this line of thought, structural similarity between eastern Antarctica and parts of Australia and South Africa suggests the occurrence of uranium. Further, the Antarctic Peninsula, an extension of the Andean orogeny, is thought to be endowed with deposits of copper and molybdenum, and the igneous stratiform complex that characterizes the Dufek Massif of Antarctica is similar to others around the world where chromium, platinum, copper and nickel are mined in commercially important quantities. In fact, low grade copper materialization has been studied on the Antarctic Peninsula, and coal deposits have been located in the Transantarctic Mountain region. In the Prince Charles Mountains, enough iron has been discovered to be considered a conditional resource; that is, potentially commercial if the price of iron were to sufficiently increase.

Playing a controversial role in resource speculation, the existence of oil in the Bass Strait near New Zealand, between Tasmania and Australia, has led to supposition that such deposits exist in formerly adjacent regions of Antarctica, as supported by the Gondwanaland hypothesis. The theory that Antarctica was once a province of the temperate zone further supports the possibility that the continent may bear oil and natural gas. In fact, thick layers of unmetamorphosed tertiary sediment—matter that frequently contains oil—have been found in the Bellingshausen, Weddell and Ross Seas. In addition, oil indicators such as methane, ethane, and especially ethylene have been found in holes drilled beneath the Ross Sea. A 1973 U.S. Geological Survey study, though speculative, estimated that up to 45 billion barrels of oil as well as 10 trillion m^3 of natural gas may lie beneath the continent, although this opinion has yet to produce any meaningful estimate based on actual data. Offshore, ferromanganese nodules have been found containing copper, nickel, and manganese. Evidence suggests that the mineral content of such nodules is latitude dependent, however, and minerals of the Southern Ocean are likely to be of a low grade relative to those of the central Pacific, for instance.

Antarctica's icebergs are also considered a potential resource of tremendous importance, presenting a possible freshwater supply for arid countries and regions, such as Australia, Saudi Arabia, and U.S. southern California. It was agreed by the Antarctic Treaty that Antarctic ice should not be treated as a mineral. Though there has been no practical operation to move icebergs from Antarctica to places where water is needed, scientific, technological, environmental and economic curiosities are continually pursued (Anonymous, 1994).

MARINE BIOTA AND ECOSYSTEM

The seasonal advance and retreat of pack ice distinguishes Southern Ocean waters as unique. Sea ice forms a substrate for sessile plankton and associated organisms, providing a variety of salinity gradients and light conditions, and has a calming effect on the surface water. The ice thus acts to diversify the available ecological niches and promotes overall productivity of the Southern Ocean.

Most phytoplankton species are cosmopolitan in nature, but three diatoms are limited to the Antarctic region and 20 diatom taxa are restricted to the southernmost part of its area. Diatom populations in pack ice may exhibit further endemism. Although many of the Antarctic diatoms are single cells, colony formation is common during austral winters. Little is known about the abundance or distribution of dinoflagellates. Dinoflagellates, however, dominate in some water columns and their biomass in the Antarctic has likely been underestimated. In the Antarctic region, the genera *Protoperidinium* is the most abundant of dinoflagellates, and the genus

Ceratium—so prevalent in other seas—is essentially absent. The degree of dinoflagellate endemism in the Southern Ocean, at 80—85%, is higher than that of dinoflagellates in any other oceanic region. Not less than 35 species of dinoflagellates are limited to Antarctic waters.

Krill are circumpolar in distribution (Fig. 6). They appear to be most abundant in the South Atlantic Sector, however, and occur in large swarms dense enough to discolor surface waters, commonly reaching concentrations of thousands in a cubic meter. There are seven species of krill in the Antarctic region, of which *E. superba* dominate biologically and are harvested economically. Sightings of krill include reports of swarms estimated to be as great as 2.5 million metric tons. Krill populations have been believed to be large in size and biomass on the basis of such sightings, but estimates of small areas were assumed to be the case for wide regions, and despite the tremendous size of some sightings, recent research indicates that swarms are very patchy in distribution. Heavy concentrations occur particularly in oceanic areas of convergence and divergence, and studies indicate that total zooplankton biomass at the Antarctic Convergence is 3.0—3.5 times greater than in adjacent areas. Krill swarms can reach depths of 40—50 m according to Russian research. It is in the upper 10 m of depth from the surface, however, that they are commercially most desirable.

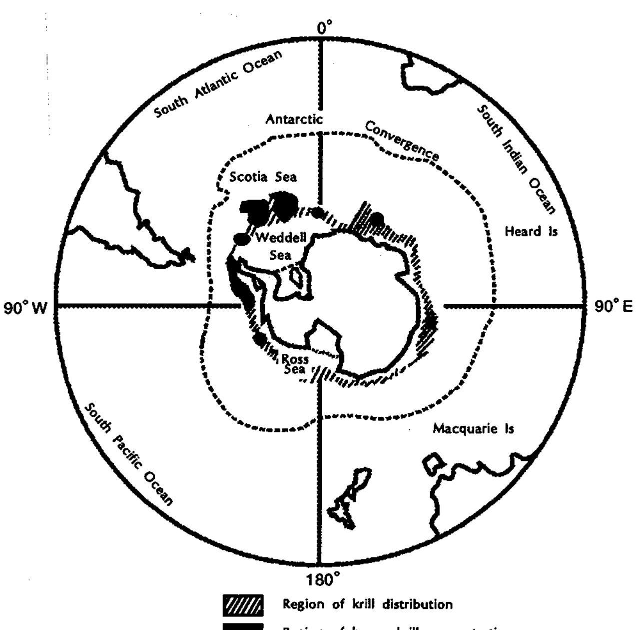


Fig. 6. Generalized distribution of Antarctic krill. Compiled from a number of sources in Nicol (1994).

Until recently it was estimated that the potential catch of krill far exceeded the total annual harvest of fish and shellfish from all the world's oceans. Great discontinuities in the distribution and swarming of krill populations, along with the variety of methods used to estimate the stocks and the relatively small areas in which sampling has been conducted, deem such estimates of little value, however. In fact, krill stock population estimates range from 45—7000 million metric tons (Everson, 1992). This wide range of estimates emphasizes the need for more complete data concerning krill populations, and it reveals the threat of overfishing in light of their uncertain numbers. Additionally, in contrast to the approximate four-year life span formerly supposed, their life span is now thought to be as long as seven years, implying that young krill require a number of years to reach a harvestable size.

The characteristically turbulent surface waters of the Antarctic Convergence keep many organisms from crossing it. More than 85% of coastal or pelagic species are endemic to the Southern Ocean, in fact, and as much as 25% of deep-sea species are endemic (Kock, 1992). Whales, however, are not. Annually, they migrate south from the tropical or subtropical waters where they breed and reside most of the time, to spend austral summers feeding around Antarctica. The principal whale populations of Antarctic waters are baleen whales, including blue, fin, sei, right and humpback whales. Odentocetes, represented by sperm and killer whales, also occur. A number of lesser known species, such as the bottlenose and beaked whales, are additionally found around Antarctica.

Limiting interspecific competition for resources, different whale species have different arrival times in the Antarctic, as well as different feeding ranges. Blue whales, *Balaenoptera musculus*, for instance, arrive first. This species, attaining lengths of 30 m and weights of 150 metric tons or more, and probably the largest animal ever to have existed, reaches the waters south of the Antarctic Convergence in November and feeds on krill at the retreating pack-ice edge until some time in February. The fin whale, *B. physalus*, is the next to arrive and is most numerous between January and March, feeding in open ocean areas. Humpback whales, *Megaptera novaeangliae*, spend December through January feeding in the northern areas of the Southern Ocean, while sei and sperm whales, *Balaenop-*

tera borealis and *Physeter macrocephalus*,—the last arrivals—feed between January and March and stay even farther north, near the Antarctic Convergence. Still, the overlap of whale feeding and commercial fishing seasons is direct.

Antarctic krill is the chief food source of whales in the Antarctic. Krill swarming behavior makes it easy for whales to consume large quantities of krill at once. It appears that whales have adopted this diet because of krill availability rather than their own selection or preference. Whale distribution and concentration probably do not have a social basis but reflect the distribution of the prey species. Of further concern is the concurrent timing of commercial fishing endeavors and whale feeding, both taking place between November and May in the same open, ice-free areas.

Penguins constitute about half of Antarctica's total bird population of 350 million (USNSF, 1997). They eat krill and are eaten by seals and other predators, thus occupying a significant ecological niche in Antarctic waters. The population dynamics and life history of penguins are studied continually by scientific parties that come to Antarctica and sub-Antarctica. Breeding success and failure are monitored when possible. For instance, at Marion Island, south of South Africa, Macaroni penguins, *Eudyptes chrysolophus*, were studied at three colonies by J. Cooper, A. Wolfaardt and R. J. M. Crawford of South Africa between 1979/1980 and 1995/1996. They also studied Rockhopper penguins, *E. chrysocome*, at three colonies between 1985/1986 and 1995/1996. The CCAMLR Ecosystem Monitoring Program (CEMP) plans to determine the reproductive success and foraging behavior of Adelie penguins, *Pygoscelis adeline*, and long-term monitoring will be necessary in order to understand the range of natural variation present and the effects of fishery activities. Research practices such as flipper bonding, stomach lavage and instrument attachment, which may result in decreased breeding success, increased mortality, changes in immigration, emigration and recruitment, are recurring research dilemmas (Clark and Kerry, 1994).

Little is known about Antarctic seal populations and behavior due to the remoteness and inaccessibility of their habitat. There are six species of seal (the fur seal, *Arctocephalus gazella*, the crabeater seal, *Lobodon carcinophagus*, the leopard seal, *Hydrurga leptonyx*, the elephant seal, *Mirounga leonina*, the Ross seal, *Ommatophoca rossii*, and the Weddell seal, *Loptonychotes weddellii* within the area south of the Antarctic Convergence, two fur and crabeater of which feed primarily on krill and another is indirectly dependent. In fact, 90% of the fur and crabeater seals' diet is krill. Crabeaters, in particular, are believed to consume 63 metric tons of krill a year individually, thus collectively consuming more krill than the amount eaten by the surviving Antarctic baleen whales. They are circumpolar in distribution and are the most abundant of the seals, with estimates ranging from 15—40 million. In fact, one out of every two seals in the world is a crabeater, although census data indicated declines in crabeater populations from eleven seals to four seals per nautical square mile in the mid-1980s in the Weddell Sea (Erickson and Hansen, 1990). Leopard seals are distinct in that they have evolved into predators of warm-blooded mammals. In addition to the direct intake of krill, which composes 37% of the leopard seal diet, leopard seals prey heavily on krill-dependent crabeater seals.

EXPLOITATION OF ANTARCTIC MARINE LIVING RESOURCES

As research on krill population dynamics continues, so does commercial krill fishing. Recently, active participants in the Antarctic krill harvest have been Japan, Poland and the Ukraine. In the years leading to the early 1990s, before political change took place, the Soviet Union caught and consumed 90% of all krill harvested. The combined krill catch of all fishing nations during the early 1980s was estimated at 300 000 to 600 000 metric tons annually. Since the Soviet Union's economy was rapidly capitalized, however, their distant-water fishing has not been profitable due to the increase in operational costs. Currently, a total of about 100 000 metric tons of krill is harvested annually in the Atlantic sector of the Southern Ocean every year, and the Japanese catch comprises about 70% of this.

Commercial finfish fisheries began in the late 1960s in the Southern Ocean, and peaked in the 1970—1971 season, recording around 400 000 metric tons of catch. Due to overfishing, however, the annual catch of Antarctic cod and icefish decreased to 100 000—200 000 metric tons through the 1980s. More seriously, in the 1990s, almost all finfish fisheries collapsed except for the Patagonia toothfish, *Dissostichus eleginoides*. In the 1995—1996 season, the total catch of finfish from the South

Georgia and Kerguelen Island regions was about 9000 metric tons, of which *D. eleginoides* comprised 99% (CCAMLR, 1996). Korea, the United Kingdom, and the USA are developing recent findings on crab and squid resources in the South Georgia. Croxall *et al.* (1985) have estimated that 3.7 million metric tons of squid resources exist in the Scotia Sea, and that nearly 0.5 million metric tons are taken annually by seabirds breeding at South Georgia (Croxall and Prince, 1987).

Antarctic sealing began in the 1770s when fur and elephant seals were hunted on sub-Antarctic islands and in the area of the Antarctic Peninsula. The USA, the United Kingdom, Russia and France dominated the industry. Over one million seals were slaughtered on South Georgia alone between 1820 and 1822, and by 1830 fur seals in the area were nearly extinct, elephant seals were rare, and sealing had ceased. By 1870, seal numbers had recovered enough for sealing to resume, but populations tolerated the industry only briefly before again declining to numbers insufficient for profitable business. A similar rise and fall occurred around 1910 in the South Georgia area. The seal industry was then quiet until the USSR and Japan, in particular, resumed sealing in the early 1970s, and this return to sealing triggered international concern that led to the development of a convention. The absence of human predation has since allowed seal numbers to regenerate. Estimates of fur seals on South Georgia, for instance, grew from 100 in the 1930s to 150 000 by 1957, and 350 000 by 1976. The reduction of whale populations and resultant increase in krill numbers may also have contributed to the recent increase in seal numbers.

In the past, whales represented Antarctica's main economic resource. Antarctic waters constituted the world's major whaling grounds between 1922/1976. Indeed, the Southern Ocean sometimes produced ten times as much whale oil as the rest of the world's ocean combined until the industry collapsed in the 1960s due to diminished stocks.

Whaling in Antarctica began in 1904, with one catching device at a Norwegian station in Cumberland Bay, South Georgia. One hundred and ninety-five whales were harvested that year, the region was considered rich with whales, and the industry immediately grew. By 1912, six on-land stations, 21 floating factory ships and 62 catchers were operational, and 10700 whales were processed during the 1912/1913 season, of which most were blues, fins and humpbacks. All the whaling of the period was carried out in the South Georgia, South Orkney and Deception Island regions. Although now maritime Antarctica, these islands were then Faukland Island dependencies under British rule. During the 1930s, Japan and Germany, in addition to Norway and Britain, actively participated in Antarctic whaling. The hunting region grew to embrace the Weddell and Ross Seas and all the area in between. The 41 floating factories, six on-land stations and 205 catchers then operational reaped 40000 whales during the 1930/1931 season. To regulate the industry's development, the International Whaling Commission (IWC) was established in 1932.

The boom in whaling led to a market surplus of whale oil, and the industry relaxed in response in the mid-1930s to allow the market to stabilize. Shortly thereafter, the market picked up, only to dramatically subside during the World War II years of 1941—1945. The 1950s enabled the industry to resume, and Holland, South Africa and the USA became involved, but this was the end of the whaling era. In the 1969/1970 and 1979/1980 seasons, whale factory ships were decreased to six and three respectively (Sugden, 1982).

Established in 1976, the Biological Investigation of Marine Antarctic Systems and Stocks (BIOMASS) serves as an international cooperative research body to provide scientific information concerning the region's marine life and supply vital data used to determine harvest limits of Antarctic living resources. The World Conservation Union (IUCN), in particular, leads research efforts and data collection relating to the developing krill fishery and Southern Ocean ecosystem as a whole. Such work will hopefully provide the information needed to ensure the maintenance of ecological relationships between and among harvested, dependent and related populations, and the restoration of depleted populations. In addition, the IWC and the Convention on the Conservation of Antarctic Seals (CCAS) protect all seals and whales in the waters south of 60°S latitude, and require that catches in areas of floating sea ice north of 60°S be reported.

DISCUSSION

Since the IGY, many nations have worked together to understand the dynamics of the Antarctic region, including its ecology and fisheries. The region is essential in terms of global paleoclimatology, meteorology, climatology and biogeochemistry. Conducting field programs requires difficult logistics (USNSF, 1997). Even so, we have done much to understand the region collectively.

Two prominent field programs, the Joint Global Ocean Flux Study (JGOFS) and Global Ocean Ecosystem Dynamics (GLOBEC), are taking place in the Antarctic region now, in addition to other activities, such as the Palmer Long Term Ecological Research (LTER) program. All provide important data and information sets that will help in understanding the nature and dynamics of the region as well as in improving modeling, and both hind- and forecasting. Due to present global economic constraints, assembling these resources of Antarctic science advancement may not be easy. For instance, USNSF (1997) issued its report of the U.S. Antarctic Program External Panel and noted twelve specific recommendations to balance geopolitical importance, personal safety, needed cost-cutting actions, enhancement of joint research projects with other nations, and upholding cutting-edge, scientific research with important human consequences.

Insofar as the rational exploitation of Antarctic living marine resources is concerned, the cautious, sustainable resource utilization advocated by CCAMLR, BIOMASS, IWC, CCAS and others should preserve the viability of the Antarctic ecosystem. Apart from the import and export of organic matter from and to other regions of the globe and the sediment underneath, the overall biological productivity and consumption of the Antarctic ecosystem must be understood adequately for humanity to engage in rational, sustainable fisheries.

Krill's central role in foraging various primary producers, and as the most dominant, concentrated prey in the Antarctic ecosystem, is the subject of continuing study. It is a strong swimmer and its distribution encircles the Antarctic Peninsula. Krill, 1 g, swarming is capitalized by whales, 108 g, as well as other lighter predators. Hypothetical annual cycles of krill include foraging for food in the open water, and congregating under the ice for protection. Krill is an outstanding product of a long evolutionary process in light and under ice cover, often living six or seven years, and its eggs hatch at a safe depth of 2000 m.

As the millennium year of 1999/2000 approaches, several member nations of CCAMLR plan to investigate the distribution and biomass of krill in the Atlantic sector of the Southern Ocean. At the same time, the GLOBEC program will organize multi-national research activities to elucidate the over-wintering survival strategies of krill. These timely international research coordination should be encouraged. In the future, a functional coupling of modeling and field observation is essential to advance our understanding of Antarctic ecosystems. Even with limited data sets, we must continue to improve our climatic change prediction and attendant ecosystem and fisheries management.

Estimated secondary production of krill in the Southern Ocean is of the order of 6.4×109 wet metric tons a year. Estimated krill biomass is about $2—6 \times 108$ metric tons. Clark (1983) reports that the Southern Ocean contains much squid, of which seabirds, seals and whales consume some 34 million metric tons a year. A fisheries exploitation question we hypothetically raise here is how much krill and squid can be utilized sustainably by humanity? Since some whales consume krill directly, this too enters into the overall fisheries exploitation scheme, whether or not any whaling will be permitted.

We advocate a holistic, total ecosystem approach to set an upper limit for future fish harvests in Antarctic waters. With the advent of the profitable aquaculture of salmon, bluefin tuna, squid and shrimp, some nations may eye krill to enhance the needed aquaculture feed production. We need to learn the life cycle of the Antarctic food web to recognize intelligently the overall impact brought forth by a single species fisheries. Ecosystem modeling, when properly developed, can contribute significantly to this goal.

Finally, we wish our readers to consider that we not only have inherited Earth the beautiful from our ancestors, but also have borrowed Earth from our progeny. We encourage all of us to uphold this planet gently which care, and pass that legacy to the generation following. Antarctic studies can be a vehicle to encourage students all over the world to see that the importance of taking an interdisciplinary and networking approach to understanding, conserving and nurturing the Antarctic ecosystem is to keep Earth alive and hopeful. We applaud the student participants of the Antarctic Marine Ecology and Policy course taught at some U.S. universities starting in 1982 (Berkman, 1997), where each student becomes an ambassador to an Antarctic Treaty nation (Table 1), and recommends a practical and clearly defined solution to mitigate a specific human impact in the Antarctic marine ecosystem.

Earth, including the Antarctic ecosystem, is a complex system with interacting phenomena, requiring natural and social sciences, especially in the context of resource management (Berkman, 1997).

ACKNOWLEDGEMENTS

We thank Ms. Sukyung Kang and Mrs. Jane Keller for their editorial assitance. Two of the U.S. authors (HJS and PKP) drafted in 1988 an unpublished manuscript entitled "UNEP and Antarctica" while serving with the United Nations Environment Program in Nairobi, Kenya. The present report has evolved from the original writing. We will be delighted to send you the original writing upon request (please address to PKP).

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Manuscript received April 19, 1998
Revision accepted May 30, 1998