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**Workshop to Identify Significant Uncertainties Concerning
the Effects of Climate Change and the Antarctic Toothfish Fishery
on the Ross Sea Marine Ecosystem,
27-30 March 2012, La Jolla CA**



Photo: J Meirs

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Contents:

I. Executive Summary	3
II. Purpose and background of the workshop	8
• Location & dates	8
• Expertise of participants	8
• Workshop goals	8
• Background	10
• Management context	12
III. Principal Workshop Findings, with respect to determining and monitoring the structure and function of the Ross Sea ecosystem	13
• Physics	14
• Biology	16
• Fishery	18
IV. Questions considered by participants to apply workshop findings to the climate-fishery problem.	19
• How do we identify the nature and possible effects of climate change on key components of the Ross Sea Ecosystem over the next 10, 20, and 50 years?	19
• What research and monitoring would be required to resolve critical uncertainties concerning the life history and demography of the Ross Sea toothfish population and its numerical and functional relationships with its principal predators and prey?	21
• What are the most significant uncertainties concerning the effects of the Ross Sea toothfish fishery on the target toothfish population and other components of the Ross Sea ecosystem, and what research, monitoring, or changes in the CCAMLR management procedures that would be required to resolve the uncertainties?	22
• What are the possible climate-related changes in the Ross Sea ecosystem that could require consideration and response by the CCAMLR Scientific Committee and Commission to meet the population and ecosystem objectives of the Convention?	25
• What additional research and monitoring and possible changes in management philosophy and procedures identified in the preceding discussions according to their relative importance for minimizing the risk that the combined effects of the fishery and climate change will lead to population or ecosystem effects inconsistent with the objectives of the Convention?	28
V. Summary, Conclusions and Recommended Actions	29

VI. Appendices	34
1. Participants	35
2. Agenda	36
3. Abstracts	
4. References and papers tabled prior to workshop	38
5. Non-exclusive list of possible hypotheses to guide management of the Ross Sea region	48
6. Ross Sea/McMurdo Sound LTER workshop final report	50

CURRENT “SPATIAL CONSERVATION MANAGEMENT” IN THE ROSS SEA REGION

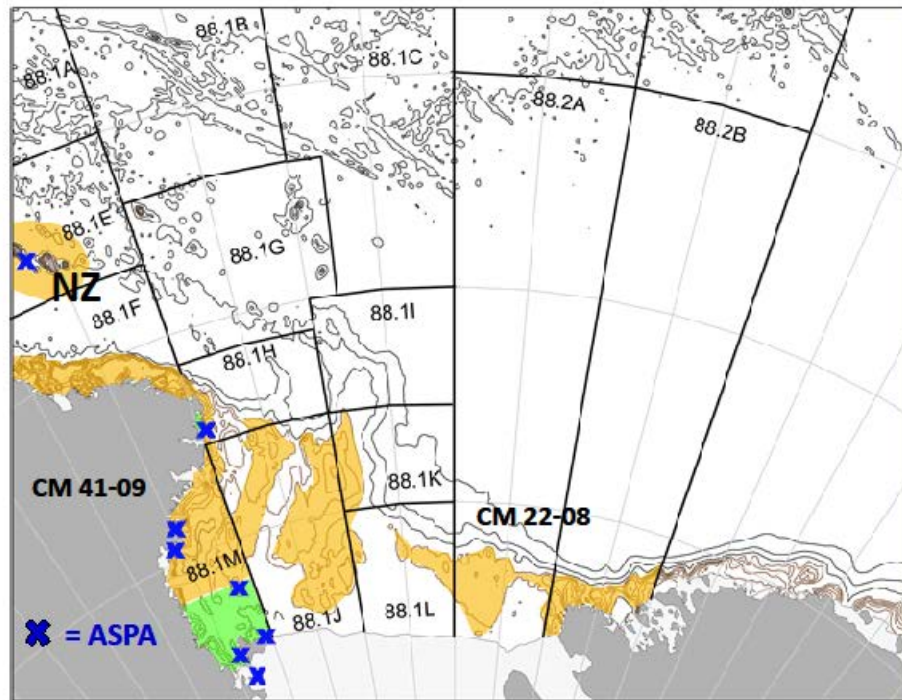


Figure 1. Ross Sea Region, from 157°E to 150°W, demarcated by Small-Scale Research Units (SSRUs) of statistical areas 88.1 and 88.2. SSRUs separate an exploratory fishery into spatial “research” units; catch statistics and characteristics are collected and reported for each separately. Currently imposed Antarctic Specially Protected Areas (ASPA) that have a marine component and Conservation Measures are shown: CM 41-09, no fishing in SSRU 88.1M; CM 22-08, no long lines to be deployed in waters anywhere in the CCAMLR area that are shallower than 550m; and NZ, New Zealand fishing vessels are not allowed, by their government, to fish within 50nm of the Balleny Islands. Green designates areas where commercial hunting of seals is prohibited by the Antarctic Seals Convention.

I. Executive Summary

The Scientific Committee and Commission established by the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR) are responsible for ensuring that harvesting of marine living resources, and associated activities, in the Convention Area are conducted in compliance with the objectives set forth in Article II of the Convention – i.e., to ensure that harvesting and associated activities do not cause target, dependent or associated species and populations to be reduced below their maximum recruitment levels and prevent related ecosystem changes that cannot be reversed in 20 to 30 years. It is apparent that climate change is affecting the physical, chemical, and biological components of Antarctic marine ecosystems, including the Ross Sea, and in the future will have even greater effects. It follows, therefore, that to meet the objectives of the Convention, the management advice provided by the Scientific Committee and the Conservation Measures adopted by the Commission must take into account the uncertainties concerning the combined effects of harvesting and climate change on the target resources and related components of the affected ecosystems. Until these uncertainties are addressed and factored into the decision-making process, there can be no assurance that the management of the fishery is appropriately precautionary and consistent with the objectives of the Convention.

The Commission, acting on the advice of the Scientific Committee, has encouraged periodic fishery-independent surveys to monitor the distribution, abundance, and productivity of the Antarctic krill (*Euphausia superba*), and has instituted a CCAMLR Ecosystem Monitoring Program (CEMP) to detect the possible impacts of the krill fishery on the target krill resource and krill-dependent species and populations. These measures and ongoing climate change studies by various nations, including the US AMLR (Antarctic Marine Living Research) and LTER (Long-term Ecological Research) programs, should enable the Scientific Committee to provide management advice to the Commission that reflects the combined effects of climate change and the krill fishery on the krill resource and dependent and associated species. To date, however, comparable steps have not been taken for the Ross Sea ecosystem, which is being affected collectively by climate change and the fishery for Antarctic toothfish (*Dissostichus mawsoni*). While the Commission, in consultation with the Scientific Committee, is considering establishment of marine protected areas (MPAs) to conserve biological diversity and ecosystem processes in the Convention Area, it is not clear what consideration is being given to how this network would contribute to meeting the objectives of the Convention. In this regard, both the United States and New Zealand tabled, for preliminary discussion at last year's CCAMLR meetings, concept papers regarding the establishment of MPAs in the Ross Sea region (Figure 1) [1,2]. Neither concept paper provided an indication of the management, research and monitoring programs needed to ensure that the MPAs would contribute to meeting the conservation objectives of the Convention.

The La Jolla workshop was held to further the establishment and development of a management and monitoring plan for a Ross Sea MPA by identifying the research and monitoring needed to resolve uncertainties concerning the effects of the toothfish fishery and climate change on key components of the Ross Sea ecosystem.

The principal workshop findings with respect to the fishery-climate interaction problem follow:

1. Climate change is having dramatic but essentially opposite effects on the components of the marine ecosystems in the Antarctic Peninsula and Ross Sea regions. In the Peninsula region air and upper water temperatures are increasing rapidly and seasonal sea ice duration and extent are decreasing. Conversely, in the Ross Sea region air and ocean temperatures have declined, including both sea surface temperature and intrusions of Modified Circumpolar Deep Water, and the average sea ice extent and sea ice season have increased, respectively, by about 10% and about 80 days since 1979. Most sea ice variability in the Ross Sea is due to delayed ice break-up and retreat in spring;
2. A large body of research indicates that Ross Sea primary and secondary productivity as well as upper trophic level organisms, including predators and prey of toothfish, are responding to interannual and decadal climate variation in their environment. In fact, relationships of predator population variations to sea ice and climate variability are among the best known in the Ross Sea of all regions in the Southern Ocean.
3. Until the nature and extent of longer-term effects can reasonably be identified, it will be impossible to verify that current management is precautionary and to determine the actions required to ensure that the fishery and its associated activities are not causing or contributing to ecosystem effects contrary to the objectives of the Convention;
4. The Antarctic toothfish is considered a key predator, and in some cases prey — therefore a “mesopredator” --- in the high latitude, shelf and slope habitat of the Southern Ocean. Significant uncertainties exist concerning the life history and the current and pre-fishery distribution, abundance and productivity of the Ross Sea toothfish population. As examples, working hypotheses about phenology and location of spawning are based on the timing and catch locations of two gravid females and the timing and locations of catches of pre-spawning mature fish with developing gonads. It is known that spawning of individual fish does not occur annually, but what factors determine a fish’s reproductive effort in a given year are unknown. Its recruitment potential is unknown. Little is known about the survival of eggs, the distribution and growth of larval and juvenile fish, the predators of eggs, the predators and prey of larval and juvenile fish, and the extent to which larvae are transported away from the Ross Sea region;
5. There also are significant uncertainties concerning the data and models being used by the Scientific Committee to determine and provide advice to the Commission regarding allowable catches of toothfish in the Ross Sea region. For example, the allowable catch determinations are based on the single-species concept of maximum sustainable yield

(MSY), with no apparent consideration given to the possible effects of stock decrease on non-target populations of toothfish predators, prey, and bycatch species as mandated by Article II of the Convention.

The validity of assumptions inherent in the procedures and models being used to estimate allowable catch levels is of concern. Examples are the assumptions that (i) a 50% reduction in the toothfish spawning biomass over 35 years (starting in 1997) will result in a sustainable fishery and will have no unacceptable effects on dependent or associated species; (ii) estimates derived from catch, effort, and tag recovery data provide reliable indicators of both the pre-fishery spawning biomass and its subsequent fishery-caused reductions; (iii) spawning is annual, which evidence indicates is not the case; and (iv) there is no difference in fecundity as a function of age/size of fish. Further, it is uncertain whether the Scientific Committee is advising the Commission of the assumptions inherent in its management advice or the consequences if the assumptions are invalid;

6. No fishery-independent surveys or experiments are being conducted to validate the assumptions concerning the distribution, abundance, and natural mortality of the various life stages of the Ross Sea toothfish population. While isolated surveys have been done (e.g. Vulnerable Marine Ecosystem species, “Year of the skate”), no programs have been established to monitor toothfish predators, prey, and associated species that could be affected by harvest-related and climate-related effects on the various life history stages;
7. Although measures have been initiated to limit the local effects of the long line toothfish fishery on bycatch species and benthic communities, it is uncertain whether these measures are sufficient to ensure that the effects are consistent with the population and ecosystem conservation objectives set forth in Article II of the Convention;
8. The Antarctic silverfish is the principal forage fish in the Ross Sea shelf ecosystem. It is the principal prey of mature toothfish inhabiting surface waters of the shelf, and a key component of the diets of Weddell seals, Emperor and Adélie penguins, and several species of flying birds. It also potentially contributes significantly to the diet of minke whales and killer whales. The life history, demography and dynamics of this species are not known sufficiently to do more than speculate about changes that may be occurring due to climate change or declining toothfish predation due to the fishery-caused decline in the larger toothfish;
9. Formulating robust hypotheses about what may be expected in the next 10-20 years will be critical to devising the research and monitoring programs necessary to determine how the fishery should be managed, in response to the population and ecosystem effects of climate change, to comply with the objectives of the Convention. In this regard, the climatology of phytoplankton biomass and processes contributing to the long-term patterns in the Ross Sea are among the best known in the Southern Ocean, although much work remains to quantify the fate of different phytoplankton species in the food web. In addition, long term data sets and ongoing population studies of Weddell seals and Adélie and Emperor

penguins in areas along the southern Victoria Land coast, including McMurdo Sound, can contribute to the development of an ecosystem monitoring program in the Ross Sea. Lacking are the silverfish and krill process studies that would link these trophic levels to both lower and higher trophic levels.

10. Satellite tracking instrumentation has provided information on the seasonal movements and preferred feeding areas of high trophic level organisms, such as penguins, seals and killer whales. Continued and expanded work using these technologies is certain to provide more useful information on production hotspots and other habitat factors, as well as foraging effort. Direct observations, scat analyses, stomach and biochemical samples have in the past and can in the future provide information concerning seasonal and annual changes in diet. Recent development of satellite imagery can cost-effectively monitor the distributions and abundance of seal and penguin colonies throughout the coastal areas of the Ross Sea, and possibly could provide a cost-effective means for detecting IUU fishing.

Ideally, portions of the Ross Sea Region and adjacent areas thought to contain critical habitats for the different life stages of the regional toothfish population should be designated a no-take MPA in accordance with Article IX(2)(g) of the Convention to protect its unique ecological and scientific value and enable assessment of the ecological effects of climate change without the need to differentiate those effects from the effects of the fishery. Alternatively, the Ross Sea toothfish fishery should be suspended pending completion of the following actions to resolve the aforementioned unknowns and uncertainties:

- The decision rules, data and model(s) being used by the Scientific Committee to estimate and provide advice to the Commission regarding the allowable catches of toothfish and their effects on other components of the Ross Sea ecosystem should be reviewed by an independent group of modelers, ecologists and fishery scientists (e.g. the National Marine Fishery Service's Center for Independent Experts) to determine if the resulting advice is consistent with the objectives of the Convention, and if not to identify additional data or changes in the assessment methods needed to ensure compliance with the Article II CCAMLR objectives;
- A working model of the Ross Sea food web, incorporating the best available data and both precautionary as well as conservative hypotheses concerning the numerical and functional relationships between the key biological components of the regional ecosystem should be developed and used to help determine the research and monitoring needed to resolve the uncertainties concerning the combined effects of climate change and the toothfish fishery on the structure and dynamics of the food web. The model should reflect the uncertainties concerning the relationships among the key system components and be updated as the uncertainties are resolved;
- A prescriptive research fishery should be designed and implemented to resolve critical uncertainties concerning the life history, distribution, abundance and movements of the different life stages of the regional toothfish population;

- An ecosystem monitoring program, comparable in scope and context to the ongoing CCAMLR ecosystem monitoring program (CEMP) regarding the Antarctic krill fishery, should be designed and initiated to detect and distinguish the population and ecosystem effects of climate change from toothfish fishery effects in the Ross Sea region (the U.S. Palmer Station LTER Program in the Peninsula area provides a useful conceptual model of what is needed); and
- An assessment should be undertaken to determine the adequacy of measures that have been taken to limit the impacts of the toothfish fishery on bycatch species and benthic communities, and ensure that any damage to benthic communities are reversible in 20-30 years.

Although not ideal, development and adoption of an MPA, incorporating the features of the concept MPA tabled by the U.S. for preliminary consideration at last year's CCAMLR meetings, could provide means for both (i) minimizing the risk that the fishery will have population or ecosystem effects contrary to the objectives of the Convention, and (ii) differentiating the ecosystem effects of the fishery from the ecosystem effects of climate change. The critical elements in this regard are (1) the inclusion in the protected area of the sea mounts where spawning is believed to occur, and (2) the likelihood that establishment and comparison of monitoring results from a control area and an area where prescriptive research fishing is conducted would in fact provide the basis for differentiating the effects of the fishery from those of climate change (examples of possible hypotheses to guide this effort are given in Appendix 5). Long-term data sets from past and continuing oceanographic and climate studies in the Ross Sea and long-term studies of seals, penguins, toothfish, and benthic communities in McMurdo Sound and other parts of the Ross Sea provide much of the essential baselines needed for the development of the research and monitoring program that would be required to meet the objectives of the U.S. concept MPA.

II. Purpose and Background of the Workshop

The workshop was held at the U.S. National Marine Fisheries Service's Southwest Fisheries and Science Center in La Jolla, California, on 27-30 March 2012 (Appendix 1 is the agenda). Participants were scientists with relevant expertise in the Ross Sea (Appendix 2). The workshop was funded by the National Science Foundation and the Marine Mammal Commission, with in-kind support provided by the National Marine Fisheries Service. This report did not receive public input and does not necessarily reflect the views of the sponsoring agencies, and therefore it is not a "consensus" report.

Workshop Goals

The primary purpose of the workshop was to further the MPA designation of the Ross Sea by identifying significant threats and uncertainties concerning the effects of fisheries and climate change on the Ross Sea ecosystem, and the research and monitoring required to resolve them. In

the provisional “MPA scenario” that the U.S. tabled at the CCAMLR Scientific Committee meetings in late 2011 [1] (see Figures 2, 3), the following were the stated goals:

1. to conserve ecological structure and function at all levels of biological organization by prohibiting fishing in habitats that are important to mammals, birds, fishes, and invertebrates throughout the Ross Sea region;
2. to maintain a reference area in which there is no fishing to better gauge the ecosystem effects of climate change; and
3. to promote research and other scientific activities focused on marine living resources.

The U.S. “MPA scenario” was proposed to fulfill these goals and to seek support from CCAMLR Members with vessels fishing in the region by including only a small part of the current fishing grounds in the concept MPA. The area left open to fishing covers the central portion of the fishing ground (Figure 2). The reason for closing part of the current fishing grounds was to protect the presumed spawning area and provide two areas in which studies could compare effects of fishing and non-fishing where fishing previously had shown that commercially viable portions of the Antarctic toothfish stock resided (Figure 3).

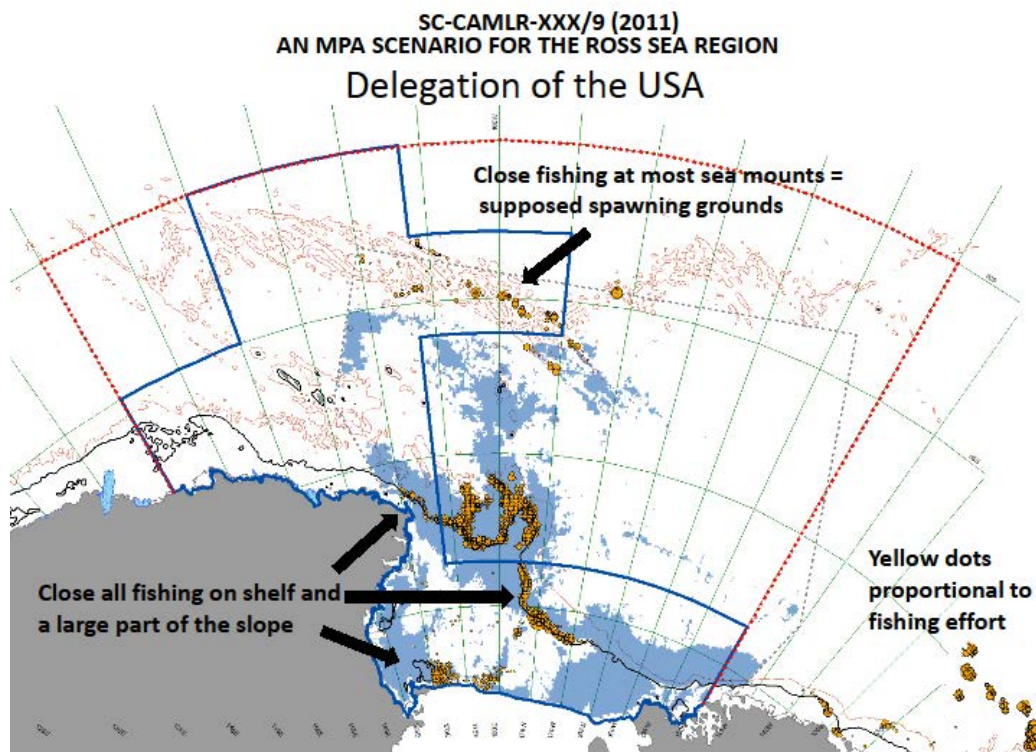


Figure 2. The “MPA scenario” proposed to the CCAMLR Scientific Committee by the U.S.A. in December 2011 [2]. Red dotted line indicates Ross Sea Region (see also Fig. 1). Yellow dots, by size, proportionately indicate where fishing for toothfish thus far has been concentrated. Boundaries were proposed as a means to compare fished with no-longer-fished areas as a means to separate climate from fishery effects in order that the fishery does not compromise CCAMLR’s founding objectives for management. Shaded blue represent areas important to marine birds and mammals as identified at workshop in April 2011 that preceded the US December 2011 proposal.

A secondary goal of the workshop was to identify the existing long-term Ross Sea biological data sets, and the results from climatological and ocean process studies in the Ross Sea, to determine how they could be used as baselines for research and monitoring to achieve a more complete understanding of, and to detect future changes in, the structure and dynamics of the Ross Sea food web (the applicable data sets are described below.)



Figure 3. The possible Marine Protected Area suggested by the U.S.A. to the CCAMLR Scientific Committee and Commission in December 2011, in a view indicating a possible scenario whereby climate and fishery effects might be experimentally separated. Treatment = fishing allowed; control = protected, commercial fishing no longer allowed.

Background

At last year's CCAMLR meetings the U.S. Delegation submitted a preliminary discussion document indicating part of the Ross Sea region that could be designated a marine protected area [1, 2], recognizing that the Ross Sea is the least anthropogenically altered ocean area on Earth [3] and a biodiversity hotspot [4, 5, 6]. Both before and since then, a number of non-governmental organizations and scientists have been advocating designation of the entire Ross Sea a no-take MPA, in some cases to include the area as far north as 60°S, ostensibly to protect the area's regionally apportioned unique characteristics and scientific values. Unlike other parts of the world ocean, including northern parts of the Southern Ocean, the Ross Sea shelf and slope have no widespread chemical pollution, no alien species, no plastic pollution, no anoxic dead zones, no Harmful Algal Blooms (HABs), no heavy ship traffic, and no minerals development. It has no legacy of lost/depleted species, other than blue whales, which in their historic habitat along the slope apparently have been replaced by minke whales. Blue whales, severely depleted in the 1920s, are slowly recovering. The biomass of upper trophic level organisms is exceptional: for example, 38% of the world's Adélie penguins and 26% of the world's emperor penguins occur

there [4, 5]. Through its Conservation Measures, CCAMLR recently prohibited long lining where depths are <550m and in waters west of 170°E in the Ross Sea (coastal waters off Victoria Land). Therefore, about two-thirds of the Ross Sea shelf is currently off limits to long lining.

The Ross Sea has been a marine science hotspot [6]. The juxtaposition of McMurdo Station, the largest logistic hub in the Antarctic, and the frequent work conducted by the U.S. research icebreaker, the *RVIB Nathaniel B. Palmer*, and earlier work from *USNS Eltanin* and U.S. Coast Guard icebreakers, make the Ross Sea one of the best studied ocean and surrounding coastal area in the Antarctic. In addition, work at the Italian and New Zealand research bases and from associated research and supply vessels has significantly contributed to the understanding of the Ross Sea.

The Ross Sea has been a primary setting for discerning the interaction of biological systems with decadal Southern Annular Mode (SAM) and shorter-term climate signals, such as the El Niño-Southern Oscillation (ENSO), as well as longer-term effects of global climate change. Biological and environmental data sets from the McMurdo Sound region are temporally longer than anywhere else in the Southern Ocean: 1) Adélie penguin population change, 1959-2011; Weddell seal population change and demography, 1960-2011; toothfish CPUE, size and condition, 1972-2011; benthic community composition, mid-1960s –2011; and hydrography, 1959-2011. There also are satellite remote sensing sea ice and meteorological data sets comparable to anywhere else in the Antarctic and dating back to the start of the scientific satellite era in 1979. The Automatic Weather Station system covers well the Victoria Land region. Further, research has been and is being conducted to assess climate relative to geologic time scales through ongoing marine and glacial coring.

The Ross Sea is particularly important in Southern Ocean climate dynamics, being one node of the climate oscillation that varies in opposition to that of the Antarctic Peninsula [7]. In both regions the prospective changes in their environment recently have been modeled through the next 90 years [8]. Relative to the intensive multinational bio-climate research occurring in the Peninsula, of which the U.S. Long Term Ecological Research (LTER) program at Palmer Station [e.g. 9] and the Antarctic Marine Living Research (AMLR) program on King George Island [10] are parts, the Ross Sea offers compelling contrasts: temperatures have changed relatively little, southerly winds are increasing, and sea ice extent and season have been increasing in a way essentially the opposite of what has been occurring in the Peninsula region.

An exploratory industrial fishery targeting Antarctic toothfish (*Dissostichus mawsoni*), an important mesopredator, began in the Ross Sea in 1996-97, with management subsequently directed toward reducing the spawning biomass by 50% over the next 25 years. Although this strategy is viewed by CCAMLR to be “precautionary” [14], it is unlikely, based on experience in other systems with large predatory fish, that fishing has been or will be ecologically neutral.

Food web alteration is already apparent after just 15 years of fishing [11, see also Biology, #5, below]. Formulating robust hypotheses about what may be expected in the next 10-20 years will be critical to devising the research and monitoring programs necessary to determine how the fishery should be managed, in response to the population and ecosystem effects of climate change, to comply with the objectives of the Convention.

Management Context

The basic objectives of the 1981 Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) are to ensure that fisheries and associated activities (i) do not cause target, dependent, or associated species and populations of marine biota in the Convention Area to be reduced or maintained below their maximum net productivity levels, or (ii) cause changes to the ecosystems of which those species and populations are component parts that are not reversible in 20 to 30 years [12]. The Scientific Committee and Commission established by the Convention are responsible, respectively, for identifying and for promulgating measures necessary to meet these objectives. Climate change is affecting weather patterns, sea ice, and water temperatures in the Southern Ocean and adjacent areas in ways that either are affecting or may affect the numerical and functional relationships among target fishery resources and dependent and associated species and populations. Thus, the Commission, in consultation with the Scientific Committee, must determine (i) how climate change may be affecting and in the foreseeable future could affect fishery resources and their interactions with other components of Southern Ocean ecosystems, and (ii) how fishery management and related research and monitoring programs in the Convention Area need to be revised, in light of climate change, to ensure that the fisheries and associated activities do not have population or ecosystem effects contrary to the CCAMLR objectives.

The Commission and Scientific Committee currently are engaged in a process aimed at establishing by 2012 a network of marine protected areas (MPAs) to protect biodiversity and ecosystem processes in the CCAMLR Area. The United States and New Zealand both advocate establishment of an MPA in the Ross Sea region, and each has developed and made public preliminary planning documents [1, 2] for consideration by the Commission and Scientific Committee. Among other things, a related policy statement from the U.S. [2] called for consultations with knowledgeable scientists and development, by the second half of 2012, of a draft research and management plan for a Ross Sea MPA.

III. Principal Workshop Findings, with respect to determining and monitoring the structure and function of the Ross Sea ecosystem

The Ross Sea overlies the broadest continental shelf (Figure 4) and is the most productive region of the Southern Ocean (Arrigo, Smith: workshop presentations). Its circulation is complex, and is tied to bathymetry, the intrusion of Circumpolar Deep Water in troughs along the shelf break, the Ross Gyre to the north, and intrusions of water from the along-slope current from the east (Figure 4; Dinniman: workshop presentation). The Ross Sea is home to an impressive fish fauna (Eastman: workshop presentation) and top trophic species (Ballard, Pitman: workshop presentations). The latter are dependent upon just a few fish and krill prey species (Eastman, Reiss: workshop presentations). The benthic communities are rich and varied as a function of substrate and food influx mediated by currents (Barry, Dayton, Kim: workshop presentations). The logistics capabilities available for the past 50 years have supported several of the longest time series of biological and environmental data in the Southern Ocean, and the feasibility of expanding those data sets using modern technology is substantial (La Rue, Ackley: workshop presentations). For example, recoverable bottom moorings, satellite-linked buoys, ocean gliders, satellite imaging, acoustic tracking and monitoring, and satellite linked tracking can provide cost-effective means for expanding collection of biological and environmental data needed for effective ecosystem conservation.

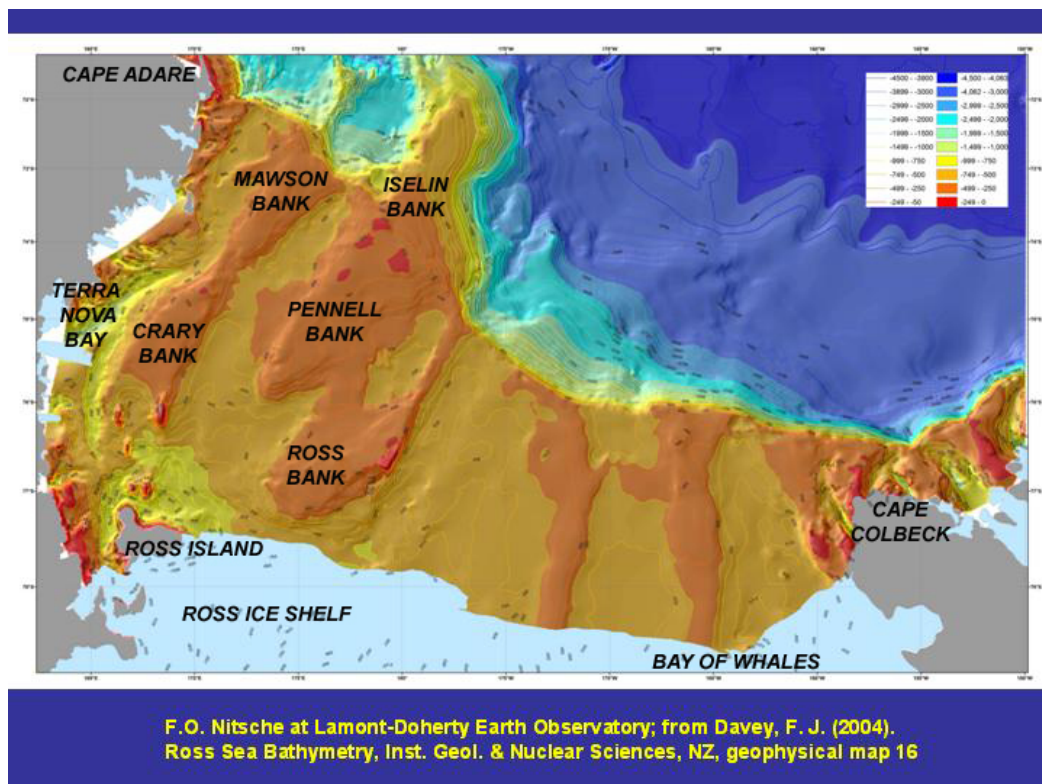


Figure 4. The Ross Sea, including its shelf and slope, showing the important banks and intervening troughs and basins [6].

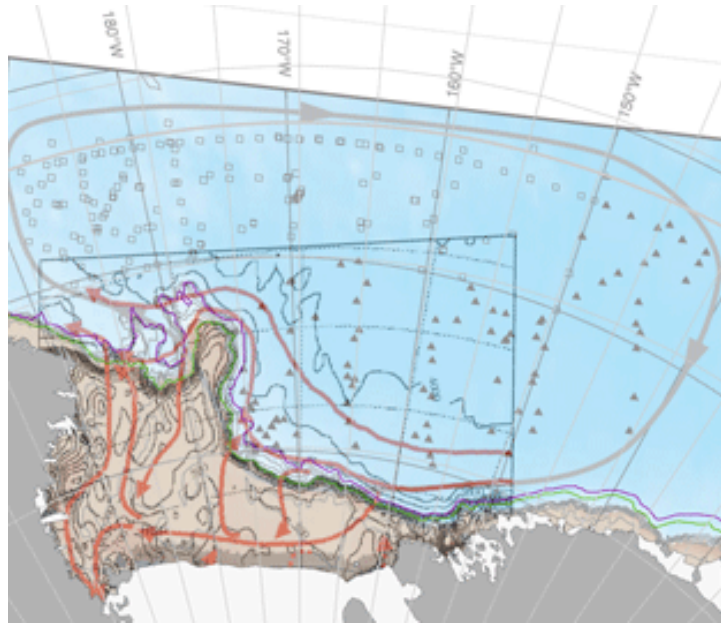


Figure 5. Circulation over the Ross Sea shelf, with complementary circulation of the Ross Gyre to the north (from Ainley et al. 2011 [6], and references therein).

Abundant evidence indicates that climate change is dramatically affecting polar systems, and in the next 10-20 years will have even more pronounced effects on seasonal weather, sea ice patterns and ocean circulation in the Ross Sea (Stammerjohn, Russell: workshop presentations). These changes, as well as toothfish removals, likely have affected and will continue to affect the numerical and functional relationships between the Antarctic toothfish, their predators and prey, and related biological components of the Ross Sea ecosystem. Ocean acidification due to increasing CO₂ could become important as well by disrupting the life cycle of pteropods, an important herbivore of the region (Barry: workshop presentation).

Information from Abstracts (Appendix III) and Presentations (which can be found at — <http://data.prbo.org/apps/RossSea/>):

Physics

1. Circumpolar Deep Water (CDW) is the parent water mass for all waters found over the Ross Sea shelf, and circulation is largely controlled by wind and bathymetry --- i.e. the troughs and shallow banks (cf. Figures 4, 5) create and restrict flow on the shelf. Linked to shelf circulation is that of the Ross Gyre, the lower portion of which runs westward along the Ross Sea slope (Figures 5, 6).
2. Atmospheric CO₂ is increasing rapidly, and the Antarctic Ozone Hole (AOH) is not dissipating because the stratosphere continues to cool, deepening the pressure differential and enhancing the polar vortex. Owing to the AOH, facilitated by mid-latitude warming, the ACC, lying immediately north of the Ross Gyre, is accelerating in response to the intensifying polar vortex. Increasing surface and katabatic winds lead to increased sea ice formation. These trends are expected to continue, resulting in greater seasonal variations: colder winters and warmer summers, more ice in winter and less in summer. Furthermore, the CDW is warming, and the stronger westerlies that are accelerating the ACC could be forcing a stronger Ross Gyre circulation (including along the shelf break). Hence, although water temperatures over

the Ross Sea shelf have not been increasing, heat input onto the shelf is expected to increase. Other changes in circulation have been occurring and are expected to intensify in the future as well (Figure 6).

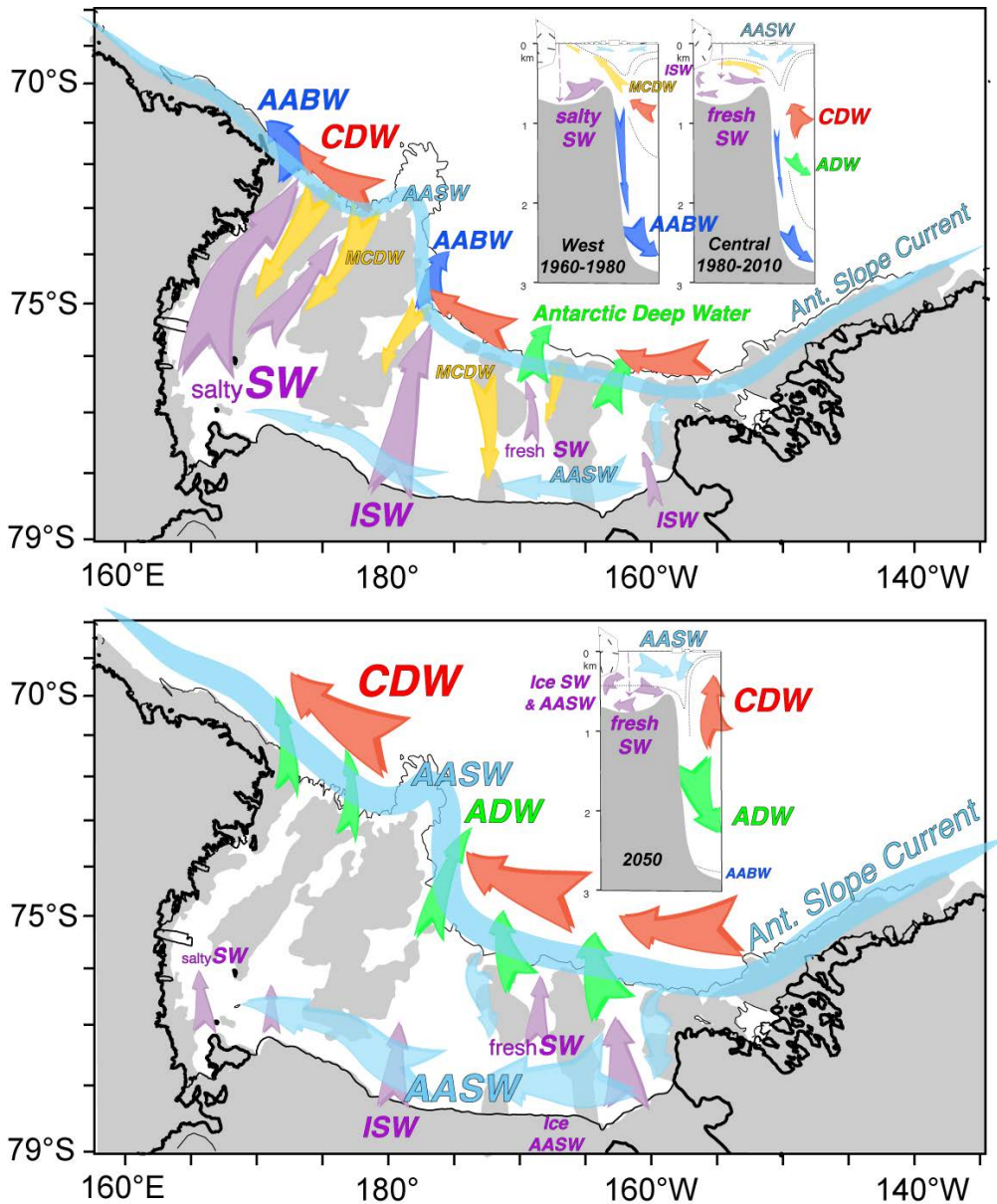


Figure 6. Potential changes in Ross Sea circulation and stratification. The upper panel illustrates the conditions observed during the past fifty years; the lower panel shows potential intensification of flow and air-sea-ice interactions leading to an alternative mode of deep ocean ventilation during the next century. Width of the arrows indicates the relative strength of each flow, and color represents individual water masses: AASW (light blue), SW (purple), MCDW (orange) and CDW (red), new Antarctic Deep (green) and Bottom (dark blue) Waters. Figure from Smith et al. in press (Ross Sea in a sea of change; J Oceanography).

3. The change in sea ice extent and persistence in the Ross Sea is among the most extensive on Earth. It is the only large area where sea ice extent and concentration are increasing. Since 1979, the ice season has increased ~80 days, with most variability coming from the timing of the spring sea ice retreat. Currently in waters over the shelf and slope, the sea ice season

averages about 300 days. At the same time average sea ice extent has expanded almost 10%, or 1.1% per decade. Such changes are in the opposite direction from those in the Antarctic Peninsula region and have implications for food web dynamics among the cryophilic species of the Ross Sea.

4. Ocean acidification (OA) due to increasing CO₂ levels will also probably affect the Ross Sea food web, where pteropods are an ecologically important organism. While organisms may partially adapt to OA, alterations in food web processes due to unpredictable effects of OA are possible.

Biology

5. Ross Sea seal and penguin populations, as well as toothfish, have responded to variability in sea ice extent and concentration at both the short- and decadal-scales. The ecological - food web links to the physical factors, however, remain obscure, due to limited research on zooplankton and forage fish. The upper trophic level populations also appear to have responded to extraction of competing species (e.g. penguins increased when whales and their consumption of common prey decreased in the 1970s; increased concentrations of seals can deplete toothfish as indicated by studies in the 1980s; and fish eating killer whales currently are disappearing from the southern Ross Sea possibly in response to the decline of large toothfish)
6. The exposure of surface waters to sunlight in the early spring, as polynyas form, can lead to high primary and secondary production. Several polynyas are present including the largest in the world. Variations of primary production in time and space are dramatic in the Ross Sea and are critical to understanding phytoplankton dynamics. Many/most of these variations are tied to physical forcing (currents, cloud cover, ice cover), but certain aspects are probably linked to biotic processes (herbivory). The importance of these variations on the food webs of the Ross Sea remain at best uncertain and can relate to phytoplankton species composition, in turn having effects on a diatom vs. *Phaeocystis*-dominated food web.
7. Marine bacterioplankton provide fundamental ecosystem services and are critical factors in biogeochemical cycles. Climate change shifts in water column stratification, carbon production, ocean temperature and sea ice cover may alter the responses of the microbial communities.
8. Although the benthic communities throughout the Ross Sea ecosystem depend on production in the surface, the distribution, abundance and composition of major faunal groups appear to be regulated most strongly by depth, seabed slope, substratum type, and local current speed, rather than the larger-scale pattern of productivity in surface waters. The communities, many of which have been mapped in the western Ross Sea by NZ and US surveys, therefore are a mosaic, with those along the shelf break and continental margins being particularly different and fragile. Growth and recovery is episodic and especially hard to predict.
9. The main forage species of the Ross Sea are limited in diversity. In the water column over the shelf there is just one fish, Antarctic silverfish (*Pleuragramma antarcticum*), and two krill species (Antarctic krill, *E. superba*, along shelf break and slope; crystal krill, *E. crystallorophias*, along the inner shelf). Myctophid fish are important over the slope. Nototheniid and macrourid fish, mysid shrimp and invertebrate larvae are important forage species in benthic habitats. The occurrence of Antarctic krill on the outer shelf is tied to intrusions of CDW in the troughs.

10. In the Ross Sea, notothenioids dominate fish species diversity (77%), abundance (92%) and biomass (91%) to a degree unparalleled by any group in any other marine ecosystem. The toothfish and silverfish are ancient, taxonomic 'sister groups' and are among the few Antarctic continental shelf fish that occur in the water column. The toothfish is a major Ross Sea predator and the latter is its principal prey over the shelf. Macrourids, found along the slope, constitute important toothfish forage there and are particularly vulnerable to bycatch mortality.
11. The life cycle of the Antarctic toothfish remains unclear. Previous studies indicate toothfish are long-lived (up to 50 years), slow-growing (<1 cm/yr after 1.4 m, with a maximum length of > 2 m), and late to mature (15-17 yrs depending on sex). Almost nothing is known about fecundity and more importantly recruitment potential. As well, nothing is known about Antarctic toothfish's role in the food web during their first several years. Important spawning areas may be the sea mounts of the western Pacific Antarctic Ridge (Figure 2). The Ross Gyre may be critical in toothfish movement, particularly dispersal of eggs, larval and juvenile fish. The 'axe handle' (tissue depleted) condition apparent among toothfish of both sexes caught at the northern seamounts is curious and possibly a post-spawning condition; nothing is known of the fate of these fish and, if a post-spawning condition, whether they recover to spawn again.
12. A 39-yr time series in McMurdo Sound indicates that after about 2000, toothfish catch, size and condition decreased markedly. Decrease in fish size is consistent with targeted removal of large fish by the long-line fishery, which is concentrated along the slope where the largest fish dwell (Figure 2). Decreases in McMurdo Sound CPUE coincided with the development of the commercial fishery.
13. The Ross Sea mesopredators (seals, penguins and flying birds), among the best known in the Antarctic, utilize the entire shelf and slope in a spatial mosaic that has seasonal as well as depth dimensions. In this way, an assemblage of upper trophic level species coexists despite a limited number of prey species. Adélie penguins, a CCAMLR indicator species, reside along the slope for as long as possible before winter darkness occurs. They then concentrate in the waters north of the western slope, where accelerated sea ice growth is evident and where polynyas exist around the Balleny Islands. The importance of this area to penguin winter foraging may be an indicator of importance for other species as well. The penguins then move throughout the Ross Gyre until arriving at coastal nesting sites the following spring.
14. Three forms of killer whales occur in the Ross Sea, two being mammal eaters and one a fish eater. Little is yet known about their seasonal movements. While some Ross Sea killer whales are known to eat toothfish, much needs to be learned about the large biomass of prey necessary to support these trophic relationships. Also, both sperm whales and colossal squid occur along the slope and are known to eat large toothfish, but their consumption of and dependence on toothfish in the Ross Sea are unknown.

Fishery

15. Knowledge of the life history and demographics of Antarctic toothfish is limited. As examples, it is not documented where, when, and how frequently spawning occurs, whether there is age (size)-dependent fecundity, where and how fertilization of eggs occur, and where juveniles <40 cm occur. Further, there essentially is no knowledge of the functional and numerical relationships between toothfish and their principal predators and prey, both now and prior to the initiation of the fishery.

16. The fishery is managed by CCAMLR under a single-species MSY strategy, assuming that there are no significant predators of Antarctic toothfish, with a goal of reducing pre-fished spawning biomass to 50% by 2025 (or 35 years from when the fishery began [14]). Pre-fished and current spawning biomass are not known, but are estimated from models and assumptions whose validity have not been confirmed with fishery-independent data. Current spawning biomass is estimated to be 80% of that prior to initiation of the fishery, based on modeling of non-random tag recovery data. Allowable catch is determined by the same unverified models and assumptions. Many of the inputs in the stock model are taken from warmer-water species. For example, in the absence of data regarding Antarctic toothfish recruitment, model input substitutes a recruitment potential averaged from several North Atlantic fish species. Sensitivity of model assumptions to climate change has not been assessed.

The 50% biomass reduction goal apparently is a feature of a general yield model endorsed by the Commission in the 1990s [14]. That model assumes that target reductions of 25% are appropriate for estimating “precautionary” catches of species, like Antarctic krill, known to be principal prey of several species of whales, seals, penguins, and other species, while target reductions of 50% are assumed appropriate for upper trophic level species, in the absence of conflicting data, not known to be preyed upon in significant quantities by other species. As noted elsewhere in this report, it is known that adult toothfish are eaten by Weddell seals, killer whales, sperm whales and colossal squid. Although apparently not considered in the decision-making process the eggs, larvae, and small size classes of toothfish no doubt are eaten by other fish, several species of birds, and other larger animals. The degree of dependence of these predators on toothfish has not been quantified. Consequently, the justification for assuming that there are no toothfish dependent predators is questionable at best.

17. It is not clear whether the CCAMLR Commission, the decision-making body, is fully aware of the assumptions inherent in the model(s) and procedures being used by the Scientific Committee to provide advice regarding allowable catch levels, or the potential consequences if the assumptions and resulting advice are not valid. It also is not clear whether there is consensus among all members of the Scientific Committee that the decision rules, data, models, and procedures being used to calculate allowable catch levels appropriately take into account the objectives of the Convention and, if not, whether dissenting views are being conveyed to the Commission in accordance with the Committee’s Rules of Procedure.

IV. Questions considered by workshop participants to apply workshop findings to the climate-fishery problem.

After considering the background papers and presentations, the workshop participants addressed the following topic areas and questions. For details, please refer to the Abstracts of talks (Appendix III) and the slide presentations (<http://data.prbo.org/apps/RossSea/>).

1. How do we identify the nature and possible effects of climate change on key components of the Ross Sea Ecosystem over the next 10, 20, and 50 years?

- What are the key physical, chemical and biological indicators of the Ross Sea ecosystem that could be affected in detectable ways by climate change?

- To what extent, including degree of confidence, might these key ecosystem components be affected by climate change over the next 10, 20, and 50 years?
- Why should these components be considered key indicators of the state of the ecosystem?
- What research and monitoring are ongoing to develop baselines and monitor these variables? Is ongoing research and monitoring capable of detecting significant climate change effects in time to take remedial action to mitigate those that might be altered, and if not, what changes in ongoing programs would be required to enable timely identification of deleterious effects?

Answers/conclusions

Physics:

The key physical indicators of the Ross Sea ecosystem that are being or could be affected in detectable ways by climate change are:

- Sea ice extent and concentration
- Sea ice season duration, including time of advance vs. time of retreat
- Sea ice thickness and snow cover
- Katabatic winds – intensity
- Strength of southerly winds over the Ross Sea, probably directly related to behavior of the Amundsen Sea low pressure system
- Clouds
- Radiation budget
- Spatial extent, speed and volume transport of Ross Gyre
- Extent of intrusions of MCDW
- Spatial and temporal stratification of the water column, including changes in mixed layer depth
- Polynya size and timing of appearance
- Air and water temperatures
- Transport of less saline water into Ross Sea from the east (e.g., can affect bottom water formation) as a result of the melting of the West Antarctic Ice Sheet

Chemistry:

The key chemical indicators of the Ross Sea ecosystem that are or could be affected in detectable ways by climate change are:

- pH
- Altered intrusion of CDW, which has a characteristic nutrient-oxygen signature.
- Bacterioplankton are the ultimate indicators that reflect chemical change caused by anthropogenic or natural factors, including carbon remineralization, iron solubilization, nitrogen transformation, phosphorus liberation, and sulfur cycling through DMSP demethylation

Biology:

The key biological indicators of the Ross Sea ecosystem that could be affected in detectable ways by climate change are:

- Adélie penguin populations
 - Number of breeding pairs
 - Proportion breeding
 - Chick growth
 - Diet
 - Age specific survival
 - Foraging effort
- Emperor penguin populations
 - Number of breeding pairs
 - Proportion breeding
 - Chick growth and survival
 - Diet
- Weddell seal populations
 - Population and pupping colony size
 - Proportion pupping
 - Maternal body mass
 - Pup mass
 - Age specific survival
 - Diet
 - Foraging effort
- Toothfish
 - Abundance and survival of different age classes
 - Fecundity
 - Seasonal distribution patterns
 - Diet
 - Body condition
- Phytoplankton biomass, seasonal distribution, and functional group composition
- Silverfish production and frequency in diets of principal predators
- Benthic species composition
- Killer whale group size, body condition and frequency of occurrence, foraging effort

2. What research and monitoring would be required to resolve critical uncertainties concerning the life history and demography of the Ross Sea toothfish population and its numerical and functional relationships with its principal predators and prey?

- What are the critical (most significant) uncertainties concerning the life history and demography of Antarctic toothfish in the Ross Sea?
- What are the critical uncertainties concerning the numerical and functional relationships between the Ross Sea toothfish population and its principal predators and prey?
- What related research and monitoring are currently being conducted, and what if anything more would be required to resolve the most significant uncertainties

concerning the numerical and functional relationships between the Ross Sea toothfish population and its principal predators and prey?

Answers/Conclusions

Toothfish demography and life history:

- Size-related fecundity?
- Where, when, how often and how deep does spawning occur? Does this cycle differ between sexes?
- Eggs benthic or pelagic?
- Fate, geographic location and location within the water column of eggs, larvae, and young fish? What are the principal predators and prey at each life stage?
- Recruitment, natural and fishery-related variability?
- Cause and fate of axe handle fish?
- Original spawning biomass?
- Validity of 50% reduction in spawning biomass and effects on ecosystem structure and function relative to the CCAMLR objectives?
- Relationship between spawning/condition, growth, survival and environmental conditions?

Toothfish, uncertainties in regard to predator vs prey:

- What is/was the importance of different toothfish size classes to Weddell seals, killer whales, squid, and other species?
- Given the current CCAMLR working assumptions about toothfish occurrence by life stage and summer-only, sea-ice free fishery sampling, how do toothfish recover condition after spawning while remaining, as currently assumed, on the bottom along the slope where the majority of stomach samples indicate little if any foraging?
- Alteration in sea-ice, phytoplankton, and water mass circulation on toothfish prey in relation to climate change?
- Life stage diet variability?

Silverfish (important toothfish prey in shelf waters):

- Interannual variation in production and year class strength?
- Fecundity?
- How abundant are they at sizes relevant to penguin, toothfish, cetacean and seal predators?
- Spatial and temporal distribution and abundance of different age classes?
- Effect on abundance and predator consumption by fishery removal of large toothfish?

- Environmental factors affecting spawning; relationship between population size and sea ice conditions?

Macrourus whitsoni (important toothfish prey in benthic, slope waters)

- Population status and effects on dependent and related species as a function of bycatch mortality?
- Is the apparent decrease in prevalence as bycatch in the fishery along the slope due to decreased fishery-related abundance, or effectiveness of management (i.e. “move on rule”)?

Chionobathyscus dewitti (important toothfish prey in benthic, slope waters)

- Population status and effects on dependent and related species as a function of bycatch mortality?

Antarctic & crystal krill

- Abundance?
- Spatial and temporal distribution of age classes?
- Relationship to sea ice extent/concentration in RS region in comparison to the pattern in the Antarctic Peninsula/ Scotia Sea area?
- Sensitivity to climate change (including ocean acidification)?

3. What are the most significant uncertainties concerning the effects of the Ross Sea toothfish fishery on the target toothfish population and other components of the Ross Sea ecosystem, and what research, monitoring, or changes in the CCAMLR management procedures would be required to resolve the uncertainties?

- **How and to what extent might the Ross Sea toothfish population and its principal predator and prey populations be affected by the regional toothfish fishery?**

Answers/conclusions:

- Spawning biomass is estimated to have been reduced to 80% of that before initiation of the fishery, but there are no actual data regarding either the current or pre-fishery spawning biomass
- The abundance of the toothfish sizes targeted by the fishery has been reduced, and it appears that there has been a corresponding increase in their principal prey species, but the magnitude of the reductions and corresponding increases are unknown
- It is assumed, based on density-dependent population theory, that the survival of larval and juvenile fish has increased as the abundance or density of larger fish decreased, but there are no actual data to confirm that the assumption is correct
- The removal of the large fish targeted by the fishery likely has had some effects on both their predators, such as Weddell seals and killer whales, and their prey, such as silverfish and smaller toothfish, but the nature and magnitude of the effects are unknown. Recent research appears to indicate that foraging effort of these predators has increased since initiation of the fishery
- Changes in the distributions and abundance of toothfish predators and prey likely have had and are continuing to have some effects on the predators and prey of

those species, but the numerical and functional relationships among the various species are not well enough known to even hypothesize the magnitude or ecological significance of the changes

- **What assumptions are inherent in the decision rules, model(s) and procedures being used to determine the allowable toothfish catch levels and their effects on the target, dependent and associated populations?**

Answers/conclusions:

- That a 50% reduction of spawning biomass over 35 years has a high probability of resulting in a sustainable MSY fishery, with no effects on dependent or associated species is consistent with the objective of the Convention
 - That the modeling-derived estimates of initial and current spawning biomass reliably reflect the actual initial and current spawning biomass
 - That the toothfish tagging and tag recovery programs are providing reliable data on the distribution, movements, and abundance of the size classes targeted by the fishery – e.g., sufficient numbers of fish are being tagged and released, selection of fish for tagging is random and representative of the sizes of fish being caught, tagging has no undetectable effect on growth and survival of the tagged fish
 - That allowing fishing in the presumed spawning area (northern sea mounts), where only large, presumably fecund individuals have been caught, has no adverse effect on production or recruitment
 - That determining and monitoring possible changes in the distributions and abundance of the size classes of fish not targeted by the fishery are not essential to ensuring that the fishery does not affect either the target toothfish population, or populations of dependent and associated species, in ways inconsistent with the objectives of the Convention
 - That the “move-on rule” and other steps taken to limit the bycatch of non-target species are sufficient to ensure that populations of non-target species are not being reduced below their maximum net productivity level
 - That the steps taken to limit the effects of the long-line fishery on benthic communities are sufficient to ensure that the affected communities could recover to their original state within 20-30 years if the fishery is stopped
 - That there is no need to establish baselines and monitor the status of toothfish predator and prey species that could be affected by removals of the target toothfish and bycatch species
-
- **What has been or is being done to validate the assumptions?**
- Answers/conclusions**
- 2012 cruise by NIWA to detect abundance of small fish over the Ross Sea shelf
 - Year of the skate tag-recapture effort

- **What would be required to resolve the critical uncertainties and are there different ways that this might be done?**

Answers/conclusions

- The decision rules, data, models and procedures being used by the Scientific Committee and its working groups to estimate allowable toothfish catch levels should be reviewed by an independent group of knowledgeable modelers, ecologists, and fishery scientists to determine if the advice being provided to the Commission regarding allowable catch levels and related matters are consistent with the objectives of the Convention. If not consistent, why not, and what additional data or changes in the decision rules, models, assumptions, or assessment procedures are needed to ensure consistency with the objectives of the Convention
- Fishery-independent surveys should be initiated and carried out periodically to document recruitment and monitor the status of the toothfish resource
- Fishing in the presumed spawning location should be prohibited, except for prescriptive research fishing designed to resolve critical uncertainties regarding the life history of the Ross Sea toothfish population
- As a cost of access to the fishery, every vessel engaged in the fishery should be dedicated during parts of each fishing season to collecting needed information on the distribution, movements, predators and prey of the pre-reproductive life stages of the toothfish
- An interactive model of the Ross Sea food web should be developed and used to formulate testable hypotheses concerning the effects of the fishery on dependent and associated species and populations
- The fishery should be suspended until available data are sufficient to ensure that the effects of the catches and fishing methods have not caused and will not cause changes in the target, dependent, or associated populations inconsistent with the population and ecosystem objectives of the Convention

4. What are the possible climate-related changes in the Ross Sea ecosystem that could require consideration and response by the CCAMLR Scientific Committee and Commission to meet the population and ecosystem objectives of the Convention?

- **What possible changes in the Ross Sea ecosystem could be precipitated by climate change?**

Answers / Conclusions

- Increase in sea ice extent and delay in the spring sea ice retreat could affect primary and secondary production and have corresponding effects on upper trophic levels, including adult and early life stages of toothfish and their predators and prey
- Increasing sea ice and winds could shorten the fishing season and increase the risk of fishing vessels being trapped and damaged in the ice, with loss of human life and fuel contamination of the environment

- Based on findings of research on year-to-year, and decadal time scales, toothfish competitors and predators, such as killer whales, Weddell seals and penguins, should exhibit decreased survival and productivity as sea ice season lengthens and winter ice extent increases
- **What if any kinds of changes in the present assessment and monitoring of the direct population and indirect ecosystem effects of the Ross Sea toothfish fishery might the CCAMLR Scientific Committee and Commission have to make in response to the effects of climate change in order to meet the population and ecosystem objectives of the Convention?**

Answers/Conclusions:

- To date, it appears that the effects of the toothfish fishery on non-target and associated species have received little if any consideration in the development and regulation of the fishery. As indicated earlier, the decision rules, data, model(s), assumptions, and procedures being used by the Scientific Committee and its working groups to estimate and provide advice to the Commission on allowable catch levels and related matters should be reviewed by an independent group of modelers, ecologists, and fishery scientists to determine additional data or changes in the estimation procedures needed to ensure that the fishery does not have effects on the target toothfish population or other components of the Ross Sea ecosystem contrary to the objectives of the Convention
- Also as indicated earlier and described below in greater detail, an ecosystem monitoring program should be designed and implemented to detect changes in the principal predators and prey of toothfish and non-target species caught in the fishery.
- Establish monitoring programs: grid of ocean stations for e.g., prey, plankton, along with continuation of long-term data sets (Appendix 5), similar in purpose to the CEMP and LTER Program in the Peninsula area
- Periodic process studies in which inter-relationships of ecosystem components are measured
- Use the fishery as a more effective research tool
- Revise and periodically update the food web model incorporating recently acquired data
- **Are ongoing fishery and ecosystem research and monitoring programs in the Ross Sea sufficient to detect and distinguish the population and ecosystem effects of climate change from those of the fishery?**

Answers/Conclusions:

- No
- Also, with some exceptions (see below), existing baseline data regarding the principal predators and prey of toothfish are insufficient to serve as a basis for monitoring programs, the results of which would enable distinguishing the effects

of climate change from the effects of the fishery. The only way to solve this dilemma would be to suspend the fishery long enough to collect baseline data regarding the status quo of the toothfish population and dependent and associated populations, and to formulate and establish programs to prove or disprove hypotheses for distinguishing cause-effect relationships

- **If the answer to the preceding question is “no,” what changes in or additions to ongoing research and monitoring programs would be required to be able to detect and distinguish the population and ecosystem effects of climate change from those of the fishery in time to take remedial actions that may be necessary to meet the population and ecosystem objectives of the Convention?**

Answers/Conclusions:

- One or more fishing or research vessels should be dedicated to fishing in areas and at times of the year when spawning is presumed to occur to resolve uncertainties concerning the timing, geographic location, and location in the water column where spawning occurs, the average number of eggs produced by spawning females, and the post spawning condition and survival of both male and female toothfish
- Assess available technology and, if feasible, develop an acoustic tracking program to determine the movements and fate of pre- and post-spawning fish
- Surveys should be conducted to establish baselines and subsequently monitor the distributions, movements, and, as possible, the natural mortality or survival rates of the early life history stages of the Ross Sea toothfish population
- Ongoing long-term studies of Weddell seal, Adélie and Emperor penguin colonies in the McMurdo region should be continued and expanded to include (i) satellite imagery monitoring of seal and penguin colonies elsewhere along the ice-free coast of the Ross Sea, (ii) satellite-linked radio-tagging to determine the winter distributions and movements of known-age seals and penguins with known reproductive histories; and (iii) scat, fatty acid, and isozyme analyses to determine seasonal and annual variations in diet
- One or more appropriate control areas where fishing is prohibited, and comparable experimental areas where prescriptive fishing is allowed, should be established and monitored to distinguish the population and ecosystem effects of climate change from those of fishing and associated activities. Hypotheses should be developed to guide these comparisons (examples given in Appendix 5)
- Research should be undertaken to understand the life history and dynamics of toothfish prey, particularly silverfish and macrourids
- Surveys should be conducted to locate, characterize, and monitor representative benthic communities that have and have not been impacted by long line fishing to determine the recovery time of impacted communities and the likelihood that

they would be able to recover to pre-impact conditions in 20-30 years in accordance with CCAMLR Article II(3)(c)

- **What if any changes in the present philosophy and procedures for regulating the toothfish fishery in the Ross Sea could / should the CCAMLR Scientific Committee and Commission initiate to minimize the likelihood that the combined effects of the fishery and climate change will lead to avoidable population or ecosystem changes inconsistent with the objectives of the Convention?**

Answers/Conclusions:

- There is no doubt that climate change is affecting sea ice conditions, weather patterns and water and air temperatures in the Ross Sea and that these changes likely are having and in the future may have greater effects on the numerical and functional relationships among many biological components of the ecosystem. Consequently, it is imperative that the Commission and Scientific Committee take immediate action to anticipate the effects of climate change that may necessitate changes in the toothfish fishery and related activities to ensure that they are not having population or ecosystem effects contrary to the objectives of the Convention. As a first step, the Scientific Committee should (i) formulate hypotheses as to how climate change may directly and indirectly affect the target toothfish population and its principal predator and prey populations in ways that may necessitate changes in management of the fishery to ensure compliance with the objectives of the Convention, and (ii) advise the Commission of the research and monitoring needed to test the validity of the hypotheses

5. What additional research and monitoring and possible changes in management philosophy and procedures identified in the preceding discussions merit consideration according to their relative importance for minimizing the risk that the combined effects of the fishery and climate change will lead to population or ecosystem effects inconsistent with the objectives of the Convention?

Answers/Conclusions:

- Develop a CEMP focused on the ecosystem effects of the toothfish fishery and climate change on the Ross Sea comparable to what has been and is being done with respect to the krill fishery in the Peninsula region.
- Develop a long term ecological research program in the Ross Sea, similar to the Palmer LTER, to assess, detect, and monitor changes in the key components of the region using the most cost effective technologies and techniques (see for example Appendix 6: Final Report of Workshop on Prospects for a Ross Sea/McMurdo Sound LTER, April 2004)

V. Summary, Conclusions, and Recommended Actions

The Ross Sea marine ecosystem has a number of unique physical and biological features, and is the world's most pristine marine system. There is compelling evidence that climate change is dramatically affecting and will continue to have significant effects on the weather, water masses, and sea ice conditions in the Ross Sea and adjacent areas. Evidence exists that certain well-studied species have been affected by these environmental changes and in the foreseeable future there can be no doubt that there will be even greater effects on these and other biota of the region.

An important component of the Ross Sea ecosystem is the Antarctic toothfish, a mesopredator that, depending in part on size, is both a predator and prey of other species. It is likely that there have been and in the foreseeable future will be more pronounced climate change effects on the regional Antarctic toothfish population, the target of the ongoing exploratory fishery in much of the area, on the predators and prey of the toothfish, and on other components of the regional ecosystem. Consequently, the regulatory Commission and advisory Scientific Committee established by CCAMLR will have to take into account the effects of both climate change and the fishery on the target toothfish population and populations of dependent and associated species to determine and take actions necessary to meet the objectives set forth in Article II of the Convention – i.e., to ensure that, as the effects of climate change are manifested, harvesting and associated activities do not alter the ecological relationships between target, dependent, and associated species and populations, or cause ecosystem changes that cannot be reversed in 20-30 years .

There are critical uncertainties regarding:

- (1) the life history and demography of the regional toothfish population and its ecological relationships with its predators and prey;
- (2) the validity of the decision rules, data, models, assumptions, and procedures being used to calculate toothfish catch levels consistent with the objectives of the Convention; and
- (3) the adequacy of steps being taken to ensure that the fishery does not have effects on benthic communities or bycatch species inconsistent with the CCAMLR objectives.

With regard to point 1, for example, the timing and location of spawning are broadly assumed based upon the location and time of year of catches of two gravid females and the catch locations of mature male and female fish undergoing gonad development prior to spawning. Similarly, it is assumed that eggs, larvae, and juvenile fish are entrained in and carried more or less passively in the Ross Gyre as they mature [13], but virtually nothing is known about these early life history stages – e.g., growth rates, what they eat, what eats them and where they occur. Therefore, the validity of the Ross Gyre hypothesis is not known. Further, it is known that physically mature fish do not spawn annually, but it is not known how often individual fish do

spawn and what factors determine the frequency of spawning. Also not known is variability in fecundity by size/age, which is an important aspect of fish biology. Finally, it is suspected, but not verified that some portion of larvae escape the Ross Gyre (relegated to natural mortality) and are advected toward the east to supplement toothfish populations near the Antarctic Peninsula. This proportion could increase as the ACC continues to strengthen in response to climate change.

With regard to point 2, the decision rules, models and procedures being used to calculate allowable toothfish catch levels are based on the outdated single-species concept of maximum sustainable yield (MSY [14]) and appear not to account for the possible effects of the catches and fishing practices on dependent and associated species in accordance with Article II(3)(b) of the Convention. Further, it appears that a variety of assumptions are inherent in the input parameters and other aspects of the model(s) and procedures being used by the Scientific Committee and its subsidiary working groups to calculate and provide advice to the Commission regarding allowable catch levels. Examples are the assumption that (i) a 50% reduction in the toothfish spawning biomass over 35 years (starting in 1997) will result in a sustainable fishery and will have no effects on dependent or associated species inconsistent with the CCAMLR objectives [14]; (ii) estimates derived from catch, effort, and tag recovery data provide reliable indicators of both the pre-fishery spawning biomass and its subsequent fishery-caused reductions; (iii) spawning is annual, which evidence indicates is not the case; and (iv) there is no difference in fecundity as a function of age/size of spawning fish.

On a related matter, it is not clear whether the Scientific Committee routinely advises the Commission of the assumptions inherent in its advice and the consequences if the assumptions are not valid, and whether these factors are appropriately reflected in the Conservation Measures subsequently promulgated by the Commission. Also, it is not clear whether all Members of the Committee believe the advice provided to the Commission is consistent with the CCAMLR objectives and, if not, whether the dissenting views are conveyed to the Commission as provided for in the Committee's Rules of Procedure. Further, while programs have been designed and undertaken to assess and address the effects of the Antarctic krill fishery on both the target krill population(s) and populations of dependent and associated species, there has been no corresponding development to date of fishery-independent programs to assess and monitor the toothfish population and its principal predators and prey in the Ross Sea region or elsewhere.

With regard to point 3, the Commission, acting on the advice of the Scientific Committee, has taken steps to assess and limit the effects of the toothfish fishery on bycatch species and on benthic communities impacted by fishing methods. As examples, the Commission has adopted Conservation Measures requiring fishing vessels to "move-on" when the proportion of non-target species, including Vulnerable Marine Ecosystem (VME) species, being caught exceeds certain levels, and setting aside and prohibiting fishing in selected areas to protect unique bottom communities. However, it is not clear whether these measures are sufficient to

ensure that the impacts of the toothfish fishery on the bycatch species and benthic communities are consistent with the objectives of the Convention – i.e., whether the affected bycatch species and benthic communities would be able to recover to their pre-fishery states within 20-30 years following possible future conclusion of the fishery.

A number of non-governmental organizations and scientists have advocated including the entire Ross Sea shelf and slope area in a Marine Protected Area to conserve the unique, relatively pristine characteristics and scientific values of the area. At the 2011 meetings of the CCAMLR Commission and Scientific Committee, New Zealand and the United States both submitted, for preliminary consideration, concept papers regarding establishment of Marine Protected Areas (MPAs) in the Ross Sea and adjacent areas [1, 2]. Acknowledging that it is important to protect the large, spawning fish in any fished stock, the boundaries of the United States concept MPA included the sea mounts north of the Ross Sea where toothfish are presumed to spawn during the Austral winter [13; Figure 2]. The New Zealand concept paper did not include this presumed spawning area or any other restrictions on the areas being fished. The U.S. paper envisioned establishment, which the New Zealand paper did not, of a no-fishing area and directed fishing area as a possible means for differentiating the population and ecosystem effects of climate change from those of the toothfish fishery (Figure 2). Neither concept paper specifically acknowledged the uncertainties regarding the population or ecosystem effects of the fishery. Likewise, neither acknowledged the need to develop and undertake an ecosystem-based research and monitoring program, the results of which would enable the Scientific Committee to assess and the Commission to promulgate Conservation Measures necessary to ensure that harvesting of toothfish and associated activities do not have unacceptable population or ecosystem effects as defined in Article II of the Convention.

Given the unique features and relatively pristine condition of the Ross Sea ecosystem, the Ross Sea shelf and slope and, as well as the sea mounts where Antarctic toothfish are believed to spawn, ideally, should be included within an MPA closed to commercial fishing to protect the unique scientific and ecological values of the region and provide an opportunity to detect and monitor the effects of climate change, without the need to differentiate those effects from the effects of the fishery. This might not be possible if some CCAMLR Members value the economic returns of the fishery above the potential ecological and scientific values of the region in the absence of a fishery.

Article IX(2)(g) of CCAMLR recognizes the value of “opening and closing of areas, regions, or sub-regions for purposes of scientific study or conservation, including special areas for protection and scientific study.” Given the uncertainties regarding the life history of the regional toothfish population and its ecological relationships with other ecosystem components, it logically follows that all but prescriptive research fishing for toothfish should be suspended in the entire Ross Sea MPA and adjacent areas thought possibly to contain critical habitat for the

different life stages of the toothfish population at least until the tasks described below have been accomplished. With the resulting information it should then be possible to design more focused research and monitoring programs and agree on one-or-more smaller MPAs to ensure that, given the ongoing and potential future biological and ecological effects of climate change, any future commercial fishery will not have population or ecosystem effects inconsistent with the corresponding objectives of the Convention. The following are the tasks necessary to resolve the aforementioned uncertainties concerning the population and ecosystem effects of the existing Antarctic toothfish exploratory fishery and to ensure that any future commercial toothfish fishery in the Ross Sea MPA will not have population or ecosystem effects inconsistent with the objectives of the Convention:

1. The decision rules, data, model(s), assumptions, and procedures being used by the Scientific Committee to calculate and provide advice to the Commission on the allowable catches of toothfish, by-catch species and related issues in the Ross Sea region should be reviewed by an independent group of knowledgeable modelers, ecologists and fishery scientists to determine if the resulting advice is consistent with the objectives of the Convention, and if not changes in the assessment methods that should be made to correct the identified discrepancies;
2. A model of the Ross Sea shelf and slope food web, incorporating the best available data and hypotheses concerning the interactions of the key biological components of the Ross Sea ecosystem, should be developed and used to help determine the research and monitoring needed to resolve uncertainties concerning the numerical and functional relationships among the key food web components. The model should include a range of variables that capture the profound uncertainty now inherent in our understanding of food web relationships.
3. A prescriptive research fishery should be designed and carried out to resolve the critical uncertainties concerning the life history and the current distribution, abundance, movements and natural mortality of the different development stages of the Ross Sea toothfish population;
4. An ecosystem monitoring program, comparable in scope and purpose to the ongoing research and monitoring program regarding Antarctic krill, should be designed and initiated to detect and provide sufficient time to reverse any population or ecosystem effects of the current and any future commercial toothfish fishery inconsistent with the objectives of the Convention;
5. An assessment should be undertaken to determine the consistency with the CCAMLR objectives of measures that have been taken to limit the impacts of the ongoing toothfish fishery on bycatch species and benthic communities and, if inconsistencies are identified, determine additional measures necessary to ensure that any future toothfish or other commercial fishery in the Ross Sea region does not cause changes in the distributions, abundance or productivity of non-target species or damage biologically significant benthic communities in ways that are not potentially reversible in 20-30 years; and

6. The CCAMLR Scientific Committee should, as a matter of priority, (i) formulate hypotheses as to how climate change could directly or indirectly affect the distribution, abundance, and productivity of the Ross Sea toothfish population and its ecological relationships with other biota, (ii) identify ways that management of the fishery may need to be changed to ensure consistency with the CCAMLR objectives to account for the possible effects of climate change on the target toothfish population and its principal predator and prey populations, and (iii) determine and advise the Commission of the research and monitoring needed to appropriately evaluate the possibilities.

Whether or not the Commission agrees that the fishery should be suspended, the aforementioned tasks should be undertaken. Further, given the budget and financial obligations set forth in Article XIX of the Convention, it would be reasonable to (i) expect all Commission members to contribute equally to meeting any costs associated with tasks 1, 2, 3, 5, and 6, and (ii) expect, as a business expense, that those countries with vessels engaged in the fishery to share the costs of task 4 -- the ecosystem monitoring program needed to confirm that the fishery is not having population or ecosystem effects contrary to the objectives of the Convention -- in proportion to the amount of fish their vessels are catching.

Although not ideal, development and adoption of a MPA proposal, incorporating the features of the concept MPA tabled by the U.S. for preliminary consideration at last year's CCAMLR meetings, could provide means for both (i) minimizing the risk that the fishery will have population or ecosystem effects contrary to the objectives of the Convention, and (ii) differentiating the ecosystem effects of the fishery from the ecosystem effects of climate change. The critical elements in this regard are (1) the inclusion in the protected area of the sea mounts where spawning is believed to occur, and (2) the likelihood that establishment and comparison of monitoring results from a control area and an area where prescriptive research fishing is conducted would in fact provide the basis for differentiating the effects of the fishery from those of climate change (examples of possible hypotheses to guide this effort are given in Appendix 5). Long-term data sets from past and continuing oceanographic and climate studies in the Ross Sea and studies of seals, penguins, toothfish, and benthic communities in McMurdo Sound and other parts of the Ross Sea provide much of the essential baselines needed for the development of the research and monitoring program that would be required to meet the objectives of the U.S. concept MPA. Recent developments in technology and research techniques provide cost effective opportunities for continuing and expanding the collection of needed baseline and monitoring data. The technologies and techniques include satellite-linked monitoring of data buoys, anchored recoverable data buoys, satellite-linked radio tracking and behavior and habitat monitoring of seals, penguins and killer whales, use of gliders and instrumented seals and whales to collect oceanographic data, satellite photography and monitoring of seal and penguin colonies, scat and isozyme analyses to determine seasonal diets of penguins and seals, and acoustic tagging and monitoring to determine the underwater movements of fish and seals.

V. Appendices

1. Participants

2. Agenda

- 3. Abstracts**
- 4. References and papers tabled prior to workshop**
- 5. Non-inclusive list of possible hypotheses to guide management of the Ross Sea region.**
- 6. As an example of a research and monitoring program to understand ecosystem response to climate change: Workshop Report, McMurdo Sound, Antarctica: An Opportunity for Long Term Investigation of a High Latitude Polar Ecosystem**

APPENDIX 1. Participants in 28-30 March Ross Sea workshop

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George Watters, NOAA-NMFS-SWFSC, La Jolla CA; George.watters@noaa.gov

APPENDIX 2. AGENDA: Ross Sea Workshop, La Jolla, 27-30 March 2012

DAY ONE, 27 March

09:00 – Welcome, Summary of how we got here and where we're going, and Adoption of agenda

0945 - M Dinniman: review of ocean circulation and water masses of Ross Sea and vicinity

1030 - Break

1045 - J Russell: latest climate model results

1130 – S Stammerjohn: effects on the Ross Sea physics by shorter term climate (ENSO, SAM)

1215 - Lunch

1315 - D Ainley: summary of Ross Sea studies that have detected biotic responses to short-term climate variation

1400 - K Arrigo: variation in size and phenology of Ross Sea Polynya and relationship to primary production

1445 - W Smith: factors that affect spatial and temporal variation in primary production

1530 - Break

1545 – J Barry: implications of ocean acidification to the Ross Sea ecosystem

1630 – A Murray: bacterioplankton, microbial loops etc, comparison of So Ocean sectors

1700 – Discussion: links among the day's talks

1730 – Adjourn

DAY TWO, 28 March

0900 - C Reiss: summary of abundance and distribution of zooplankton, relationship to climate factors

0945 - Dayton/Kim/Barry – Benthic community patterns including long-term changes in composition

1030 Break

1045 – J Eastman: a review of species composition and dynamics of the fish fauna

1130 - C Brooks: a review of what is known about Ross Sea Antarctic toothfish natural history

1215 - Lunch

1300 - D Ainley: update on results of 39 yr time series of toothfish catch in McMurdo Sound

1330 - G Watters: review of the Ross Sea fishery stock modeling

1415 - R Pitman: musings on cetaceans, especially killer whales, and role in Ross Sea ecosystem

1500 – Break

1515 - G Ballard: review of spatial modeling of upper trophic level species

1600 - M LaRue: remote sensing capabilities for monitoring the Ross Sea ecosystem

1645 – S Ackley: review of SOOS, and how it might apply to the Ross Sea

1730 – Adjourn

DAY THREE (29 March)

0900 – Facilitated discussion to consider and agree on the possible nature and effects of climate change on key components of the Ross Sea ecosystem over the next 10, 20, and 50 years (*see the questions provided later to illustrate how this and the other facilitated discussions might be orchestrated*)

1030 - Break

1045 – Facilitated discussion to consider and agree on the research and monitoring that would be required to resolve critical uncertainties concerning the life history and demography of the *D. mawsonii* population in the Ross Sea and its numerical and functional relationships with its principal predators and prey

1215 - Lunch

1300 – Facilitated discussion consider and agree on the research and monitoring that would be required to resolve the critical uncertainties concerning the effects of the *D. mawsonii* fishery on the target toothfish population and other components of the Ross Sea ecosystem

1430 – Facilitated discussion to consider and agree on research and monitoring that would be required to resolve the critical uncertainties concerning the effects of a potential krill fishery on the target population and other components of the Ross Sea ecosystem

153 Break

1600 –Facilitated discussion to consider and agree on possible climate related changes in the Ross Sea toothfish population and dependent and associated species that would require consideration and action by the CCAMLR Scientific Committee and Commission to meet the population and ecosystem objectives of the Convention (as enumerated by R Hofman).

1730 - Adjourn

DAY FOUR, 30 March (Small group: Ainley, Ballard, Brooks, Hofman, Jonsomjit, Siniff)

0800-1100 – Preparation, copying, and distribution of the draft workshop report. This is a report to NSF. However, it should form an important part of a paper that the US will be submitting to CCAMLR.

APPENDIX 3. ABSTRACTS OF PRESENTATIONS

Review of ocean circulation and water masses in the Ross Sea and vicinity

Michael S. Dinniman & Eileen E. Hofmann, Old Dominion University

An overview of the ocean circulation and water masses in the Ross Sea sector of the Southern Ocean and on the Ross Sea continental shelf itself is given with particular emphasis on two features important to ecosystems in the area: Intrusions of Modified Circumpolar Deep Water (MCDW) onto the continental shelf and model experiments of advection of passive neutrally buoyant drifters in the Ross Sea relevant to Antarctic toothfish pathways. First, the circulation features of the Ross Gyre are presented along with information about Circumpolar Deep Water, the parent water mass for all the water masses found on the Ross Sea continental shelf. The different water masses on the continental shelf and slope are then discussed with respect to how they are formed and how they circulate in the Ross Sea, with special emphasis on how bathymetry controls much of the circulation. Locations of MCDW intrusions are shown to be fairly well known in the Ross Sea and, because of the importance of bathymetric controls on the circulation, can be successfully simulated with numerical models. However, the time scale and forcing mechanisms at the shelf break of the intrusions are less well known. Finally, experiments using neutrally buoyant passive drifters within a numerical circulation model of the Ross Sea are used to show that early life stages of Antarctic toothfish in the slope front current could be transported to different areas in the Ross Sea where juveniles have been caught. Deeper flow along the continental slope is shown to facilitate the movement of adults back into the Southeast Pacific Basin where spawning adults have been found.

Rickard et al. 2010: models of Ross Gyre

Strongest tides along shelf break, esp western (Cp Adare, Pennell Bank)

Ice-Climate Variability in the Ross Sea on Seasonal to Interannual Timescales

Sharon Stammerjohn & Colleagues (as cited in the presentation), Institute of Arctic and Alpine Research (INSTAAR), University of Colorado Boulder

We reviewed the variability and trends in the timing of sea ice advance, retreat and ice season duration for the 1979/80 to the 2010/11 period for the Ross Sea region in relation to changes elsewhere in the Southern Ocean and in the Arctic (for global perspective) (e.g., Stammerjohn et al., 2012). We discuss these sea ice trends in relation to El Nino Southern Oscillation (ENSO) (e.g., Yuan and Martinson, 2000; Liu et al, 2004) and Southern Annular Mode (SAM) variability (e.g., Lefebvre et al, 2004; Turner et al., 2009), as well as in relation to warming of the West Antarctic Ice Sheet (WAIS) (e.g., Steig et al, 2009; Ding et al., 2011; Schneider et al., 2012).

Some key points include the following:

- The northwestern Ross Sea is one of 4 polar regions changing the fastest, but is the only region showing rapid sea ice increases (versus decreases).
- Total sea ice change over 1979/80-2010/11 in the *northwestern* Ross Sea:
- Sea ice advance is earlier by 42 days
- Sea ice retreat is later by 38 days
- Open water summer season is shorter by 80 days
- Sea ice changes in the *southwestern* Ross Sea are similar as described above but are of smaller magnitude with greater year-to-year variability (thus, less statistical significance)
- Seasonally: there is more variability in the timing of spring sea ice retreat than in autumn sea ice advance, particularly in the Ross Sea polynya area
- Yearly (interannually): variability in the northwestern and southwestern Ross Sea is not well correlated (particularly during spring, i.e., in the variability of the spring sea ice retreat), suggesting different ocean and atmosphere controls on sea ice variability along this latitudinal gradient; further sea ice variability in the eastern Ross Sea is quite different as well and currently does not show discernable trends

Some Implications:

- Shorter (open water) growing season, mostly northwest of the continental shelf break
- Greater sea ice production & export from southwest Ross Sea
- Though trends are weaker and variability greater, there are indications that the open water season in the Ross Sea polynya area is becoming shorter as well

Some Key Questions (for better understanding the causes of sea ice changes in the Ross Sea):

- Can we better relate local-scale wind changes (e.g., katabatic winds over the Ross Sea polynya area; seasonal variability in cyclonic winds over the Ross Sea) to the large-scale atmospheric circulation changes (e.g., position/intensity of the Amundsen Sea Low as influenced by strength/location of the circumpolar westerlies)
- In turn, can we better resolve the seasonal changes & trends in the Amundsen Sea Low, as it relates to:

- ENSO variability
- Warming in the southwestern tropical Pacific in austral winter-spring and its teleconnection to variability in the high latitude South Pacific (e.g., Schneider et al., 2012)
- SAM-related changes in austral autumn
- For the future, will decreased ozone depletion (in austral spring) result in more neutral SAM's, weakening the current (increasing) sea ice trends in the Ross Sea? (See Joellen Russell's presentation and abstract)
- Or, will continued increases in greenhouse gases lead to continued positive SAM's, perhaps shifted seasonally (towards austral winter)? (Again, see Joellen Russell's presentation and abstract)

The Ocean's Role in Climate: The Ross Sea

Joellen Russell, Department of Geosciences, University of Arizona

In global warming simulations of future climate, poleward-intensified westerlies (due to both ozone-forcing in the stratosphere and to greenhouse gas forcing in the troposphere) maintain a robust deep water overturn around Antarctica even as rising atmospheric greenhouse gas levels induce warming that reduces the density of surface waters in the Southern Ocean. Under future projections, our ensemble of climate models projects a continuation of the poleward shift of the Southern Hemisphere Westerly winds due to weak recovery of the ozone hole and a continued atmospheric warming. Early changes over the Ross Sea, underway now, include increasing sea ice, followed by an eventual decrease in average ice thickness by as much as 10 cm and an increase in air temperatures by 1°-2°C (in the annual mean) over all locations with larger changes near Ross Island. The models simulate an increase in the amount of precipitation: possibly greater than 10 cm per year, consistent with the warming.

Summary of Ross Sea studies that have detected biotic responses to short-term climate variation

David Ainley, HT Harvey & Associates

Several long term time series of demographic data exist for the Ross Sea. These include: Emperor penguin chicks counts (measure of colony size) at various colonies since about 1980; Adelie penguin colony size at Capes Royds and Crozier since the late 1960s; Weddell seal rookery size as well as seal body mass and pupping success since the 1960s; leopard seal invasions of Macquarie Island; and toothfish catch per unit effort and fish size since the early 1970s. To attempt to explain long- and short-term variation in population size and demographic factors that contribute to population change a number of analyses have been performed. As environmental covariates, authors have used the Southern Oscillation Index (SOI), Southern Annular Mode (SAM), sea surface temperature, sea ice extent at various times of the year, and amount of open water. It was shown by Kwok & Comiso (2002) that with positive SOI, winds are stronger, sea ice is more extensive, temperatures are colder, and coastal polynyas are more prevalent; evident in longer term patterns described by Parkinson (2002), Stammerjohn et al. (2008).

With positive (negative) SOI, greater (lesser) SIE, larger (smaller) coastal polynyas:

Adelie penguin – smaller colony 5 years later --- must be related to juvenile survival

Emperor penguin – fewer chicks (smaller colony) 5 years later --- juvenile survival

- more chicks in present year --- adult foraging enhanced

Leopard seal – more subadult males visit Macquarie Island --- ice is closer to Macquarie?

Weddell seal – more pups --- adult feeding must be enhanced

Ice previous Winter (Sept) --- more ice = more open coastal ocean

- higher annual recruitment (more females pup)

- maternal body mass higher

- pup weaning mass higher

Toothfish – larger fish in McM Snd --- fish movement facilitated by more ice cover?

Silverfish – benefit from more open water, higher primary production

Studies of longer-term variation in population trajectory, i.e. Adelie penguins, indicate that population growth correlates with stronger winds, thinner ice and more reliable coastal polynyas that come with a positive SAM.

These studies point to the need to determine the biological implications of more or less open water, more or less sea ice extent, etc.

Indicating the very strong trophic coupling that characterizes the Ross Sea ecosystem, at least in its upper trophic levels, are: 1) decrease in penguin populations with industrial take of minke whales in 1970s; 2) increased foraging effort of penguins when large numbers of whales appear in foraging area; 3) prevalence of toothfish as an inverse function of distance to seal rookeries; 4) decrease in killer whale prevalence as availability of large toothfish decreases.

Variation in size and phenology of the Ross Sea polynya and relationship to primary production

Kevin Arrigo, Stanford University

Satellite-derived time series of sea ice extent and primary production were constructed for three polynyas in the Ross Sea (Ross Sea Polynya, Terra Nova Bay Polynya, McMurdo Polynya) for the years 1997-2012. There were no secular trends in polynya size or date of formation during this time period and no relationship to the Southern Oscillation Index (SOI). In addition, there was no secular trend in the magnitude of primary production, except for the Terra Nova Bay Polynya, and no relationship to SOI. There was high spatial and temporal variability in the magnitude and timing of primary production in all three of the study regions (Ross Sea - $87 \pm 24 \text{ g C m}^{-2} \text{ yr}^{-1}$; Terra Nova Bay - $53 \pm 19 \text{ g C m}^{-2} \text{ yr}^{-1}$, McMurdo - $38 \pm 21 \text{ g C m}^{-2} \text{ yr}^{-1}$). Phytoplankton bloom start date in the three polynyas (Ross Sea - November 20 ± 13.2 , Terra Nova Bay - December 4 ± 10.1 , McMurdo - December 14 ± 18.1) was statistically significantly related to timing of polynya formation. In addition, the length of the phytoplankton bloom is positively correlated to polynya persistence, driven almost entirely by variability in the timing of ice retreat.

Factors that affect spatial and temporal variations in phytoplankton biomass, flux and production

W. Smith, Virginia Institute of Marine Science

Phytoplankton biomass and production in the Ross Sea is influenced by a number of factors that influence growth (such as irradiance and iron inputs) and losses (such as grazing and fluxes due to aggregate formation). Irradiance varies substantial on all scales – daily, monthly, seasonally and interannually – and is influenced by seasonal changes in solar angle, clouds, and more importantly, ice concentrations. Ice concentrations in turn vary tremendously in both pattern of retreat, concentration and thickness, and are expected to be influenced by climate change. Ice in turn influences the water column, and if melting occurs in situ, then changes in mixed layer depths can be expected, which in turn will influence not only growth but assemblage composition. Modeled changes in mixed layer suggest strong variations in time and space that confirm variations observed in situ. Changes in phytoplankton composition have been noted previously, and are highly significant in both space and time. Specifically, interannual changes are extreme, and estimates of production of the two major functional groups (diatoms, haptophytes) range from 13 – 57% of the annual production. Such variations are not replicated using present regional models and are poorly understood, although the appearance and success of both groups seems to be linked to irradiance availability. Iron can be limiting in summer, and substantial variations in iron inputs and sources have been determined. Variations in those inputs remain poorly constrained.

Losses due to grazing have been considered to be minor, but results from recent sediment trap measurements suggest that over short periods the flux can be overwhelmingly due to zooplankton fecal pellet production. Substantial variations on all time and space scales undoubtedly occur with loss processes, but these need to be better understood before significant effects of food web alterations and climate change occur. A poor understanding of the entire Ross Sea food web and phytoplankton restrict our predictive capabilities of the impacts of anthropogenic factors.

Southern Ocean bacterioplankton: modulators and indicators of ecosystem function.

A.E. Murray. Earth and Ecosystem Sciences, Desert Research Institute

Marine bacterioplankton provide fundamental ecosystem services to the Southern Ocean pelagos including carbon remineralization, iron solubilization, nitrogen transformation, phosphorus liberation, and sulfur cycling – importantly through DMSP demethylation. Bacterioplankton biomass and heterotrophic activities have a strong seasonal signal in which they increase following phytoplankton blooms in austral summer. Though, unlike phytoplankton, their metabolisms are not entirely reliant on the energy from the sun, they are present and active throughout the entire water column and they harbor an extensive repertoire of physiological and phylogenetic diversity. Recent advances in genome-enabled technologies and reduction in DNA sequencing cost are now providing the ability to survey the marine environment in terms of diversity and genome-encoded and expressed function which is enabling tracking of bacterioplankton and their physiological state through the water column. The results of recent efforts to compare bacterioplankton diversity across 16 sites in the Southern Ocean has revealed that the coastal regions harbor significantly higher levels of diversity in comparison to open ocean zones, that there is a bioregional clustering between sites, and that seasonal turnover of community composition can be as high as 80% (Ghiglione and Murray, 2012). Further, metagenome and metaproteome studies in the Antarctic Peninsula surface waters conducted at the peaks of austral summer and winter have revealed that the high turnover in composition is mirrored by shifts in genome-encoded function such that the winter bacterioplankton are both more phylogenetically and physiologically diverse, and are using metabolic pathways of that are not dependent on phytoplankton-derived organic carbon. Rather, they are using chemoautotrophic pathways in which reduced electron donors are the energy source (Grzymalski et al. *in press* and Williams et al., *in press*). We are now primed to begin a more substantial effort to apply these tools to addressing ecosystem function and its variability in the Southern ocean. The bacterioplankton are ultimate modulators and I would propose, can be useful reporters of ecosystem change effected by anthropogenic or natural factors. Some groups (i.e. the *Roseobacter* genera) are plastic at the genome level and capable of modifying their metabolism to accommodate shifts in resources, while the community as a whole has a depth of diversity that can be tapped to access resources necessary for adaptation to the environmental conditions that present themselves. Shifts in climate that influence

stratification in the water column, increased carbon production, shifts in ocean temperature or the duration of sea ice cover will all be detectable through studying responses in the microbial community, though a baseline of understanding has to be established and the microbial community not considered in isolation, but as a component of the Southern Ocean ecosystem. It is also possible that the microbial signatures reporting on ecosystem status could be used to indicate other anthropogenic impacts such as fishery pressures if they alter the trophic interactions in the ecosystem that effect, in part, the carbon cycle for example.

Benthic Communities in the Ross Sea Ecosystem: considerations for the effects of climate change and protection of Antarctic living marine resources

James Barry, Paul Dayton, Stacy Kim

Monterey Bay Aquarium Research Institute, Scripps Institution of Oceanography, Moss Landing Marine Labs

Benthic communities in the Ross Sea Ecosystem (RSE) vary considerably in composition and abundance across the continental shelf and slope to the abyssal plain. Although the benthos throughout the RSE depend nutritionally on production in the upper water column and sea ice, the distribution and abundance of major faunal groups appear to be regulated most strongly by habitat characteristics such as depth, seabed slope, substratum type, and local current speed, rather than the pattern of productivity near the surface. Some faunal groups are nearly wholly benthic, with larval stages having highly limited dispersal, while others use benthic environments for only a portion of their lives (eg. toothfish). Although various aspects of the Ross Sea benthos have been investigated over several decades, most have focused on local scales over short periods, and provide rare glimpses of broad scale or long term patterns for the benthos. Comparison of the Ross Sea benthos with studies of other Antarctic benthic communities indicate that the major taxa inhabiting the Ross Sea are part of a circum-Antarctic faunal assemblage.

CCAMLR operates with a mandate to protect Antarctic living marine resources, using a precautionary approach that aims to minimize risk related to unsustainable practices in conditions of uncertainty. With regard to this mandate, the influence of at least 2 currently active factors must be considered to understand and ensure conservation efforts for Antarctic living marine resources;

1. Conservation concerns for benthic communities in relation to the toothfish fishery
2. Response of Antarctic benthic communities to climate change

Conservation concerns for benthic communities in relation to the toothfish fishery

While few data are available to evaluate the impact of the toothfish fishery on benthic communities in the RSE, there is increasing evidence that the toothfish take is influencing the structure and function of the RSE. Toothfish use benthic habitats for at least a significant portion of their juvenile development, during which they depend upon benthic food resources (mainly fishes). Removal of toothfish (fishery) modifies predation pressure on benthic and benthopelagic fishes in fished areas as well as non-fished areas that experience a reduction in toothfish abundance. The precipitous reduction in toothfish catch rates in McMurdo Sound that coincided with the ramp-up of the shelf / slope toothfish fishery suggests strongly that toothfish abundance has dropped near McMurdo owing to fishing mortality. Reduced toothfish abundance in the McMurdo areas appears to have affected diets of Weddell Seals and Type C killer whales, and is also likely to affect the benthic communities on the shelf, though the consequence of changing toothfish abundance on the benthos is not known.

Proposals to create one or more Marine Protected Areas (MPA) in the RSE may enable some inference concerning the impact of the fishery on benthic community patterns and processes. One alternative to close fishing along the eastern shelf break in the Ross Sea (control area) while allowing fishing along Iselin? Bank – the continental slope in the central to NW Ross Sea, is not ideal in terms of a statistically rigorous design for evaluating fishery effects. Nevertheless, this design may allow studies of the abundance and distribution of benthos in both areas, over relatively long time periods (10+ years?), that could provide a coarse understanding of changes in the benthos due to fishing. In addition to reducing toothfish abundance in fished areas, toothfish abundance is also expected to drop in unfished areas in relation to the generally known ontogenetic migration of fishes in the Ross Sea sector. This will impair, to some degree, the ability to assess changes in benthic communities in relation to fishing through comparisons of the ‘control’ and ‘treatment’ areas designated in the MPA proposal. Methods to evaluate fishing effects on benthos are discussed below.

Response of Antarctic benthic communities to climate change

Climate change is very likely to affect the structure and function of benthic communities in the RSE, though any details concerning future changes are not understood. If the productivity of surface waters increases with warming climate, then energy input to the benthos is likely to increase, leading to higher benthic standing stock and production. Warmer temperatures will raise the metabolic rates of all ectothermic (cold-blooded) organisms, thereby increasing food demand. If sufficient food is available, higher rates of growth and perhaps reproduction are expected for a most taxa.

Ocean acidification driven by rising ocean carbon levels will result in waters undersaturated with respect to aragonite, leading to a general reduction in calcification potential for both aragonitic (e.g. the bivalve *Laternula* sp., cup corals) and

calcite (e.g. most gorgonians, and nearly all organisms with calcium carbonate skeletal structures). Warming temperatures may offset the higher energy requirements for calcification, so long as ample food is available.

Sampling strategies for assessing the impacts of the toothfish fishery and the response of RSE benthos to climate change

- Structure of benthic communities
 - Benthic sampling program
 - Box cores
 - Imagery (drop cameras (time lapse?), photo sleds, imaging AUVs, acoustic surveys?)
 - Stratified among subhabitats in fished, unfished areas, shelf, slope, abyss
 - Food habits of toothfish (if not known)
 - Permanent _____ and _____ random _____ stations
- Function of benthic communities
 - Growth rates of key taxa (juveniles)
 - Recruitment of key taxa (settlement plates?, cleared areas?)
 - Age and growth studies of taxa with tractable hard parts
 - Rings
 - Radioisotopes
- Effects of toothfish fishery
 - Comparisons of fished, unfished areas
 - Analysis of bycatch
 - Detailed study of fished areas – how have benthos changed? Not sure how to find control stations. May need to have creative approach to assessing long line impacts.
- Effects of climate change
 - There are no ‘control’ locations, since climate change is global.
 - Time series studies of environmental changes (physical factors, primary production, carbon flux) and biological changes (shifts in abundance, distribution, recruitment, growth)
 - May need to compare these between fished and unfished areas to discriminate between fishing and climate change effects – will be difficult unless the magnitude of effects for one or the other is very large.

Considering the conservation value of the Ross Sea Ecosystem, it can be argued that any fishing lies outside the bounds of a precautionary approach to sustainable human activities in the RSE. We expect that a majority of scientists favor more effective protection of the RSE, including a reduction or prohibition of toothfish harvesting.

Zooplankton and krill in the Ross Sea: Designing a monitoring program within a Proposed Marine Protected Area.

Despite the large number of colonies and high density of individuals of seals and penguin species in the Ross Sea relatively little is known about the zooplankton population dynamics. Species diversity and abundances of copepod species seem low relative to other areas near the Antarctic Peninsula, for example. However, basic patterns of species distribution of the two main krill species (*Euphausia superba* and *Euphausia crystallorophias*) are fairly well documented. *E. superba* is more abundant in slope waters while *E. crystallorophias* is found on the shelf reflecting its neritic life history. Acoustic biomass estimates from part of the Ross Sea suggest the biomass of *E. superba* and *E. crystallorophias* to be ~ 2 million and 1 million tons, respectively. Data from nearby areas suggests that both krill species exhibit episodic recruitment fluctuations, but little is known about links to ice dynamics or primary productivity cycles. Data from diets shows that *E. crystallorophias* is most

abundant as a prey item farther south in the Ross Sea while *E. superba* increase in frequency in diets northward. Less is known about the pelagic zooplankton, although there is a suggestion that *Limacina helicina*, a pelagic gastropod may be an important component of the summer zooplankton community. development of a monitoring program in the Ross Sea as part of a management plan as required by CCAMLR Conservation Measures, will require monitoring zooplankton dynamics. Reconstructed krill and fish size frequency from both avian and mammalian species could cheaply inform CCAMLR regarding the links between zooplankton communities and the impacts of climate change on marine protected areas within the Ross Sea ecosystem. Process oriented cruises to elucidate basic biological and ecological relationships could also be beneficial given the paucity of studies, in general, and the lack of any dynamical understanding of the zooplankton community interactions.

Species Composition & Nature of the Fish Fauna of the High Antarctic Shelf & Ross Sea

Joe Eastman, Biomedical Sciences, Ohio University

There are 327 species of Antarctic fishes in the Southern Ocean, 227 over the shelf and slope and about 100 in the Ross Sea, a small number considering the global diversity of 32,000 species and the large size of the Southern Ocean, about 10% of the world's ocean. The most speciose taxa are notothenioids, liparids (snailfishes) and zoarcids (eelpouts). Although higher taxonomic diversity is restricted and species diversity is low in comparison to other shelf areas in the world, the nature of the fish diversity on the shelf and in the Ross Sea overshadows the numbers. The isolated waters of the shelf form a unique evolutionary site where the dominance by notothenioids overshadows the relatively small number of species. In the Ross Sea notothenioids dominate species diversity (77%), abundance (92%) and biomass (91%) to a degree unparalleled in any other marine ecosystem. This is the result of the historic absence of competition from other fish groups that allowed them to exploit new habitats and trophic regimes. The best examples are seen in the benthic family Nototheniidae that underwent an adaptive centered on alteration of buoyancy. They occupy an array of pelagic, cryopelagic, epibenthic and benthic habitats at various depths on the shelf and upper slope. Diversification in buoyancy, to the point of neutral buoyancy, is the ecological hallmark of the nototheniid radiation and, in the absence of swim bladders, was accomplished by a combination of reduced skeletal mineralization and lipid deposition. Although neutral buoyancy is found in only a few nototheniids, *Dissostichus mawsoni* (Antarctic toothfish) and *Pleuragramma antarcticum* (Antarctic silverfish) are relevant examples and are central and important in the food web of the Ross Sea. *Dissostichus* is the top piscine predator and *Pleuragramma* is the primary forage fish. Their differing mechanisms of buoyancy will be explained and known and unknown aspects of the biology of these two species will be presented. Finally, the bycatch of the longline fishery at 1000–2000 m is composed primarily of the macrourid (grenadier) *Macrourus whitsoni* and the nototheniid ice fish *Chionobathyscus dewitti*. The biology of these species will be considered in the light of their vulnerability to exploitation.

Antarctic toothfish: Understanding life history and spatial distribution of the top piscine predator in the Ross Sea

Cassandra Brooks, Stanford University

Concern over fishing for Antarctic toothfish (*Dissostichus mawsoni*) has led to calls for a marine protected area (MPA) in the Ross Sea, yet population spatial structure and life cycle remain unclear. Previous studies indicate toothfish are long-lived (up to 50 years), slow-growing (<1cm/yr after 1.4m, with a maximum length of >2m), and late to mature (13 and 17 years of age for males and females respectively). A working hypothesis suggests that Ross Sea toothfish form a single population with a spawning migration from the continental shelf and slope out to seamounts and the Pacific Antarctic Ridge (PAR) hundreds of kilometers north in the Southeast Pacific Basin (SPB). We recently tested this hypothesis by estimating ages and measuring otolith chemistry of juvenile and adult toothfish captured commercially in the Ross Sea and SPB, and compared them with simulated particle transport based on a circulation model. Material in the otolith nuclei, laid down during early life, showed no differences between sampling areas in the SPB and northern Ross Sea. Age data indicated only adult fish on the PAR; in the northern Ross Sea, the proportion of adults to juveniles decreased westward along the shelf slope in association with rapid tidal sinking into the western SPB, consistent with movement northwards. Particle simulations predicted that early life stages following the flow in the Ross Gyre would be transported to juvenile habitats in the eastern, central and south-western Ross Sea and the northern shelf-break; whereas adults would be predominantly transported along the shelf slope, and back to spawning grounds in the SPB. Taken together, the three techniques indicate a single, self-recruiting population with a life history structured by the large-scale circulation in the SPB and Ross Sea. With a life cycle tied to the Ross Gyre, most successfully spawning fish may pass during their life history through an area around the Iselin Bank where fishing effort is concentrated. This study further supports the growing evidence that Ross Sea toothfish spawn on the seamounts and ridges associated with the PAR, suggesting this will be an important area to protect from fishing. While Antarctic toothfish are relatively fecund (GSI up to 30% and more than 1 million eggs), the proportion of the population that spawns each year remains unknown. Many adults likely skip spawning for one or more years. Eggs or larval Ross Sea Antarctic toothfish have yet to be found.

Decadal trends in abundance, size and condition of Antarctic toothfish in McMurdo Sound, Antarctica, 1972-2011

David G. Ainley, Nadav Nur, Joseph T. Eastman, Grant Ballard, Claire L. Parkinson, Clive W. Evans and Arthur L. DeVries

H.T. Harvey & Associates; PRBO Conservation Science; Department of Biomedical Sciences, Ohio University; NASA Goddard Space Flight Center; School of Biological Sciences, University of Auckland; Department of Animal Biology, University of Illinois

Analyses of a dataset spanning 39 years of near-annual fishing for Antarctic toothfish *Dissostichus mawsoni* in McMurdo Sound, Antarctica, 1972-2011 were recently completed. These data constitute one of the longest biological time series existing in the Southern Ocean, and are by far the longest for any fish species. Moreover, it is one of the only such data sets that precedes and continues through the initiation of a major, industrial fishery. Data on fish total length, condition and catch per unit effort were derived from the >5500 fish caught, the large majority of which were measured, tagged and released. Contrary to expectation, the length-frequency of the McMurdo Sound catch lack the small fish (<90cm) that contribute 50% of the industrial toothfish catch for the Ross Sea shelf. McMurdo Sound fish length and condition increased from the early 1970s to the early 1990s and then decreased. Fish length was positively correlated with Ross Sea ice extent in early spring, a relationship possibly due to more ice encouraging larger fish to move farther south over the shelf and into the study area. Fish condition was positively related to the amount of open water in the Ross Sea during the previous summer (Feb), perhaps reflecting greater availability of prey with the higher productivity that more open water often brings. Decreasing fish size in the McMurdo catch during the last decade corresponds to the onset of the fishery, which targets the large individuals. Catch per unit effort was constant through 2001 and then decreased dramatically, reflecting the noted change in fish length and condition. The authors hypothesize that this decrease is related to the industrial fishery, which began in the 1996-97 austral summer, and which concentrates effort over the ice-free Ross Sea continental slope. Due to limited prey choices and close coupling among mesopredators of the region, Antarctic toothfish included, the fishery appears to be dramatically altering the trophic structure of the Ross Sea.

Coexistence of mesopredators in an intact polar ocean ecosystem: The basis for defining a Ross Sea marine protected area

Grant Ballard, Dennis Jongsomjit, Samuel D. Veloz, David G. Ainley, PRBO Conservation Science and H.T. Harvey & Associates

Designation of an effective marine protected area (MPA) requires substantial knowledge of the spatial use of the region by key species, particularly those of high mobility. Within the Ross Sea, Antarctica, the least altered marine ecosystem on Earth, unusually large and closely interacting populations of several marine bird and mammal species co-exist. Understanding how that is possible is important to maintaining the ecological integrity of the system, the major goal in designating the Ross Sea as an MPA. We report analyses of niche occupation, two-dimensional habitat use, and overlap for the majority (9) of mesopredator species in the Ross Sea considering three components: (1) diet, (2) vertical distribution and (3) horizontal distribution. For (1) and (2) we used information in the literature; for (3) we used maximum entropy modeling to project species' distributions from occurrence data from several ocean cruises and satellite telemetry, correlated with six environmental variables. Results identified and ranked areas of importance in a conservation prioritization framework. While diet overlapped intensively, some spatial partitioning existed in the vertical dimension (diving depth). Horizontal partitioning, however, was the key structuring factor, defined by three general patterns of environmental suitability: (1) continental shelf break, (2) shelf and slope, and (3) marginal ice zone of the pack ice surrounding the Ross Sea post-polynya. In aggregate, the nine mesopredators used the entire continental shelf and slope, allowing the large populations of these species to co-exist. Conservation prioritization analyses identified the outer shelf and slope and the deeper troughs in the Ross Sea shelf to be most important. Our results substantially improve understanding of these species' niche occupation and imply that a piecemeal approach to MPA designation in this system is not likely to be successful.

The Hunger Games: Killer Whales in the Ross Sea

Robert L. Pitman and John W. Durban, Southwest Fisheries Science Center, NOAA Fisheries

Killer whales (*Orcinus orca*) of three forms (possibly species; types A, B and C) have been documented in the Ross Sea where relatively little is known about their specific feeding habits, population sizes and migratory movements. Type A is a rare visitor, possibly occurring only when the Ross Sea polynya opens up to outside waters; it occurs in open water where it appears to prey mainly on Antarctic minke whales (*Balaenoptera bonaerensis*) but also southern elephant seals (*Mirounga leonina*). Type B is uncommon; it preys on ice seals (and possibly penguins), and in the Antarctic Peninsula area it has shown a clear preference for Weddell seals (*Leptonychotes weddellii*). Type C ('Ross Sea killer whale'; RSKW) is a dwarf form (maximum length 6 m, versus ca. 9 m for type A and possibly B); it is commonly encountered in the Ross Sea where it can be locally abundant (or at least it was historically). It is a presumed fish specialist because to date all that is known about its feeding habits is that it has been observed several times carrying around large Antarctic toothfish (*Dissostichus mawsoni*). Very little is known about migration in Antarctic killer whales: satellite tagging of type B killer whales in the Antarctic Peninsula area, along with anecdotal data (e.g., cookiecutter shark-bite scarring) suggest that all three forms undergo regular, but perhaps aseasonal, long-distance migrations to lower latitudes where they may or may not feed. Knowing the degree to which RSKW feeds on the very large toothfish (to 150 kg) and the Antarctic silverfish (*Pleuragramma antarcticum*), a much smaller species (0.2 kg,) that nevertheless may contribute >90% of the midwater fish

biomass on the Ross Sea continental shelf, will be critical in assessing the impact of commercial toothfish extraction on killer whales within the Ross Sea.

Monitoring the Ross Sea from space: applications of high-resolution imagery

Michelle LaRue, University of Minnesota

High-resolution satellite imagery (0.6-5m resolution, acquired by DigitalGlobe satellites WorldView-1, WorldView-2, and QuickBird-2, and GeoEye satellites GeoEye and IKONOS) has become increasingly useful as a tool for ecological research in the Antarctic. The combination of high-resolution and fast return rate of these polar-orbiting satellites allows for repeat imagery (i.e., up to daily) of key areas in Antarctica. In this presentation, I reviewed the recent literature (<2 years old) on the use and capabilities of this imagery and provide suggestions for future studies. The first example study was conducted by Fretwell et al. (in press), who used pan-sharpened QuickBird-2 imagery to census the entire emperor penguin population during October 2009. We found 44 colonies in Antarctica and a population estimate of 238,000 breeding pairs of emperor penguins, with 56,000 breeding pairs in the Ross Sea. I then reviewed LaRue et al. (2011), who compared ground counts of adult Weddell seals in Erebus Bay to counts of seals from satellite imagery during the same dates. We found a positive correlation ($r^2=0.96$, $P<0.001$) between ground counts and satellite counts, suggesting that counts from satellite imagery can be a reliable way to estimate populations of Weddell seals. I also discussed the capabilities of high-resolution imagery in the detection, identification, and species differentiation of Adélie, chinstrap, gentoo, and macaroni penguins in the Antarctic peninsula (Lynch et al. 2012), and how we can combine historic air photos, population estimates, and satellite imagery to better understand the Beaufort Island population of Adélie penguins. Preliminary results of the latter showed nesting space use by Adélie penguins increased by 21% during 1983-2010 as the glacier to the north receded by 250m. Finally, I displayed how the combination of high-resolution imagery and RADAR data can detect the presence of ships in the Southern Ocean. Suggestions for future work include the expansion of these data and techniques to monitor the Ross Sea (i.e., annual population estimates of Weddell seals, and Adélie and emperor penguins), and investigating uses for identifying whales, crabeater seals, and potentially, fishing vessels.

The Southern Ocean Observing System (SOOS)-Rationale and Themes

S.F. Ackley, Member SOOS Science Steering Committee

The observations to date suggest the Southern Ocean is changing: the region is warming more rapidly than the global ocean average; salinity changes driven by changes in precipitation and ice melt have been observed in both the upper and abyssal ocean; the uptake of carbon by the SO has slowed the rate of climate change but increased the acidity of the SO; and there are indications of ecosystem changes. However, the short and incomplete nature of existing time series means that the causes and consequences of observed changes are difficult to assess. Sustained, multidisciplinary observations are required to detect, interpret and respond to change. The SOOS will provide the long-term measurements required to improve understanding of climate change and variability, biogeochemical cycles, and the coupling between climate and marine ecosystems. The six themes to be studied and monitored under SOOS over the coming decade are:

- 1.The role of the Southern Ocean in the planet's heat and freshwater balance.
- 2.The stability of the Southern Ocean overturning circulation.
- 3.The role of the ocean in the stability of the Antarctic ice sheet and its contribution to sea-level rise.
- 4.The future and consequences of Southern Ocean carbon uptake.
- 5.The future of Antarctic sea ice.
- 6.The impacts of global change on Southern Ocean ecosystems

SOOS is co-sponsored by SCAR and SCOR and had the initial meeting of the Science Steering Committee in February 2012. An International Program Office is located in Hobart Tasmania, staffed by an Executive Director, Louise Newman (www.soos.aq), can be contacted for further and continuing information.

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APPENDIX 5. LIST OF HYPOTHESES, certainly not exhaustive, relative to the U.S.A. goal to protect structure and function of the Ross Sea ecosystem.

Assuming fishing will continue along the central Ross Sea slope, targeting largest fish for as long as possible (striving for 50% reduction in spawning biomass of pre-fished stock).

CENTRAL HYPOTHESIS #1: Removing a large proportion (50%) of spawning biomass of Ant toothfish, i.e. the large fish, will alter the structure and function of the Ross Sea ecosystem.

1. Owing to severe reduction in large toothfish in the water column over the shelf (which is happening), silverfish, the main food of large toothfish in the water column over the shelf, will increase in prevalence, one measure of which, owing to competitive release, will be increased populations of penguins and increased pupping rates of Weddell seals. Both penguin numbers and seal productivity have been measured for decades in the Ross Sea, thus a good baseline is available. Another measure would be direct acoustic surveys of silverfish done systematically, not opportunistically or occasionally.

a. One complexity (probably others), as silverfish increase, crystal krill should decrease, because silverfish are the most important predator of crystal krill. So, cannibalism within silverfish should increase, e.g. occurring earlier in season than observed thus far. What will be needed is analysis of silverfish diet over time within a season and between seasons.

2. Prevalence of small toothfish over the shelf will increase, thus leading to reduced prevalence of benthic nototheniid fish or shrimp (toothfish prey). Camera or equivalent surveys needed. Cascades to benthic communities, see #4, could be detected with stable isotope analysis to reflect diet change.

3. Populations of Weddell seals will decrease depending on reliance on large toothfish as prey; pattern could be population/area specific depending on ability of seals to prey switch. Can be assessed using satellites.

4. Growth rate, and therefore foraging pressure in benthic communities, of small toothfish will increase. Progressive change in size at age would be detected in otoliths.

5. Residence time of Ross Sea killer whales will decrease locally, i.e. movement rates will increase, as large toothfish disappear from over the shelf leading to increased KW search effort (Hanchet et al. 2008 don't allow large toothfish to be over the shelf, but Ainley et al. 2012 reports data on >5000 fish >100cm caught and released in McMurdo Sound). Satellite tags and/or moorings to listen for whales. Another measure of this would be changes in the geographic extent of foraging by post-breeding female seals.

a. Foraging efficiency will decrease over time. Determined from GPS/tdr tags.

CENTRAL HYPOTHESIS #2: concentration of longlining over the slope (and sea mounts) is degrading/has degraded habitat for toothfish.

6. VME species prevalence is significantly different in fished vs unfished areas. Camera surveys.

7. Macrourid density (main prey of benthic toothfish in slope waters) is lower in fished vs unfished areas of slope. Camera surveys.

8. Owing to #7, condition of toothfish differs in fished vs unfished areas. Complicating factor: density of toothfish might be different in fished vs unfished areas, thus affecting toothfish trophic competition (food available per fish) and therefore, ultimately, condition.

9. Recovery of benthic community in fishing area is episodic at unknown periodicity (appears to be the case in McM Sound). Regular camera surveys and moorings needed in unfished area to measure current rates and food availability. Comparison with long time series in McMurdo Sound to determine if system-wide process is involved (= climate).

10. Toothfish are more concentrated (higher density) in areas of 'lush' benthic communities. Camera surveys.

CENTRAL HYPOTHESIS #3. Climate or global change effects will mask fishery effects. These effects should be easy to separate among those hypotheses (6-10) related to direct longlining effects on benthic communities. As for other hypotheses.....

11. Year-class strength of silverfish (as revealed from otoliths) is related to physical properties as assessed remotely (from space) and by moorings: ice cover, spatial and temporal variation in algal blooms, water temperature in spawning areas (McMurdo Sound, Terra Nova Bay). Then modeling would be used to integrate expectations with respect to frequency/severity of climate events (ones that lead to strong year class strength) vs silverfish prevalence. Silverfish are 98% of the ichthyoplankton in the Ross Sea.

12. Search effort for prey by predators of toothfish is different in fished vs unfished areas; should be no difference if it's climate. Satellite tagging, acoustic moorings.

13. No change in prevalence of cannibalism in silverfish, indicating no change in prevalence of crystal krill.

14. Prevalence and swarm characteristics of Antarctic krill over the slope decreases/changes as blue whales increase. May be too slow a process to be worthwhile in MPA RMP.
15. Prevalence of Antarctic krill in waters over eastern over slope decreases as expanding persistence of sea ice allows longer residence by crabeater seals.

**McMURDO SOUND, ANTARCTICA:
AN OPPORTUNITY FOR LONG TERM INVESTIGATION OF A
HIGH-LATITUDE COASTAL ECOSYSTEM**

Report of a Workshop held in San Jose, California, 13-15 April 2004



Preamble

A workshop to discuss the needs and potential for establishment of a Long-Term Ecological Research (LTER) program in the McMurdo Sound region near Ross Island, Antarctica, sponsored by the Office of Polar Programs of the National Science Foundation, was held in San Jose, CA, 13-15 April 2004. Participants in the workshop included representatives from both the polar research community as well as from existing LTER projects in North America and Antarctica (see Appendix). The stated objective of the meeting was to assess the feasibility and challenges of initiating an LTER program in McMurdo Sound, Antarctica. The meeting provided information on various LTER sites, objectives and description of the LTER Network, components of the McMurdo Sound ecosystem, and the existence of various long-term and integrative McMurdo Sound data sets. A broad discussion resulted concerning the opportunities, challenges and direction of a potential LTER site. The attendees were in agreement that the site offers a unique and important opportunity to understand basic ecological processes that are occurring in a coastal, polar marine system, and would provide an invaluable comparison with the existing more pelagic Palmer LTER project as well as other coastal LTERs in the Network.

This report summarizes the results of the meeting, and provides broad recommendations to the National Science Foundation on the need for the establishment of Long-Term Ecological Research Project in McMurdo Sound, Antarctica.

Table of Contents

Preamble	2
Table of Contents	3
Executive Statement	4
Introduction	6
Table 1. Existing long-term data sets	9
Table 2. Integrative data sets	10
Brief description of the greater McMurdo Sound ecosystem	11
Physical attributes	11
Primary production	12
Sea-ice microbial communities	14
Benthos	16
Middle trophic levels	19
Top trophic levels	22
Major Data Gaps	24
Why an LTER at McMurdo Sound?	25
How an LTER could be implemented	28
Linking to the LTER Network	30
International Collaborations	32
References Cited	33
Appendix A. Workshop agenda	41
Appendix B. Workshop participants	42

EXECUTIVE STATEMENT

Long-term research in ecology is required to understand slow or transient processes, episodic or rate events, trends, multi-factor responses, and processes that exhibit significant time lags. To investigate these phenomena, the National Science Foundation established the Long-term Ecological Research (LTER) program in 1980. The program has grown to more than 24 sites. Herein, we explore the desirability and feasibility of adding an Antarctic coastal site to the LTER Network.

McMurdo Sound is the southernmost reach of the open ocean, and despite being far removed from civilization, it has received considerable attention from scientists for several decades. As a result it is the best-studied neritic system of the southern high latitudes, being adjacent to the logistics hubs of the Antarctic research programs of the United States, New Zealand, and Italy. The longest time series of marine biological data in the Antarctic exist for several components of this neritic ecosystem, and various process-related sets of information provide further insights into the structure and function of the region's food web. Portions of the highest trophic level and benthic communities are also well studied. Despite this substantial scientific effort during the past four decades, the links between production, food-web structure and ecosystem function remain poorly understood.

Given the background information available, a significant opportunity for understanding the basic ecological processes that govern neritic Antarctic systems exists in a co-ordinated study of the ecosystem dynamics of the south western Ross Sea, centered on McMurdo Sound. Moreover, this area is one of the few oceanic systems that have not been impacted by direct anthropogenic factors, such as wide-spread pollution, resource extraction, and introduction of non-indigenous organisms; both bottom-up and top-down ecosystem forcing are in place. Therefore, an integrated study of the ecology of McMurdo Sound stands to make major contributions to our understanding of ecosystems in the Antarctic, as well as in polar and marine systems elsewhere.

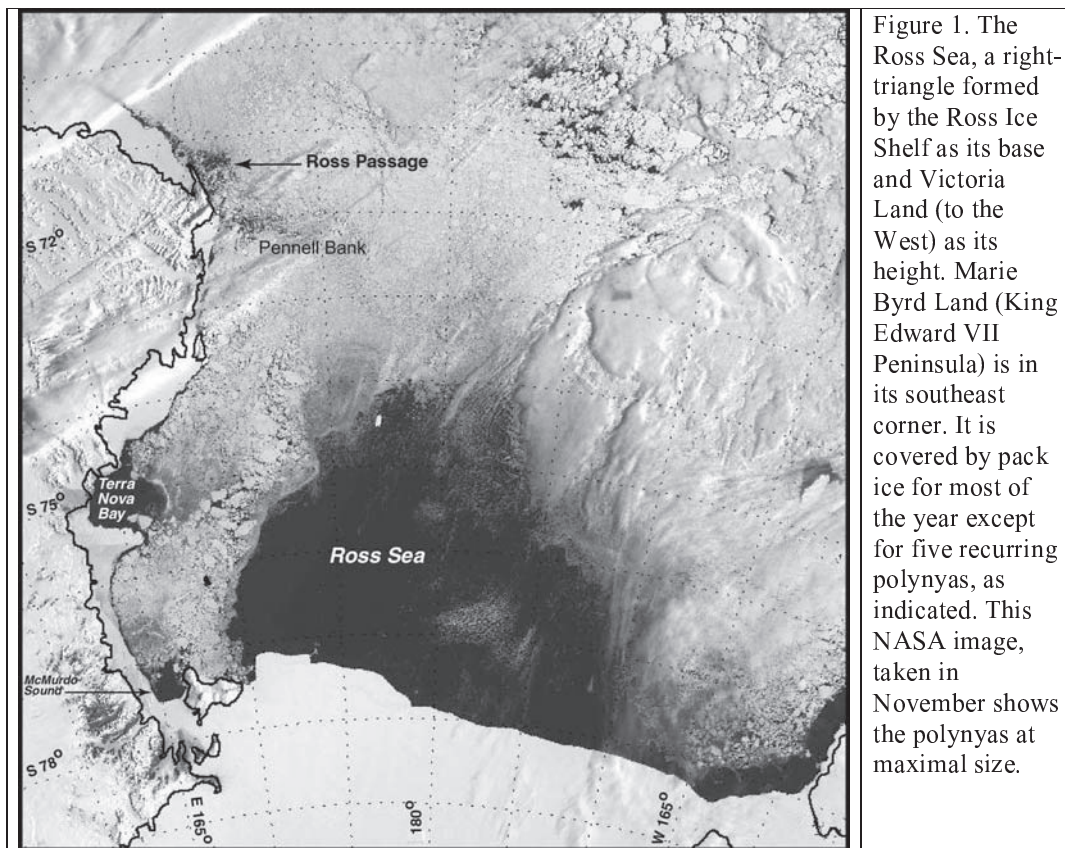
The southern Ross Sea is an extreme in polar systems, at least insofar as physical forcing. As such, McMurdo Sound experiences biologically-effective radiation for only a few months per year and cold temperatures year round. Despite the relatively short burst of primary production, supplemented by phytoplankton advected in from the adjacent Ross Sea, its fauna is incredibly rich at all parts of the food web (e.g., from the benthos to highest trophic levels). Therefore, it offers a contrast to the dry desert of the adjacent McMurdo Dry Valley's LTER and directly complements the existing LTER at Palmer Station, which investigates a pelagic system at lower latitude. The study of McMurdo Sound and vicinity would directly complement other studies at other coastal sites in the LTER Network — all of which occur in low latitudes, are shallow, and receive considerable influx of nutrients from terrestrial sources.

In order to fulfil the ecological research potential of McMurdo Sound, a long-term investigation of the ecological linkages within the system must be initiated. Such an effort would need to be continued for long periods of time, and seek to understand the responses of the major components of the system over a variety of space and time scales. Given the remoteness (but not absence of logistic support), novel techniques of sampling would also be required, and indeed, such a study would require a substantial investment of capital. However, there is no doubt that

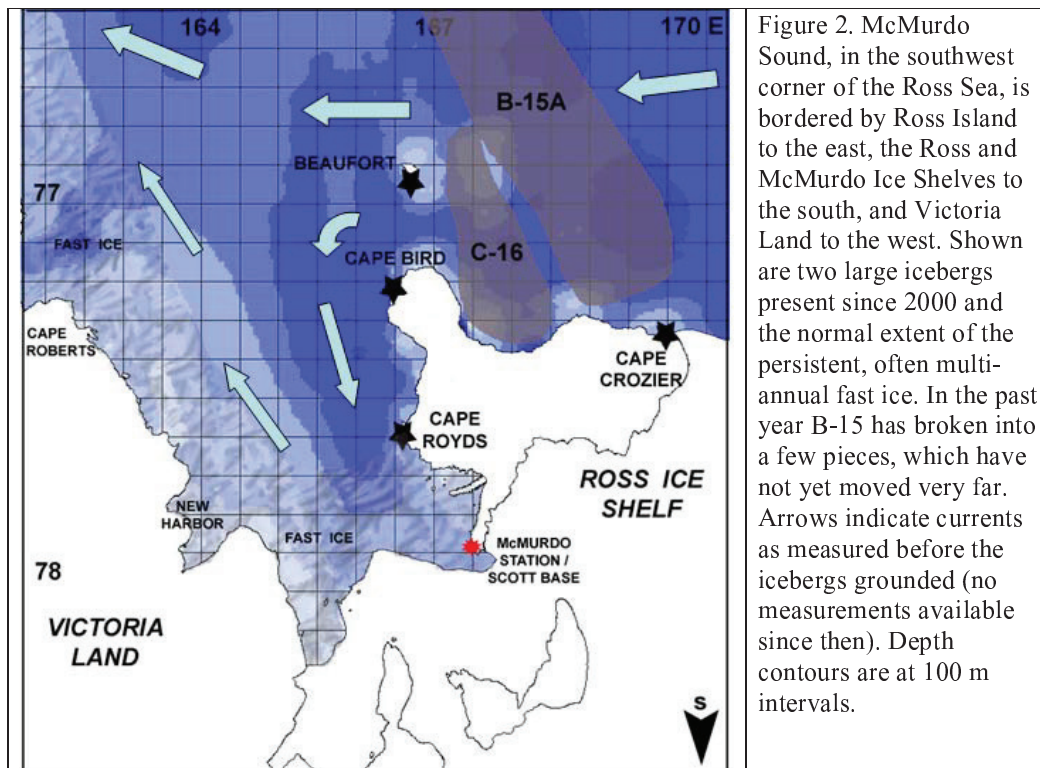
the scientific insights into basic ecological interactions gained from such a study would surely justify such efforts and expenditures. The establishment of a new LTER site in McMurdo Sound is strongly recommended.

Introduction

The Ross Sea, in the Pacific Sector of the Southern Ocean, is a well-defined embayment bounded by Victoria Land to the west, King Edward VII Peninsula (Marie Byrd Land) to the east, the Ross Ice Shelf to the south, and the continental shelf break to the north (Figure 1). Its waters are produced and modified *in situ*, with influence from intrusions of waters from the Antarctic Coastal Current (Jacobs et al. 2002). The biology and ecology of the shelf, characterized by a unique biota, is driven by the physical factors, such as ice, temperature, and irradiance, as well as ecological processes, like production and predation. Such processes, for at least some of the components, include regular migrations and exchanges with waters outside the continental shelf (e.g., cetaceans, penguins). The Ross Sea Shelf Ecosystem is not part of what has been referred to as the 'Antarctic marine ecosystem,' which is pelagic and is dominated in mid-trophic levels by Antarctic krill (*Euphausia superba*; e.g., Laws 1977, May et al. 1979, Hempel 1985, and others). McMurdo Sound, the most southerly extension of the Ross Sea, is a neritic (shelf) system and, except for waters to the south underlying the Ross Ice Shelf, is the southernmost location of open water in the entire ocean. The Sound is bounded by Ross Island to the east, the Ross and McMurdo ice shelves to the south, and Victoria Land to the west (Figure 2).



Scientific investigation of McMurdo Sound and vicinity initially was sporadic, but began with the very first explorers to the Antarctic. Named after Archibald McMurdo, third lieutenant of *HMS Terror*, this area of the southwest Ross Sea was first explored at the end of January 1841 by a British expedition under James Clarke Ross. The Sound was first entered on 16 February of that year, and visited again the following year. On board were Joseph Hooker and Robert McCormick, who subsequently became well-known for their biological observations in the Southern Ocean. However, it wasn't until the first two decades of the 20th century that further research was conducted, this time by those persons associated with British expeditions under the leadership of Robert Scott and Ernest Shackleton. During operations related to the International Geophysical Year (1957-59), the United States and New Zealand established permanent research bases on Ross Island. Marine science, principally confined to McMurdo Sound with some efforts in the Ross Sea, has been continuous ever since. The US and NZ programs immediately began to archive data on specific areas of interest that have proven to be some of the longest time series in the Antarctic (Table 1). During the 1990s, the Italian Antarctic Program established a base at Terra Nova Bay, on the Victoria Land coast at 75°S, about 200 km north of McMurdo Sound. Despite this important research emphasis, as well as the fact that McMurdo Station is the major logistics base for all Antarctic research, none of the Antarctic-wide marine biological initiatives (e.g., BIOMASS, CCAMLR-ecosystem monitoring, Southern Ocean GLOBEC) have included McMurdo Sound or the Ross Sea in their programs. Nevertheless, an impressive array of integrative, cross-component data sets has arisen toward establishing a better understanding of marine processes in the Ross Sea and, in general, Antarctic neritic waters (Table 2).



The Ross Sea represents a ‘model’ study area for understanding neritic processes in the Antarctic region, largely because it is a very wide shelf (relative to the rest of the Antarctic continental shelves). The Ross Sea’s geology and sedimentary environment is very well known. In part this effort has been stimulated by interest in climate change and the history of the West Antarctic Ice Sheet, which during the last glacial maximum had overlain the entire Ross Embayment (and now covers half; e.g., Stuiver et al. 1981, Anderson 2000). The physical oceanography and hydrography has been investigated since the 1960s through numerous *R/V Eltanin* surveys and later projects such as RISP (Ross Ice Shelf Project) and JGOFS (Joint Global Ocean Flux Study), while satellite investigations have included work on sea-ice dynamics (e.g., Barry 1988, Jacobs & Comiso 1989, Jacobs & Giulivi 1998, Jacobs et al. 2002, van Woert et al. 2003; Dinimann et al. 2003). Biogeochemical processes that contribute to sediment characteristics have been investigated by JGOFS and ROAVERRS (Research on Ocean and Atmospheric Variability and Ecosystem Response in the Ross Sea), and the temporal patterns and controls of primary productivity have also been elucidated (e.g., Smith & Sakshaug 1990, Arrigo et al. 1998, Arrigo & van Dijken 2004). The ecology of fast-ice epontic microalgae and microbial communities is better known than anywhere in the Antarctic (e.g., Sullivan et al. 1983, Grossi et al. 1987, Ackley & Sullivan 1994, Arrigo et al. 1994). Some top-trophic levels are well known: seals (Testa & Siniff 1987, Testa et al. 1990; Ackley et al. 2003), and birds (e.g., Ainley et al. 1983, 1984, 1998, 2003a, b). Baleen whales, however, have only been surveyed in open water, or very rarely in the pack-ice (Ainley 1985, Ichii et al. 1998, Branch & Butterworth 2001), and little is known of their ecology. Added to this body of knowledge is 40 years of investigation of the ecophysiology of McMurdo Sound fishes (e.g., DeVries & Eastman 1981, Eastman & DeVries 1986, Eastman 1993), thus, continuing a scientific tradition that began with the James Clark Ross expedition, one of whose major scientific contributions was toward understanding Southern Ocean fish biology.

Considering the fifty years of research that has ensued since the IGY, the workshop participants agreed on the following as a central and overarching statement that might ‘steer’ a McMurdo Sound LTER:

The structure and function of the McMurdo Sound ecosystem, occurring against the backdrop of marine life near its latitudinal limit, reflects a series of remarkable and unique adaptations to extreme variability in seasonal and interannual climate, nutrient inputs, productivity, and community composition. The overall, robust and cold-adapted ecosystem, composed of resident benthic and seasonally abundant pelagic faunas, is sensitive to this extreme variability. In response, component species and communities, through specific life-history strategies, make adjustments to this variability at different temporal scales.

Table 1. Summary of existing long-term data sets with their approximate geographic domain and period of collection.

Data Type	Geographic Domain	Period Collected	Selected References
Weather	McMurdo Sound	Continuously since 1979	Automatic Weather Systems; University of Wisconsin
Weather	McMurdo Sound	Continuously since 1959	New Zealand Antarctic Program, Scott Base
Temperature and salinity	SW Ross Sea	Since 1960s	Jacobs et al. 2003
Sea ice extent and concentration	McMurdo Sound, Ross Sea	Continuously since 1979	Jacobs & Comiso 1989 Parkinson et al. 2002
Fast ice extent	McMurdo Sound	Annually since 1959	US Coast Guard US Antarctic Program
Incident UV and visible radiation	McMurdo Sound	Continuously since 1988	Booth et al. 1994
Nutrient and phytoplankton concentrations	McMurdo Sound, Ross Sea	Since the early 1970s; concentrated in the southern Ross Sea	Holm-Hansen et al. 1977 El-Sayed et al. 1983 Smith & Nelson 1985 Arrigo et al. 1999
Vertical POC flux	McMurdo Sound, Ross Sea	Since 1985 at some sites	Dunbar et al. 1985, 1998 DiTullio et al. 2000
Adélie penguin colony size	Ross Island region	Continuously since 1959	Wilson et al. 2001 NZ Antarctic Program
Seal population size	McMurdo Sound	Annually since 1960s	Stirling 1969 Cameron 2001
Benthic communities	McMurdo Sound	Annually since 1988, some data since 1960s	Dayton 1989 Conlan et al. 2000
Toothfish CPUE	McMurdo Sound	Since 1960s	DeVries (unpubl.)

Table 2. Summary of existing integrative data sets bearing on ecological processes in McMurdo Sound and vicinity.

Data Type	Geographic Domain	Period Collected	Selected References
Holocene glacial and sea ice history	McMurdo Sound, SW Ross Sea	Ice and sediment cores detailing recent 10,000 years	Andrews et al. 2002 Cunningham et al. 1999
Phytoplankton biomass	Ross Sea	Within specified oceanographic cruises and by satellite	Arrigo & McClain 1994 Smith et al. 1996 Smith et al. 2003
Shallow benthic community composition and processes	McMurdo Sound	Intermittently since 1974	Dayton 1990 Dayton & Oliver 1977 Barry et al. 2003
Sea ice microbial communities	McMurdo Sound	1981-1988	Sullivan et al. 1983 Grossi et al. 1986
Fish dynamics	McMurdo Sound	Since 1970	DeVries & Eastman 1981
Seal natural history patterns	McMurdo Sound	Since 1960s	Stirling 1971 Testa & Siniff 1987
Adélie penguin natural history patterns	Ross Island	Since 1960s	Ainley 2002
Marine bird and mammal distribution and ecology	Ross Sea	1970-80s	Ainley et al. 1984 Ainley 1985

Brief Description of the Greater McMurdo Sound Ecosystem

Physical attributes

Owing to isostatic pressure from the immense Antarctic ice sheets, the Ross Sea shelf is deeper than most other continental shelves. Its shallowest portions, except for the narrow and steep coastal margin, are often removed from the coast and the ice sheets (e.g., the Pennell, Iselin and Ross banks). McMurdo Sound itself is characterized by an exceptionally steeply sloped bathymetry, especially on the Ross Island side. Its maximum depth is slightly more than 500 m.

A general clockwise, cyclonic, sluggish circulation is evident within the confines of the Ross Sea (Ainley & Jacobs 1981, Dinneman et al. 2003). Along the shelf-break this current opposes the easterly-flowing East Wind Drift (Klepikov & Grigoryev 1966, Jacobs et al. 1970) that encircles the continent south of the Antarctic Circumpolar Current (ACC; which flows in a westerly direction). Within McMurdo Sound waters communicate with the Ross Sea directly to the north, but also by a deeper, under ice-shelf connection. McMurdo Sound circulation during summer includes a southward current along the east shore and a northward current along the west shore; the southward current may be seasonal (Figure 2). Waters overlying the Ross Sea shelf are referred to as High Salinity Shelf Water (HSSW), or Ross Sea Shelf Water (RSSW) (Ainley & Jacobs 1981, Dinimann et al. 2003). The high salinity is derived from sea-ice formation (and salt rejection) that persists for much of the year, as well as the long residence time of water within the Ross Sea (ca. 4 years; Jacobs & Giulivi 1998). Jacobs et al. (2002) have noted a gradual freshening of RSSW to the extent that, recently, it lost its attribute of having the highest salinity surface water in the Antarctic. There is also evidence of mesoscale and small-scale circulation patterns that have significant effects on productivity (e.g., Hales et al., in press).

Throughout most of the year (ca. 8 mo.), the Ross Sea is covered almost entirely by annual sea ice (Figure 1). At its maximal extent this ice extends well north of the Ross Sea and reaches the southern boundary of the ACC (Comiso et al. 1993). Maximal ice extent in the Pacific Sector of the Southern Ocean is reached in August-September, but the Ross Sea is largely covered much earlier (in March or April). By January, the ice has retreated well south of the southern boundary of the ACC, leaving rich waters available to many seasonal organisms (Tynan 1998). In winter, the ocean immediately bordering the Ice Shelf is kept largely ice free (or with greatly reduced ice concentrations) by the development of strong, off-shelf katabatic winds. This area is termed the Ross Sea Polynya. In October the sea ice begins to recede over a much wider area, essentially outward from the polynyas. In the northern portion of the Ross Sea it begins to melt to the south (vicinity of Ross Passage Polynya), at the same time that the Ross Sea Polynya enlarges due to a rapidly changing heat budget. The disappearance of ice continues and accelerates through mid-December, and by February the ice reaches its annual minimal extent. At that time the western Ross Sea is generally clear of sea ice except for a narrow band along the southern Victoria Land coast. In most years the eastern Ross Sea retains extensive sea ice year round, as substantial interannual variability exists in the timing of ice removal, and the distribution and concentration of ice; in years of greatest winter extent much more sea ice remains in the subsequent summer and *vice versa* (Jacobs & Comiso 1989, Jacobs & Giulivi 1998). Such variability is expected to have effects on biotic resources, but those effects are at present poorly known.

Three polynyas, the large Ross Sea Polynya along the front of Ross Ice Shelf and the smaller

McMurdo Sound and Terra Nova Bay polynyas (at ca. 75°S off the coast of Victoria Land), are significant oceanographic features in the southern Ross Sea (Jacobs & Comiso 1989, Arrigo et al. 1998). The polynya in Terra Nova Bay is a latent-heat polynya formed solely in response to persistent, katabatic winds that continually sweep away newly formed ice, and hence continuously generates more ice. It also generates a large amount of cold, saline water which may flow off the shelf and contribute to deep-water formation in the Southern Ocean. The Ross Sea Polynya also is forced by katabatic winds, but also has a heat source from outside the continental shelf that enhances the melting of ice. Specifically, waters from the ACC are intruded onto the shelf, and eventually mixed to the surface whereby they provide heat to melt the pack ice. As such, it should be considered a mixed-type of polynya and intermediate between a latent- and sensible-heat polynya. These polynyas allow early access of the southern Ross Sea by ships, access to the food web by air-breathing top predators, are pivotal in the timing and extent of primary production, and are also closely involved in the life cycle of important middle-trophic level species (crystal krill; see below).

In McMurdo Sound, persistent fast ice exists along the Victoria Land coast; in the past 100 years it has rarely broken out (Figure 2). In the eastern Sound, fast ice is more or less annual, residing from Cape Royds southward from May to December, but usually being clear of ice south to the shelf boundaries during the remaining months. This pattern has changed recently due to the grounding of two very large icebergs (named B15A and C16 based on their geographic sector of origin), which have helped to increase the extent of fast ice and hold it in place without breakout.

Primary production

Primary production in McMurdo Sound is ultimately related to the production generated *in situ* or that is advected into the area from the southern Ross Sea (Figure 2). The three likely sources of production are: phytoplankton, the sea ice microbial community, and macroalgae. All have been studied previously in McMurdo Sound as has phytoplankton production in the Ross Sea.

Phytoplankton in McMurdo Sound and the Ross Sea undergo an extreme seasonal cycle, which generally exhibits a unimodal peak of biomass in late-December or early January. Chlorophyll concentrations approaching $15 \mu\text{g L}^{-1}$ have been measured in the southern Ross Sea, and values similar to that have been repeatedly observed by satellites (Arrigo & McClain 1994; Arrigo et al. 1999; Smith et al. 2000; Smith & Asper 2001, Smith et al 2003; Figure 3). The limitation of growth earlier in the growing season is largely due to the irradiance available for growth (Knox 1994), and growth in early December is near maximal. During January-February, when irradiance is optimal, micronutrients apparently limit growth in the open Ross Sea (i.e., those regions away from any inputs from ice; Sedwick & DiTullio 1997; Olson et al. 2000). As ice begins to form, vertical mixing increases (along with iron inputs from below), but irradiance again becomes limiting, and by mid-March phytoplankton growth effectively ceases. The seasonal pattern in McMurdo Sound is similar, although apparently more extreme due to the strong influence of advective inputs relative to *in situ* production. Phytoplankton biomass increases abruptly (by an order of magnitude and more) over a time span of days (S. Alexander, pers. comm.), indicating advection of blooms from the southern Ross Sea (Barry 1988; see Figure 2). Algal growth in McMurdo Sound is likely limited by irradiance as mediated by the presence of ice, and because of the proximity to glacial inputs, bottom sources, and ice, iron

limitation is likely less significant. Much of the phytoplankton biomass does not appear to be grazed within the water column (Arrigo et al. 2003), but sinks and is utilized either by heterotrophic bacteria in the water column and/or by benthic communities.

Sea ice microbial production is temporally separated from that of phytoplankton, in that it is initiated earlier in the growing season, and is terminated by the melting or disruption of the ice. It can occur at different horizons within the ice (e.g., Garrison et al. 1986, Horner et al. 1992, Ackley and Sullivan 1994, Lizotte 2003), but in McMurdo Sound the most predominant production appears to be the under-ice community (Sullivan et al. 1983, Arrigo et al. 1995). The growth of this assemblage is largely limited by irradiance (Grossi et al. 1987), and the biogenic material is sloughed off abruptly upon basal melting, and thus represents a significant, episodic flux to the benthos. Chlorophyll concentrations in the ice can be up to two orders of magnitude greater than in the water column (when compared volumetrically), and over a single order of magnitude when integrated over the entire ice and water column. Thus, the material generated in the ice is likely a critical component of the seasonal cycle of production in McMurdo Sound.

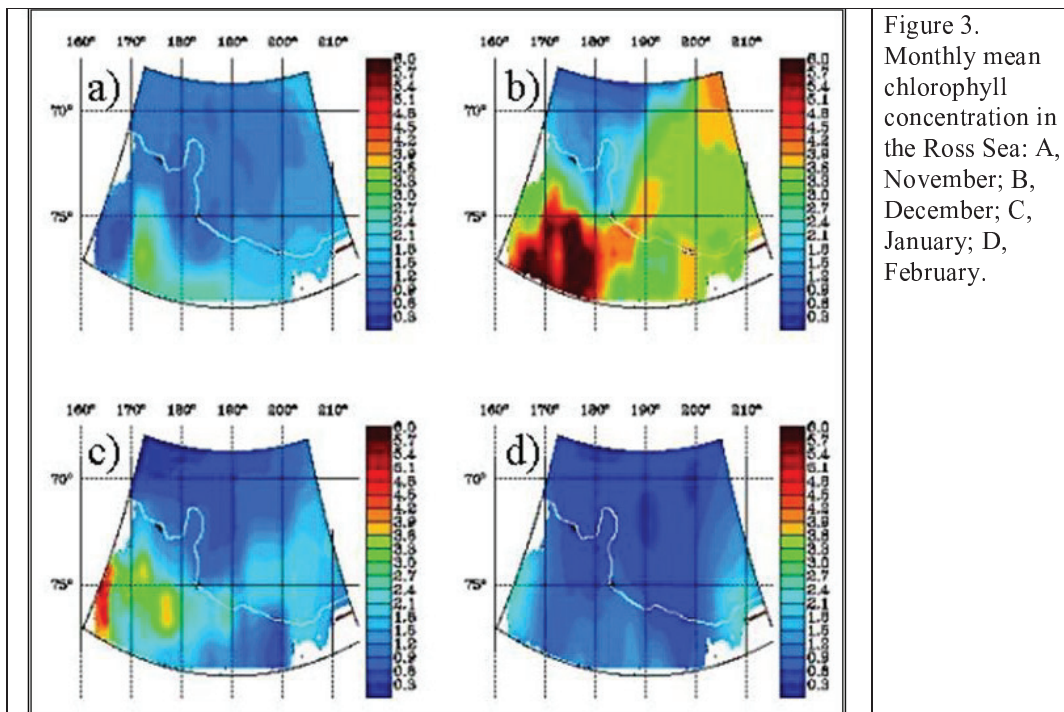


Figure 3.
Monthly mean
chlorophyll
concentration
in the Ross Sea: A,
November; B,
December; C,
January; D,
February.

A third component of organic genesis is that of macroalgal production. Growth of macroalgae is limited by available substrate in some locations, but in McMurdo Sound is largely limited by irradiance. Thus, production is limited to areas where hard substrates are within the euphotic zone, and the production necessarily is a minor component of the overall carbon budget of the region. In localized areas, however, it can be quite substantial. The growing season of

macroalgae is extremely short (ca. 3 weeks), but rates of biomass increase are substantial (Schwartz et al. 2003). The fate of this material is unknown, but it likely is largely transformed microbially and incorporated into a detrital component in the Sound.

Sea-ice microbial communities (SIMCOs)

Microbial communities are pervasive in the annual and multi-annual sea ice of McMurdo Sound (Figure 4). Typically, luxuriant microalgal blooms grow at the base of the congelation ice and within the platelet ice (when present) in the austral spring (October to December). These spring blooms are among the most concentrated microalgal communities in the oceans and can reach extremely high biomass (Arrigo et al. 1995). Chlorophyll concentrations in the ice can be two orders of magnitude greater than in the water column (when compared volumetrically), and over a single order of magnitude when integrated over the entire ice and water column. These stocks of microalgae stain the ice brown to black and effectively block penetrating solar radiation into the water column below to levels less than 0.1 % of surface values (Palmisano et al. 1985, SooHoo et al. 1987).

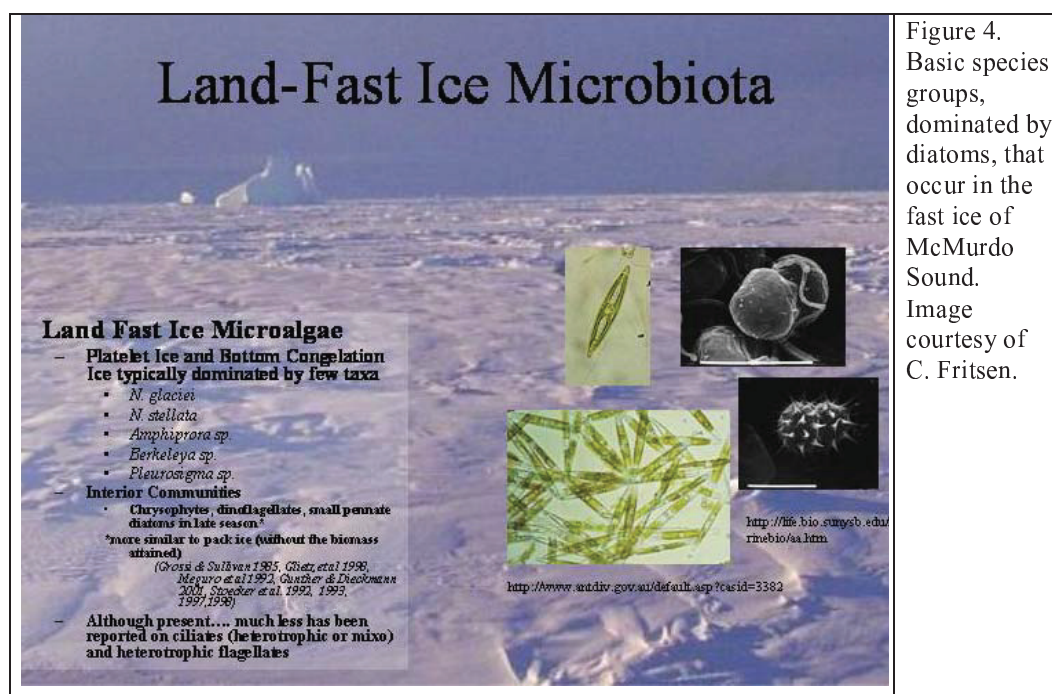


Figure 4. Basic species groups, dominated by diatoms, that occur in the fast ice of McMurdo Sound. Image courtesy of C. Fritsen.

The termination of these luxuriant spring blooms is initiated by the melting of the base of the ice that releases the biomass into the water column (Grossi et al. 1987). Hence, sea ice microalgal production and accumulation is temporally separated yet linked to that of phytoplankton. Later in the season- as the ice column warms, surface and internal habitats also foster the development of productive microbial communities. However, the biomass attained and

the rates of production attained by SIMCOs in these habitats are reduced when compared to the bottom ice habitats (Stoecker et al. 1998).

Diatoms typically dominate the microalgal component of the communities in the lower congelation ice and platelet ice habitats. However dinoflagellates, prymnesiophytes, prasinophytes, chrysophytes, cryptophytes, chlorophytes and euglenophytes also have been present and actually have dominated in numbers and biomass within internal or surface ice habitats at times.

Bacteria and protists (e.g. ciliates and amoeba) have always been recognized as integral components of the McMurdo SIMCOs (Figure 5). Yet, the use of molecular phylogenetic methods has allowed a better appreciation of the diversity and identities of the prokaryotes. For instance, molecular techniques have allowed the identification of Archaea in sea ice habitats and have allowed studies suggesting that the bacteria within SIMCOs appear to be dominated by the alpha-proteobacter and flexibacter-bacterioids-cytophaga groups. Cyanobacteria also have been found in surface fresh-water melt ponds, which are not as prevalent in Antarctic as in Arctic sea ice.

The current understanding of sea ice microbial food webs and their role in biogeochemical cycles and the food webs of McMurdo Sound is limited by a lack of measurements beyond biomass accumulation, photosynthetic production and bacterial production rates. Despite this general lack of study, it is believed that the sea-ice microbiota constitute an important source of food for under-ice grazers, such as copepods and euphausiids, which are important to higher trophic organisms. Moreover, in McMurdo Sound, with its persistent sea-ice cover, and relatively abrupt release of biomass upon bottom-ice melting (Grossi et al. 1987), SIMCOs are thought to have particularly strong importance to the benthic food webs.

Bacterial Biomass and Secondary Production

- Follows primary production spatial and temporal patterns.
- Bacterial community seasonal succession has generally not been addressed.
- However, preliminary culturing surveys have shown a preponderance of pigmented, highly cold-adapted epiphytic and free living strains (Bowman et al 1997).
 - *Colwellia*, *Theresea*, *Marinobacter*, *Planococcus*, *Pseudomonas*, *Psychrobacter*, *Halomonas*, *Hyphomonas*, *Sphingomonas*, *Arthrobacter*, *Planococcus*, *Halobacillus*.
- Preponderance of γ -proteobacteria, CFB divisions w/ some gram positives, and Verrucomicrobia. A hint of CFB's increasing in "algal-rich" environments (12 samples) (Brown and Bowman 2001)

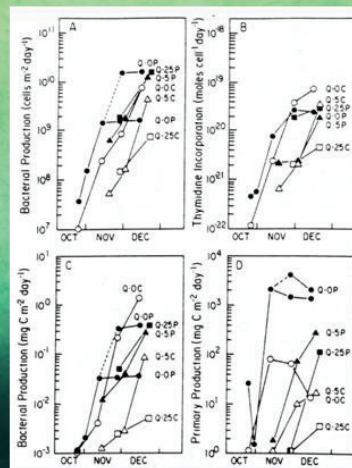
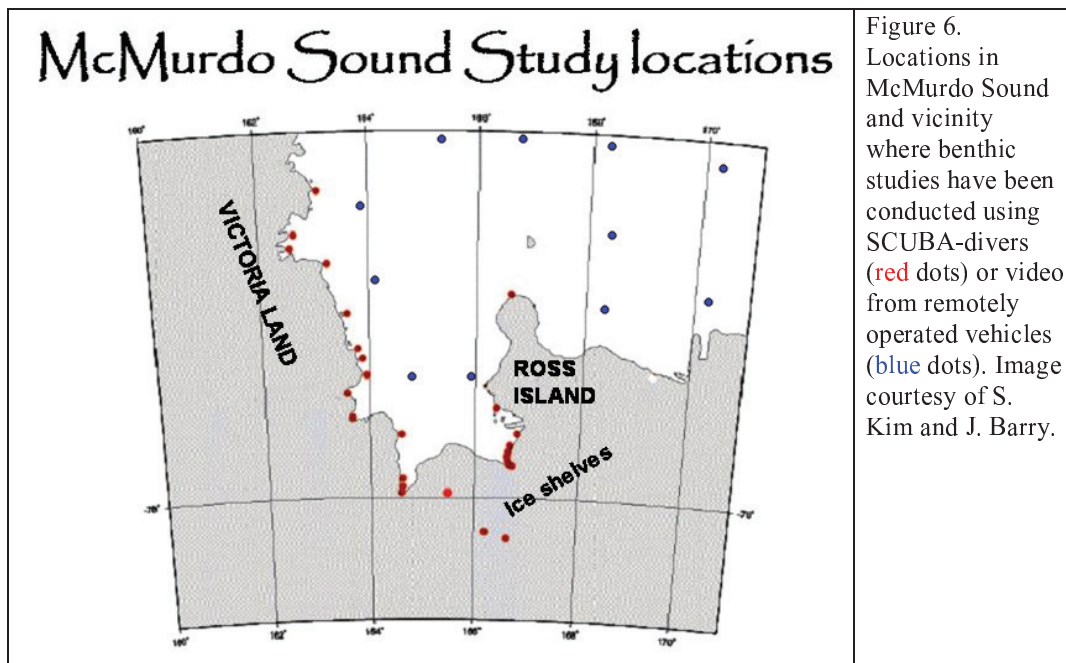


Figure 5. A brief review of the bacterial component of SIMCOs in McMurdo Sound. Image courtesy of C. Fritsen.

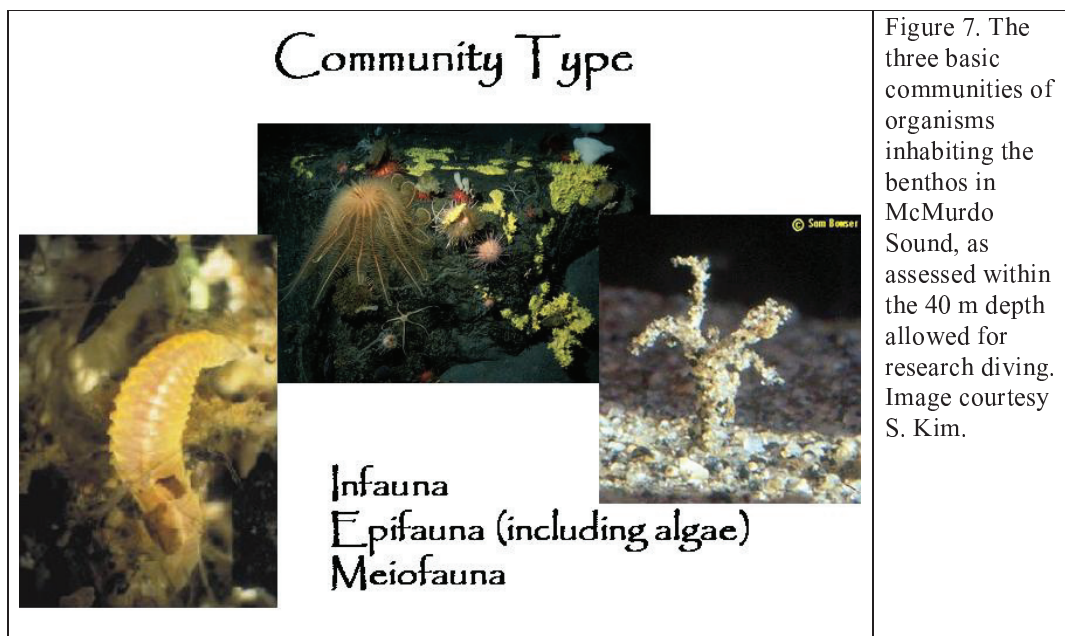
Benthos

Conditions that differentiate the Southern Ocean intertidal and subtidal benthic communities from the marine benthos elsewhere have been well described (Dayton et al. 1992, Arntz et al. 1994, Clarke 1996). Effects of the highly pulsed primary production are especially pronounced in benthic ecosystems that do not receive nutritional inputs from elsewhere (e.g., riverine sources that are prevalent in the Arctic; Knox 1970). In contrast to the highly variable light regimes, water temperatures exhibit minimal fluctuation, with the result that many benthic organisms are stenothermal. Many also have unusual adaptations to enable survival at temperatures below freezing (Arnaud 1977, Somero et al. 1998). Low temperatures combined with low annual productivity (in one large pulse) lead to generally slow growth rates, with concomitant slow maturation (Arnaud 1977, Arntz et al. 1994). Despite the physiological and biochemical adaptations of individual species, community recovery rates from natural disturbances in the Antarctic (Dayton et al. 1969, 1970, Gutt et al. 1996, Bockus 1999) are comparable with recovery rates from organic disturbances in temperate and tropical regions (Hunter & Evans 1995, Roberts et al. 1998, Bellan et al. 1999), suggesting some common ecological processes.



Much of what is known about the benthic fauna of Antarctica has resulted from a wealth of studies in McMurdo Sound. Sites include those reached by divers and by remote vehicles (Figure 6). The undisturbed shallow benthos near McMurdo Station supports diverse epifaunal, infaunal and meiofaunal communities (Dayton & Oliver 1977); these communities are highly stratified by depth (Figure 7). The epifaunal community is biomass dominated, to 15 m, by motile species

(sea stars, urchins, nemerteans, isopods); 15 to 33 m, by an intermediate community (anemones, soft corals, hydrozoans, tunicates); and > 33 m, by a sponge community (sponges, anemones, soft corals; Dayton et al. 1970, 1974). The infaunal community includes, to 6 m, motile opportunists (polychaetes *Capitella* spp., *Ophryotrocha claperedii*, *Glyptis* sp.); 6-12 m, mixed motile and sedentary species; 12-24 m, a mix of tube mat (polychaete *Spiophanes tcherniai*, tanaid *Nototanais dimorphus*, and the anemone *Edwardsia meridionalis*); and >24 m, spicule mat (Bockus 1999). Finally, the meiofauna is composed principally of foraminifera, which may be planktonic or benthic, living on shells, rock, seaweed, or in sand or mud. Their characteristic habitats, and the chemistry of their shells provide indications of when and under what conditions they lived). Thus, they are important components of core samples drilled to reconstruct climate history, including variation in sea-ice extent. Research in McMurdo Sound has indicated that foraminifera there consume a wide variety of prey, ranging from bacteria through a taxonomically diverse group of metazoans, including juvenile invertebrates.



The main factor controlling biological zonation of the Antarctic benthos is regularity of disturbance via anchor ice formation. At shallow depths, anchor ice forms each year during the coldest months; with increasing depth, increasing pressure restricts anchor ice formation so that it is more temporally variable, occurring only during colder years, and leaving longer time spans for community development between disturbance events. The depth of anchor ice formation is dependent on sources of super-cooled water, both from surface freezing and mesoscale flow patterns, as well as bottom topography. Water depth is thus a convenient descriptor but zones compress and expand depending on exposure and bottom topography, and zonation depths are slightly different in different locations. Sediments also affect species composition; near McMurdo Station are poorly sorted, coarse volcanic sands with few large rocks suitable for sponges and other sessile species (S. Kim & J. Oliver pers. comm.).

Dayton (1989) proposed that epifaunal sponge communities indicated decadal shifts in McMurdo Sound environmental conditions. In the 1960s, the sponge *Homaxinella balfourensis* and its predators were rare in waters < 30 m deep in McMurdo Sound (Dayton 1989). Any attempt by that sponge to colonize shallower depths was thwarted by the formation of anchor ice, which crystallized around colonists and, by increasing their buoyancy, ripped them out and floated them upward in the water column. The colder air temperature and longer residence time of sea ice in the Ross Sea during the 1950s and 1960s (proposed by Ainley et al. in press), would lead to a cooling of surface waters. In response, anchor ice would form to deeper depths and encourage crystallization around objects, such as sponges, that begin to grow at shallow depths (see also Hunt et al. 2003). After the mid-1970s, anchor ice formation became irregular and *Homaxinella* communities began to appear. In the 1980s the cycle again switched, with increased anchor ice formation and elimination of the *Homaxinella* population, though the sponge predators remained (Dayton 1989). Infaunal community data collected annually from 1988 to 1998, combined with previous descriptions (Dayton & Oliver 1977, Dayton 1989), provide an estimate of natural variability in the macrobenthic community. Studies on meiofauna have been restricted to specimens collected from October through early December, and cannot assess intra-annual variability.

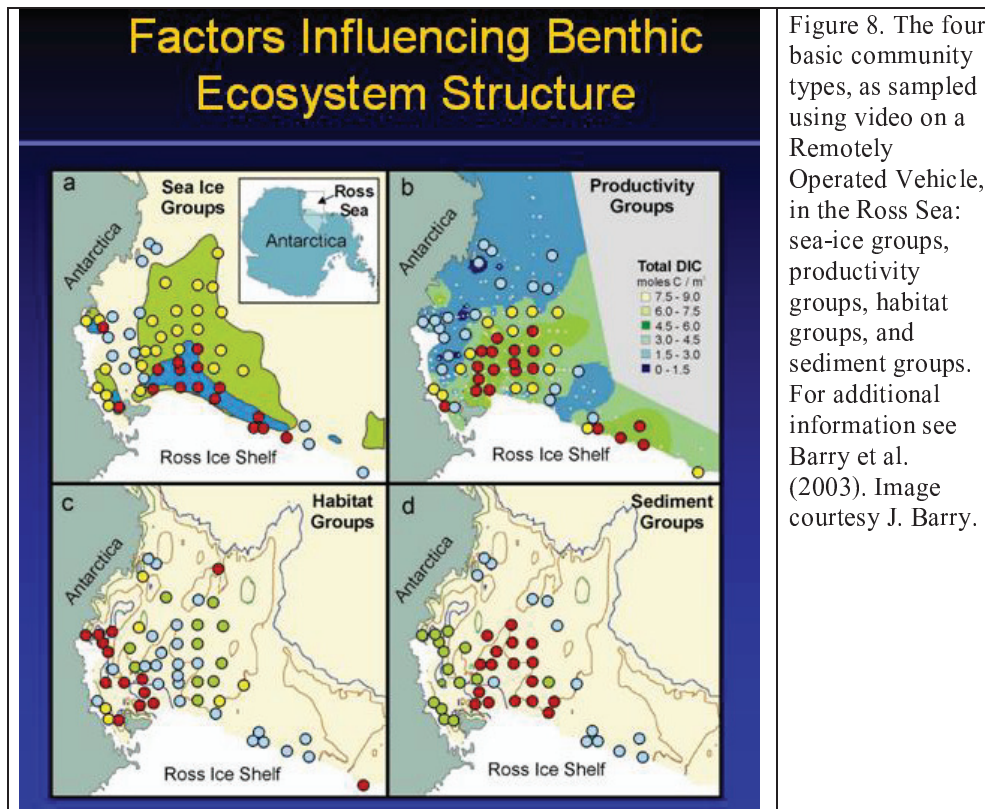


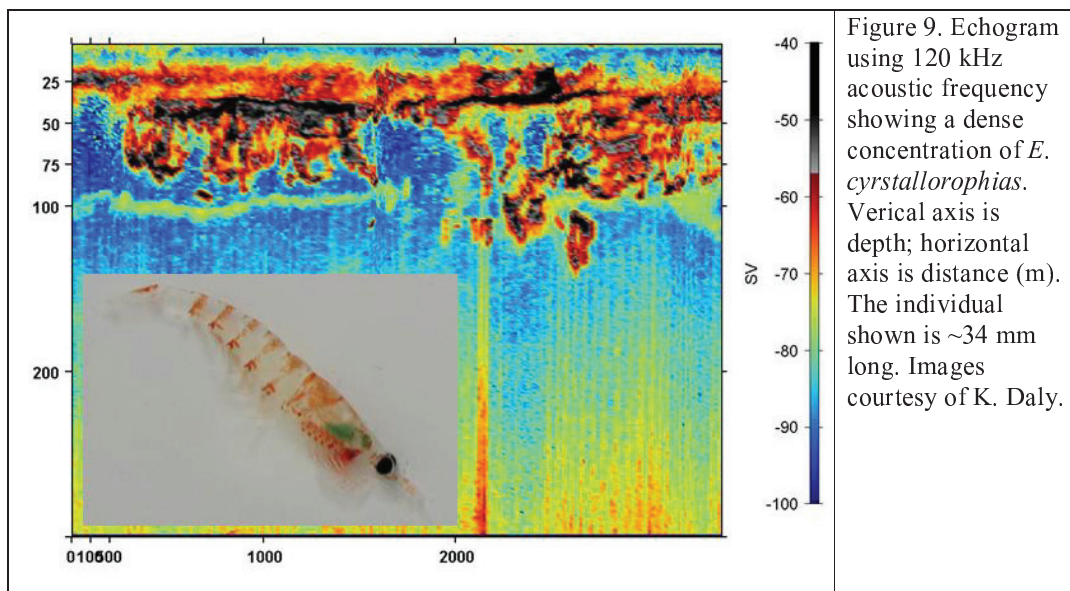
Figure 8. The four basic community types, as sampled using video on a Remotely Operated Vehicle, in the Ross Sea: sea-ice groups, productivity groups, habitat groups, and sediment groups. For additional information see Barry et al. (2003). Image courtesy J. Barry.

In contrast to the shallow water community, the deeper, soft bottomed regions have not been as well studied in McMurdo Sound or in the Ross Sea, despite the fact that these areas represent over 99% of the surface area of the region. Research in the deeper, little-studied habitats requires submersibles or remotely-operated vehicles, the use of which remains at a fledgling stage in the Ross Sea. Barry et al. (2003) presented a compendium of 55 locations within the Ross Sea (four were within McMurdo Sound; Figures 6, 8), in which they analyzed the composition of the benthic community by video. They concluded that benthic faunal patterns were associated closely with seafloor habitat characteristics and sediment organic matter content. The McMurdo Sound habitat was characterized as "rich" (sediment organic matter concentrations > 1%) but affected importantly by variable current speeds, which largely reflects the steep bathymetry.

Middle trophic levels

Relatively little is known about the life histories of organisms that comprise the middle trophic levels in the neritic community of the Ross Sea or other areas of the Antarctic continental shelf compared to our understanding of primary production and top-trophic predators. Top-trophic species feed mainly on silverfish (*Pleuragramma antarcticum*) and crystal krill (*E. crystallorophias*). However, as an example of the paucity of natural-history information, even though crystal krill may be the single major consumer of phytoplankton in neritic waters (Pakhomov & Perissinotto 1997), major points of its life history were not described until the mid-1980s (Ikeda 1986; O'Brien 1987a, b; Siegel 1987; Brinton & Townsend 1991) and otherwise a great deal remains unknown. Other than acoustic surveys conducted by Italian scientists in the central-western Ross Sea, there have been no directed studies of euphausiids in McMurdo Sound or vicinity.

A neritic species, crystal krill may reach an abundance of 25 individuals m⁻³ in waters 100-500 m deep (John 1936, Fevolden 1979, Thomas & Green 1988, Pakhomov & Perissinotto 1996; Figure 9). In the Ross Sea, crystal krill have been collected near the Ross Ice Shelf where *E. superba* are virtually absent (Bottino 1974, El-Sayed et al. 1978, Foster 1987). This is confirmed in the diet of Adélie penguins feeding in the southwestern Ross Sea (Ainley et al. 1998, 2003). Makarov et al. (1990) found numerous larval crystal krill south of the continental shelf break (with *E. superba* larvae to the north). Crystal krill occur in large swarms or layers in open water, under sea ice, and near the sea floor (Everson 1987, O'Brien 1987, K. Daly unpubl). The behavior of crystal krill varies. Dense schools of size-segregated juveniles and adults have been observed 1-5 m below sea ice during both day and night during spring (O'Brien 1987). Adults also may form layers at depth during the day and migrate to the upper 100 m at night (O'Brien 1987), remain near bottom (Pakhomov et al. 1998), or remain mid-water (K. Daly unpubl. data). Accumulating evidence from other regions of the Southern Ocean suggests that crystal krill is an opportunistic feeder, foraging over a wide range of depths. Individuals may feed primarily on micro- and mesozooplankton in spring and on phytoplankton during summer (Hopkins 1987, Pakhomov et al. 1998).



A few studies have characterized other components of the zooplankton community. Protozooplankton are dominated by non-loricated ciliates and dinoflagellates, which exhibit both low growth rates and low grazing rates by microzooplankton (Lonsdale et al. 2000). The latter is composed of heterotrophic dinoflagellates, ciliates, copepod nauplii, foraminifera, and radiolarians, with densities ranging from $< 1 - 650 \text{ cells l}^{-1}$; carbon flux to this community averages 11% of total C flux, with dinoflagellates at some sites comprising 23% of the total (Garrison & Gowing 1993). Seasonally, microzooplankton abundance varies by three orders of magnitude, with variations correlated with phytoplankton biomass (Caron et al. 2000). The larger zooplankton community of McMurdo Sound and vicinity, at least as sampled by plummets, is dominated numerically by copepods (primarily *Metridia gerlachei*, *Calanoides acutus*, *Oncaea curvata*, and *Oithona similis*), pteropods (*Limacina helicina* and *Clione limacina*), and the ostracod *Conchoecia belgicae* (Hopkins 1987, Foster 1989).

The fish fauna of McMurdo Sound is composed of species in four of five Antarctic families of the notothenioid group (Nototheniidae; Chaenichthyidae; Bathylacridae, one species; and Artedidraconidae, several species but rare) and two non-notothenioid families (Zoarcidae, two species; Liparidae, one species; Figure 10). The physiological, biochemical and ecophysiological research on these fish has no parallel elsewhere in the Southern Ocean. However, many aspects of natural history and ecological interactions remain unknown. Most members of this community are small (200 g), abundant, and bottom dwelling, with larger specimens inhabiting protective refugia. These fish feed on a varied diet: polychaetes, amphipods, juvenile fishes inhabiting benthos and fish eggs. In contrast, the Antarctic toothfish (*Dissostichus mawsoni*) and the dragon fish (*Gymnodraco acuticeps*) are strictly piscivores. Among the more epi- and mesopelagic forms, *Pagothenia borchgrevinkii* is associated with the sub-ice platelet layer and feeds on ice amphipods, copepods, and juvenile fishes; *Trematomus newnesi* occurs in schools at times over rocky bottom, but often resting on shallow bottom although rarely in the

same location from year to year; and the silverfish *Pleuragramma antarcticum*, which is found throughout most of the water column despite a “marginal” antifreeze system (If it swims through the surface waters during the winter it risks freezing to death). The latter is a key species in the neritic food web.

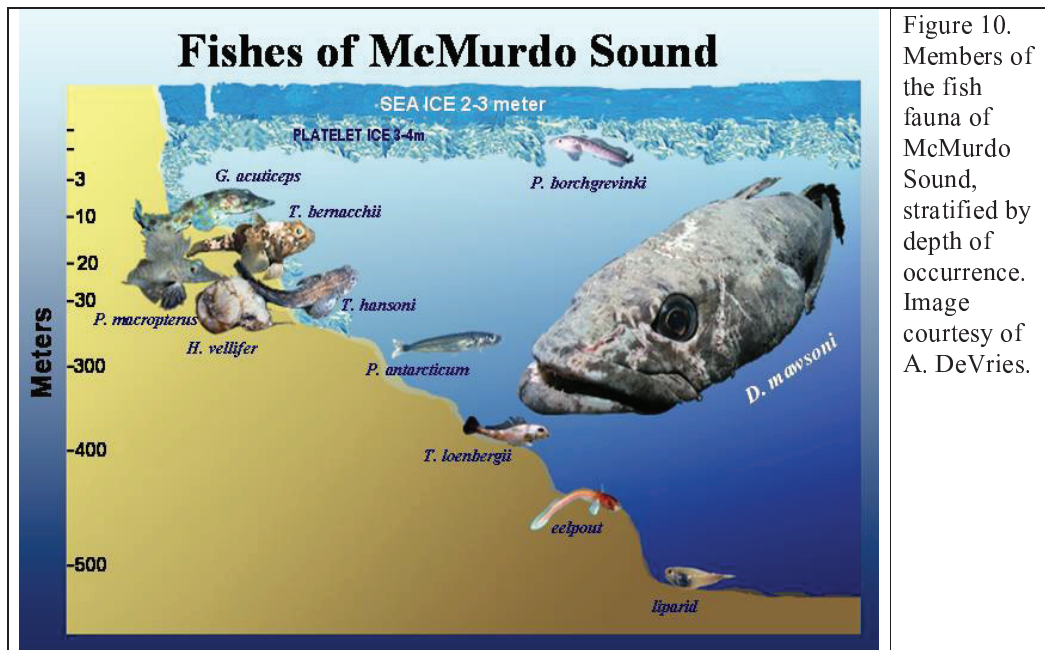


Figure 10. Members of the fish fauna of McMurdo Sound, stratified by depth of occurrence. Image courtesy of A. DeVries.

Antarctic toothfish is the largest of the notothenioid fishes, reaching a length of at least 163 cm TL and a mass > 60 kg (Eastman 1993). It is the major piscine predator south of the Polar Front (Eastman 1993), and is an important predator on silverfish in continental shelf waters. Its other major prey was a mysid *Antarctomysis*. In turn, toothfish are preyed upon by Weddell Seals (Testa et al. 1985) and killer whales (Thomas et al. 1981) and thus is an important member of the neritic food web. A fishery is developing for this species, largely in a vacuum of knowledge (see CCAMLR 2002, Huchison 2004).

Antarctic silverfish is the dominant mid-water fish in the coastal waters of Antarctica (DeWitt & Hopkins 1977, Kellerman 1996, Eastman 1993, Hubold & Ekau 1987) and a principle prey of highest trophic levels (CCAMLR 2002). Silverfish range from 6 mm TL at hatching (Regan 1916) to at least 250 mm TL at largest size (Hubold 1985). Growth rates calculated from otolith-derived ages suggest that a 245 mm specimen is ~ 21 yrs old (Hubold & Tomo 1989). In Terra Nova Bay, age 0 fish appear in the plankton during late December-early January (Granata et al. 2000, Guglielmo et al. 1998) suggesting a hatch date of late November. Spawning must occur during winter (cf. Hubold 1984). Post-larval silverfish are distributed largely in the upper 50 m where they feed on small *Limacina*, *Oncaea*, and *Oithona* (Hubold & Hagen 1997, Hopkins 1987, Hubold 1985). They move deeper with size and age. Once silverfish reach 60 mm a diet shift occurs, with the primary prey becoming the copepods *Calanoides acutus* and *C.*

propinquus (Hubold & Hagen 1997, Hopkins 1987, Kellermann 1987). Fishes > 60 mm (Age 2+ adult) are found primarily below 200 m, but some fraction (15-20%) of the age 2+ population can always be captured in the upper 200 m (Hubold 1984). Larger size classes (>100 mm) feed on furcilia (*Calanoides acutus* and *C. propinquus*) and crystal krill (Hopkins 1987, Hubold 1985). Limited data indicate a diel periodicity during seasons where there is day-night (J. Torres, pers. comm.).

Little is known of notothenioid fish reproduction except in the dragon fish, which spawns in October and hatches in late August. Egg nests are located in shallow water on flat rocks and guarded by males for 10 months; they hatch when water is at its coldest and contains the most ice. Antarctic silverfish may spawn in September or October at the underside of the ice platelet layer and hatch, as noted above, in November. They thus may have a much shorter developmental time even though the water is near its seasonal low temperature.

Top trophic levels

The broad shelf and persistent ice cover of the Ross Sea dictate the species composition and residence times of species at the top trophic levels. The species diversity of the fauna is limited and noticeably pagophilic: five seabird species (Adélie *Pygoscelis adeliae* and emperor penguins *Aptenodytes forsteri*, Antarctic *Thalassoica antarctica* and snow petrels *Pagodroma nivea*, and South Polar skua *Catharacta maccormicki*), three pinnipeds (Weddell *Leptonychotes weddellii*, leopard *Hydrurga leptonyx* and crabeater seal *Lobodon carcinophagus*), and three cetaceans (one species of balaenopterid – minke whale *Balaenoptera bonaerensis*, and two toothed whales – orca *Orcinus orca* and Arnoux's beaked whale *Berardius arnouxii*). On the other hand, in terms of the abundance of top-trophic predators, the Ross Sea shelf has no equal among other Antarctic shelf ecosystems. On the order of 38% and 26%, respectively, of the world's Adélie and emperor penguins nest within its confines (Woehler 1993). Several million Antarctic petrels, whose nesting sites are unknown, feed along the Ross Sea continental slope (Ainley 1985). Similarly, the Ross Sea contributes on the order of 45% of Weddell seals (32,000 individuals), 11% of leopard seals (8,000), and 12% of crabeater seals (205,000) of respective the world populations (cf. Stirling 1969, Gilbert & Erickson 1977, Ainley 1985). In McMurdo Sound itself, the top-trophic fauna is largely limited to the two penguins, skua, Weddell and leopard seal, and the three cetaceans. Compared to birds and seals, far less is known about the ecology and population dynamics of cetaceans in the southern Ross Sea, especially the fraction that occurs in the pack-ice.

In the Ross Sea, highest minke whale encounter rates occur south of 70° S (Ainley 1985, Kasamatsu et al. 1996, Saino & Guglielmo 2000). An unknown proportion of the population over-winters in leads and cracks in the ice pack (Aguayo-Lobo 1994); the remainder (migratory individuals) steadily penetrates into the divergent portion of the pack as the summer progresses (Ainley 1985, Ribic et al. 1991). Large-scale surveys of minke whales, conducted during the mid-1980s and the late 1990s, did not penetrate past the ice edge; however, in the open water surveyed, an order of magnitude decline was evident from 101,590 (CV = 0.32) during 1985/86 to 11,038 (CV = 0.45) during 1991-92 (Branch & Butterworth 2001). The lack of basic knowledge about minke whale occurrence patterns, foraging behaviors, seasonal prey preferences, and movement patterns relative to ice dynamics, precludes explanation of the

decrease. The decline may also reflect the large commercial catches during the 1970s and 1980s, in addition to the recent 'scientific takes' of the Ross Sea population. The killer whales that frequent the southern Ross Sea are also poorly known and may be a genetically distinct population. Ainley (1985) estimated that 3,500 killer whales occur in the region. Killer whales of the pack-ice appear to be morphologically distinct (Pitman & Ensor 2003) and some have been observed feeding on Antarctic toothfish; however, the ecology of this species is obscure. Arnoux's beaked whales are known to occur as far south as the spring ice edge of McMurdo Sound, or approximately 77° S (Ponganis & Kooyman 1995); however their ecology and demography in this region is unknown.

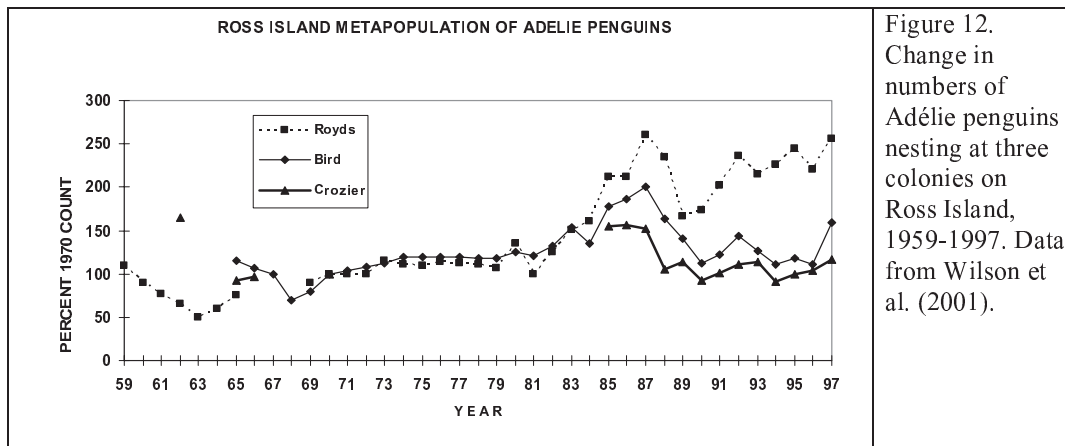


Figure 11. A group of minke whales moving along the fast ice edge near Cape Crozier, Ross Island. Image courtesy of M. Branch.

The two main prey species of many of these predators, as well as of the Antarctic toothfish, in McMurdo Sound and the southern Ross Sea are the Antarctic silverfish and crystal krill (Ainley et al. 1998, 2003; Burns et al. 1998, Cherel & Kooyman 1998, Davis et al. 1999, Eastman 1985; Ichii & Kato 1991, Ichii et al. 1998; Laws 1984, Plötz et al. 1991). A recently described form of killer whale preys on the toothfish and possibly silverfish (Pitman & Ensor 2003). The Weddell seal preys on toothfish as well (Testa et al. 1985).

The population dynamics of several top predators are very well known. The Adélie penguin and Weddell seal within McMurdo Sound have been well studied since the 1960s and the resulting data sets are now invaluable from an ecological perspective (see Tables 1, 2). Seal numbers, possibly due to removal of seals near Scott Base by NZ workers (D. Siniff, pers. comm.), decreased during the 1970s and have failed to recover (Cameron 2001). Penguin numbers began to increase during the late 1970s, and reached a maximum around 1990; since then they have fluctuated near that level (Wilson et al. 2001; Figure 12). Changes in sea ice may be responsible (Ainley et al., in press). Emperor penguin numbers at Cape Crozier began to increase during the mid-1990s owing to increased stability of their sea-ice nesting platform. Unfortunately, little is known in McMurdo Sound about the ecology or population dynamics of

cetaceans, despite the fact that their predation may have profound effects on middle-trophic species.



Major Data Gaps

The list of existing long-term data sets and process-oriented, integrative efforts should provide a platform from which a McMurdo Sound LTER could develop (Tables 1, 2). Perhaps the best known aspects of the region's ecology are 1) general physical processes, including sea-ice variability, 2) the benthic community organization and structure, and 3) the rates and processes of primary production both in the water column and the ice. Moreover, much is known about sedimentation rates of production to the benthos as a result of great interest in constructing climate histories based on sediment cores. What is least known are the factors and processes that lie between production of phytoplankton and the sedimentation that reaches the bottom; that is, predation and the food-web links. No studies have measured the important fluxes of energy and material through the various trophic levels of either McMurdo Sound or the southern Ross Sea, or of the relationship between phytoplankton composition and zooplankton ingestion. Sediment-trap studies suggest that in areas dominated by diatoms, active grazing by zooplankton occurs, but in areas where the haptophyte *Phaeocystis antarctica* dominates, little grazing occurs during summer. These suggestions remain, however, to be verified by direct, experimental observations.

While the Ross Sea, including McMurdo Sound, is the most productive stretch of ocean in the Antarctic, evidence exists that the top-trophic levels may be food limited or at least that top-trophic predators strongly affect the availability and distribution of their prey. This may be merely the characteristics of a marine system in which top-trophic predators have not been removed, the state of affairs for the remainder of the world ocean. Examples of this food limitation are 1) Adélie penguins foraging farther from large (but not small) colonies and deeper in the water column as the summer progresses (Ainley et al. 2004); 2) Weddell seal catch-per-unit effort for toothfish decreasing with increased proximity to seal concentrations (Testa et al. 1985); 3) minke whales and orca massing at the fast ice edge of McMurdo Sound each summer, rather than being distributed in open water, and waiting for icebreakers to carve away the fast ice

to provide unexploited foraging habitat (Ainley, pers. observation); and 4) whales perhaps forcing penguins to forage elsewhere (Ainley 2004). Rather, ironic is the spectacular, but short-lived production of *Phaeocystis* in the Ross Sea Polynya, which just borders on McMurdo Sound (Arrigo et al. 1999, 2003; Smith & Gordon 1997), but the virtual lack of top-trophic predators in that area (cf. Ainley 1985). On the other hand, the benthic community beneath the *Phaeocystis* bloom is quite lush (Barry et al. 2003).

Therefore, links in the middle portion of the food web (i.e., grazing rates at all levels) appear to be critical and are among the least known, currently, of McMurdo Sound or of coastal systems throughout the Antarctic. An LTER in McMurdo Sound would uncover information having immediate applicability around the Antarctic continent, where the vast majority of biological/food-web studies center on the pelagic environment of *E. superba*.

Why An LTER In McMurdo Sound?

The marine realm of the Antarctic is a heterogeneous composite of a variety of habitats and ecosystems, and there is no site that can be studied to completely characterize the entire marine sphere. However, one region that has substantial ecological importance and spatial extent is the continental shelf. This area is markedly influenced by sea ice dynamics, is highly productive, shows extreme seasonality in many features, and contains many species not found in the pelagic realm. Furthermore, there are important scientific questions regarding this area that are critical to an understanding of the structure and function of Antarctic marine ecosystems as a whole. Some examples are:

- How does the ecosystem respond to perturbations in the physical forcing, such as those induced by large icebergs?
- How is the partitioning of energy and materials controlled by ecological processes such as productivity and predation by upper trophic levels?
- How do biological processes associated with ice influence the ecological interactions in the water column and benthos?
- How do long-term changes (such as those generated by climate change) influence the food webs?

These types of questions are highly complex, and require a coordinated ecosystem approach to begin to provide answers. Furthermore, data need to be acquired over longer time scales than are usually obtained, particularly since the types of information and the time scales of change encompassed in the questions cover periods of years to decades (Ainley et al., in press). Hence, a Long-Term Ecological Research program is essential to obtaining an understanding of the variations, changes and responses of organisms in Antarctic neritic environments and McMurdo Sound is an ideal location for the study of these key questions, building on an extensive data base and information base already available.

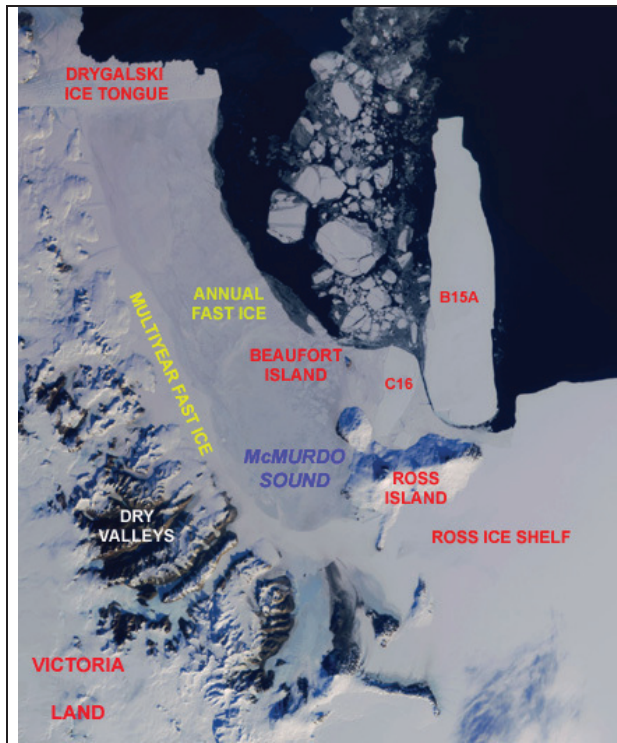


Figure 13. Two large grounded icebergs (B15A and C16) and the Drygalski Ice Tongue affect the persistence of fast ice in McMurdo Sound. In addition to fast ice that rarely breaks out, annual ice now remains longer into the summer than previously. The icebergs prevent katabatic winds from clearing McMurdo Sound of ice. Circulation may also be affected. Image taken in October 2002, NASA Jet Propulsion Lab.

An LTER investigating an Antarctic coastal ecosystem would complement the existing and continuing LTER at Palmer Station, whose focus is the ecological consequences of sea-ice variability on secondary producers (*E. superba*) and apex predators (penguins) and the linkage of ecosystem processes to environmental variables. The Palmer LTER is conducted in a region experiencing substantial climatic change, with rapid warming, alteration of ice distributions and persistence, and modifications in the biotic communities that are at least in part linked to the changes in ice (e.g., Smith et al. 1999; http://iceflo.ices.ucsb.edu:8080/ice_hp.php). Owing to its northern latitude, and location near the edge of the sea ice belt, its annual variability in environmental conditions is dramatic. It is also influenced by the frequent oceanographic intrusions of circumpolar deep water, which strongly determine the community composition of the lower trophic levels (Prézelin et al. 2000). Finally, the Peninsula region as a whole has been strongly influenced by human effects, such as reductions in fish, seals and whales.

In general, owing to the very high latitude of McMurdo Sound (78° S versus 64° S for Palmer), the sea ice regime is relatively stable in contrast to that at Palmer Station. The sea-ice season in the Ross Sea is lengthening, but the coastal polynyas are increasing in size as well (Parkinson 2002). On the other hand, the ice environment in McMurdo Sound has changed recently due to the grounding and/or passage of several large tabular icebergs (Figure 13). Whether or not this is a temporary situation remains unclear. These icebergs may have substantially altered the circulation (e.g., Dinneman et al. 2003, submitted) as well as restricted the normal northern advective flow of ice in spring (e.g., C-19; Arrigo et al. 2002, Arrigo and

Van Dijken 2003) and decreased the areal extent of open water (and its location) throughout the entire summer. Both B-15A and C-16 remain grounded in the area, and while B-15A has calved smaller bergs that have moved independently (e.g., B-15J), the region still is being severely impacted by their cumulative effects. These icebergs may be providing an unparalleled natural experiment, depending on how long the increased fast ice and, perhaps, reduced currents remain a part of the environment.

Besides the stability of its environment, McMurdo Sound is the most southerly open water marine location in the world, and as such represents an extreme with regard to a number of variables, such as:

- Influence and duration of ice;
- Influence of different types of ice (fast ice, pack ice, congelation ice, and glacial ice from ice shelves, etc.);
- Shortness of the photosynthetic season (combination of solar periodicity and ice shading); and
- Low air and sea temperatures.

McMurdo Sound is also part of the Ross Sea continental shelf, which is the broadest, most extensive continental shelf in the Antarctic. This shelf exhibits the greatest primary productivity of any region of the Southern Ocean, with annual phytoplankton blooms being a repeated and predictable feature (Arrigo & McLain 1994; Smith & Gordon 1997; Smith et al. 2000). It has substantial concentrations of higher trophic levels (toothfish, seabirds, seals, and cetaceans), and massive deposits of diatomaceous oozes with relatively large organic matter concentrations. McMurdo Sound and the Ross Sea also possess a rich benthic community.

Another important feature of McMurdo Sound and the southern Ross Sea is that it presently is largely unperturbed by direct human influences, except in highly localized areas (e.g., McMurdo Station sewer outfall), and hence is one of the few remaining ecosystems on Earth where human influences have been minimal or non-existent. Thus far, neither top-down nor bottom-up forcing mechanisms have been compromised, thus, providing promise for studying their relative importance, a condition not possible in other marine ecosystems. Other than a recent, small fishery for Antarctic toothfish on the northern western Ross Sea shelf (CCAMLR 2002, Hutchison 2004), a scientific removal of minke whales on the outer shelf (Brown & Brownell 2001), and the short-term, small-scale take of Weddell seals (mentioned above; discontinued since the early 1980s), there has been no direct large predator removal. Finally, to no appreciable degree had the great whales nor various commercially exploited pinniped species ever frequented Ross Sea shelf waters and, therefore, their demise in all other oceans of the world has had little impact.

Finally, McMurdo Sound is also the major logistics site of the entire continent, McMurdo Station. In conjunction with Scott Base, the base of New Zealand Antarctic scientific operations, it supports much of the science supported by NSF. It also is the gateway to the South Pole, and hence is frequented by aircraft for much of the year. It is open year-round, and also has a newly constructed, modern laboratory (Crary Laboratory) available to support the varied research of an LTER. It is serviced each summer by the USCGC icebreakers, as well as being the frequent site

of port call for the *RVIB N.B. Palmer*. It has extensive capabilities to transport personnel, samples and materials over ice via ground transport and helicopter. It also has the personnel and operation to assist with the fabrication and environmental monitoring of field camps, should that be part of any proposed LTER project. Moreover, southern McMurdo Sound possesses reliable sea ice to be used as a study platform (see below). Finally, McMurdo Station has operational weather stations in the region, an operational daily weather forecast, and extensive satellite reception and data processing capabilities for a variety of remote sensing applications.

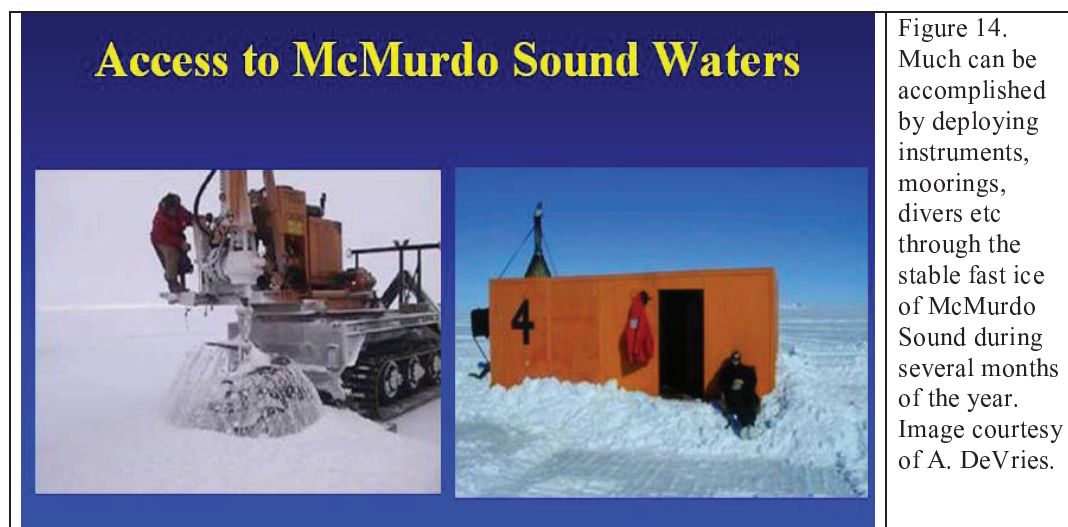
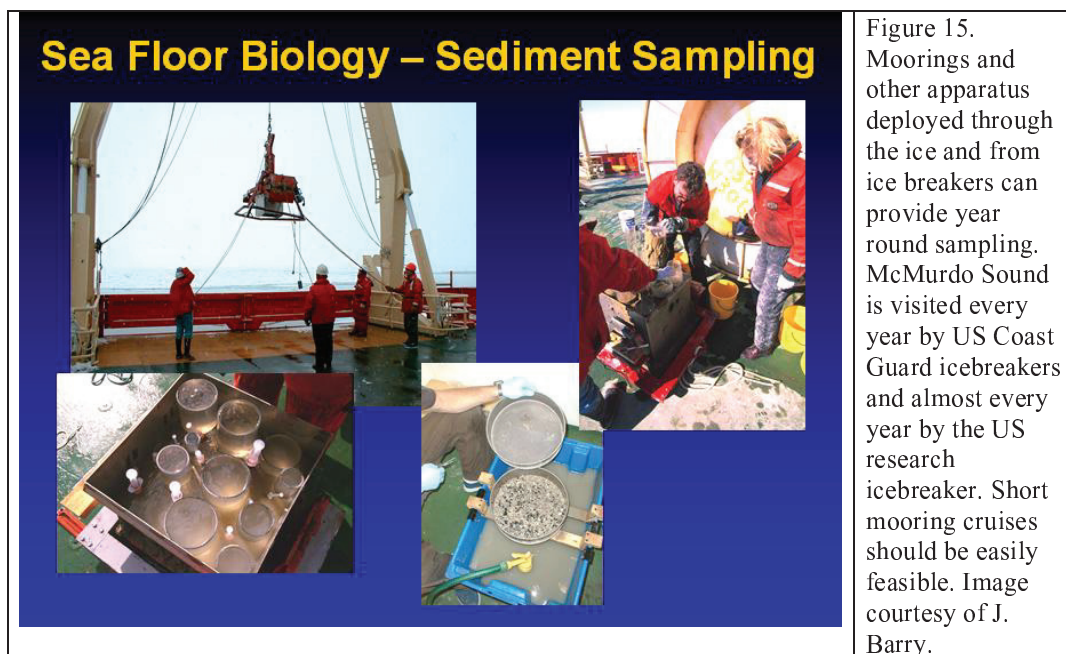


Figure 14. Much can be accomplished by deploying instruments, moorings, divers etc through the stable fast ice of McMurdo Sound during several months of the year. Image courtesy of A. DeVries.

How An LTER Could Be Implemented

Any LTER project that develops in the McMurdo Sound region will have a significant opportunity to not only build on previous data, but to explore the poorly known linkages that are characteristic of Antarctic neritic ecosystems (see above, Data Gaps). Proximity to McMurdo Station clearly enhances the abilities of any LTER project to succeed, and for much of the year, unlike the Palmer site, researchers can fly or drive vehicles to the fast ice edge or to holes drilled through the ice (Figure 14). Moorings and real time instruments can be deployed through these holes. The fact that the McMurdo Dry Valleys LTER already operates out of McMurdo Station indicates that the McMurdo logistics hub is capable of successfully supporting a coordinated, interdisciplinary, and mostly biological program. Yet there also are limitations that are obvious in such a remote site. For example, unlike Palmer Station, where a research vessel routinely and repeatedly visits and can be scheduled for annual cruises, McMurdo Sound is much farther from a marine operations base and, hence, oceanographic support is likely to be limited compared to the Palmer LTER. The ability to expand the geographic scale of study beyond southern McMurdo Sound or the temporal scale beyond the fast-ice season (May-December) represents a major challenge.

One possible means of expanding temporal and spatial scales of understanding would be through a combination of instrumentation deployments and satellite sensors, combined with infrequent oceanographic cruises. For example, moorings in the Sound region could deploy not only deep-water (below the depths of ice bergs; ca. 250 m) instrumentation (such as thermistors and CTDs, current meters, acoustic dopplers for both current and faunal detection, and sediment traps), but also could have cycling systems that are deep-tethered, but which frequently rise to the surface and which have chemical/biological sensors that collect data during the ascent and descent (Figure 15). Thus a complete description of the water column (currents, temperature, salinity, particle abundance, fluorescence, nutrient concentration, irradiance, video surveillance, and other variables) could be regularly obtained at a high frequency (e.g., daily) in critical locations.



A second way in which information could be obtained would be through the use of the USCGC icebreakers as they break the channel into McMurdo Station. Although the ships' main objective is, and will remain being, the preparation of the channel for the arrival of a fuel tanker and supply ship to McMurdo Station and Scott Base, limited time is available for science, and given the relative proximity to the suggested LTER site, it could be used effectively to expand the scales of investigation in a routine, predictable manner. Recent programs have effectively utilized the icebreakers in McMurdo Sound and the southern Ross Sea mainly to deploy and retrieve moorings.

A third possible means to expand the spatial and temporal scales of investigation would be through the use of autonomously operated vehicles (Figure 16). Such vehicles have been used successfully as part of ecological studies in the Antarctic (Brierly et al. 2000), and they have the

capability of adding a large number of instruments in a manner parallel to those of moorings. That is, temperature, salinity, depth, current velocity and direction, particle abundance, video surveillance, fluorescence, nutrient concentrations, and irradiance can all be easily measured presently, and water samples can be collected at various locations. Hence, the AUV provides the opportunity to sample in the x-z plane in a synoptic manner, and can cover scales of hundreds of kilometers. In addition, benthic studies can also be completed using either AUVs or ROVs (remotely operated vehicles). These types of samplers have been used in the Ross Sea previously with great success (Barry et al. 2003), and would allow the benthic component of McMurdo Sound to be studied more completely (see Figure 6). Use of such vehicles also would allow for the experimental manipulation of remote locations and the ability to return to the same spot and make time-series observations. These types of investigations, frequently used at lower latitudes, would represent a new and exciting mode of investigation of polar ecosystems.

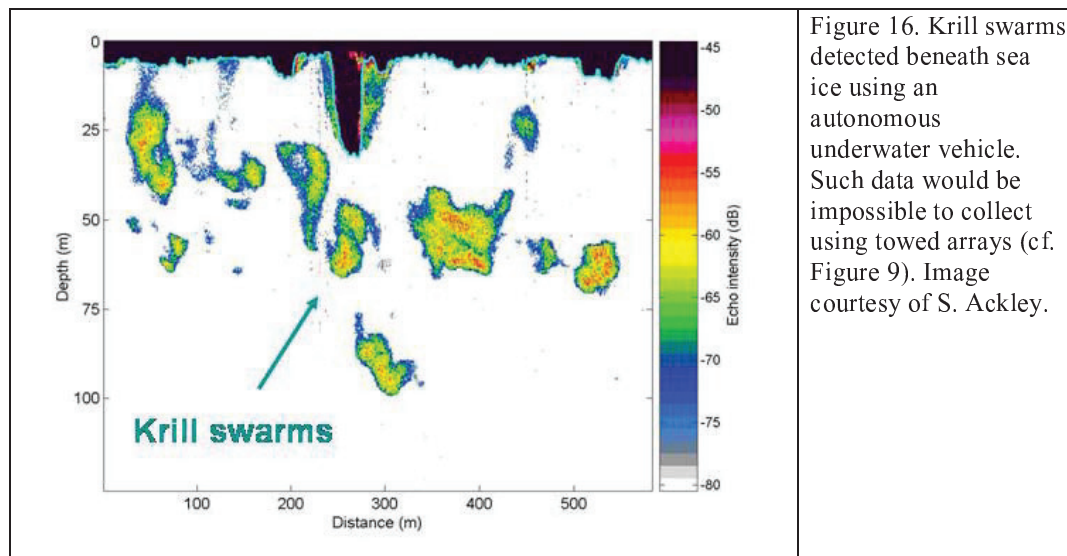


Figure 16. Krill swarms detected beneath sea ice using an autonomous underwater vehicle. Such data would be impossible to collect using towed arrays (cf. Figure 9). Image courtesy of S. Ackley.

Finally, if such an LTER project included a need for a remote field site, a number of locations might be available. For example, Cape Royds is a specially protected area, but it might be possible to construct a relatively permanent building as a field/marine laboratory for an LTER project. Similarly, New Harbor, on west side of McMurdo Sound opposite to McMurdo Station, has been used for a number of years as a field site, and could be further developed as it is near to the logistics depot at Marble Point. Transportation from these locations is quite easy given the availability of both surface and helicopter services in the McMurdo area.

Linking To The LTER Network

LTER was established in 1980 by the National Science Foundation to support research on long-term ecological phenomena in the United States. As of April 2004, the LTER Network consisted of 24 sites, including two in Antarctica, representing diverse ecosystems and research emphases.

It is a collaborative effort involving more than 1200 scientists and students investigating ecological processes operating at a range of time and spatial scales. The mission of the Network is to provide the scientific community, policy makers, and society with the knowledge and predictive understanding necessary to conserve, protect, and manage the world's ecosystems, their biodiversity, and the services they provide (B. Waide, Workshop presentation). Currently, there are five sites that entirely or in part include coastal habitats: Virginia Coast Reserve, Santa Barbara Coastal, Plum Island Ecosystem, Georgia Coastal Ecosystem, and Florida Coastal Everglades. In addition, the Palmer LTER is investigating a near-to-shore but pelagic system and the North Temperate Lakes LTER is investigating a lacustrine system. Recently, there was a competition to add additional (1-3) coastal/marine sites to the LTER Network.

Helping to tie the research together among the LTER sites is an attempt for each to address the following five areas of core research, although the emphasis may differ among the sites:

- Primary production
- Population dynamics/trophic structure
- Organic matter accumulation/decomposition
- Nutrient processing and transport
- Disturbance

As indicated in the review of McMurdo Sound and the research that has been conducted there thus far (see above), it is obvious that all five areas of investigation have received considerable attention already in this region. In fact, several of the existing long-term data sets (Table 1) and integrative data sets (Table 2) pertain to these five core research areas.

While an Antarctic Coastal Ecosystem LTER in McMurdo Sound would interface most directly with the other coastal and lacustrine LTERs, ties would exist to the terrestrial ones as well, as they all focus on fundamental ecological principles. A McMurdo Sound site would complement that of the McMurdo Dry Valleys LTER, in that both, one terrestrial and one marine, have an exceedingly short productivity pulse but, unlike the dry valleys, many trophic components in the adjacent McMurdo Sound arrive seasonally to participate or like the dry valleys 'awaken' in place from extended quiescence.

Among the coastal LTERs, four of six are estuarine on a protected coast or embayment. Many address the terrestrial inputs of nutrients into the aquatic portion of the ecosystem. McMurdo Sound seemingly receives little input of nutrients from the land, except in highly local locations such as near penguin colonies or seal rookeries, but its overall food web may be dependent on an influx of phytoplankton from outside, in this case the Ross Sea. In addition, certain micro-nutrients, such as iron, are provided by glacial sources. The two marine LTERs on more exposed coasts are the Palmer LTER and the Santa Barbara Coastal LTER. Complements and contrasts to the Palmer LTER have been addressed elsewhere (see above). In regard to the Santa Barbara Coastal site, the McMurdo Sound offers a strong comparison to the processes that affect and sustain the intertidal and subtidal communities of the California coast, including contrasting strategies of water-column and benthic organisms.

Some questions that could be answered by the LTER Network, with major contributions from a McMurdo Sound LTER, include:

- How do ecosystems with contrasting time-scales of seasonal energy fluxes differ in regard to life-history adaptations among all trophic levels (examples include, mixotrophy, stasis, hibernation, migration)?
- Over what time scales can the matching of life histories and productivity pulses be altered without affecting an ecosystem's trophic structure?
- How dynamic are the earth's ecosystems, currently and in the past?

International Collaboration

Existing knowledge of McMurdo Sound and the Ross Sea has already benefited considerably from studies by New Zealand and Italian researchers, and there is no doubt that any formalization of a marine LTER in the area will result in increased, co-operative international activity. New Zealand researchers have already expressed interest, and Antarctica New Zealand has promised increased logistic support should an LTER proceed. There has been interest shown from Italian marine scientists, and potential collaborations are also being explored with Australia and China.

Experience in the McMurdo Dry Valleys LTER has shown the benefit of close international collaboration. New Zealand researchers have filled a gap identified by the LTER review committee (in lacustrine benthic microbial ecology). This research is presently continuing, with high quality publications and several joint US/NZ research initiatives. It is of interest that several inter-institutional research collaborations that started in the Dry Valleys LTER have now extended to other parts of Antarctica and even to collaborative research outside of Antarctica.

Should the McMurdo Sound marine LTER be initiated, the New Zealand contribution will likely be focused on present areas of expertise and research, such as sea ice physics (particularly in the formation of platelet ice) and optics, and benthic primary production and carbon flux in the marine littoral zone. Year-round instrumentation is already being considered for some locations. Dive teams will be supported from Antarctica New Zealand, who, together with New Zealand's Industrial Research Limited, will also provide field-camp logistics and laboratory facilities. Other forms of logistic and science support are likely.

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**ANTARCTIC COASTAL ECOSYSTEM
WORKSHOP TO DISCUSS FEASIBILITY OF AN LTER IN MCMURDO SOUND
DOUBLE TREE HOTEL, SAN JOSE, CA; 13-15 APRIL 2004**

APPENDIX A: AGENDA

DAY 1

11:30: Introduction: Purpose of workshop and rationale for McMurdo Sound LTER --- Ainley
12:00: Lunch
13:00: History of the LTER program --- Waide
13:30: Review of the 5 core components of LTER programs --- Hobbie
14:00: Characteristics/major components of coastal LTERs --- Reed
14:30: Summary of results from the two existing Antarctic LTER sites --- Fraser
15:00: Break
15:30: Summary of existing long-term data sets in Ross Sea --- Ainley
16:00: Components of the McMurdo Sound Ecosystem: Productivity and Vertical Flux --- Smith
16:30: Components of the McMurdo Sound Ecosystem: Ice biota --- Fritsen
17:00: Dinner

DAY 2

8:30: Components of the McMurdo Sound Ecosystem: Herbivores --- Daly
8:50: Components of the McMurdo Sound Ecosystem: Benthos --- Barry, Kim
9:10: Components of the McMurdo Sound Ecosystem: Fish --- DeVries, Torres
9:30: Components of the McMurdo Sound Ecosystem: Top Trophic Levels --- Tynan, Ainley
9:50: possible contributions by NZAP; other collaboration --- Howard-Williams
10:10: Break
10:30: GROUP DISCUSSION --- Science questions best answered in an LTER framework ---
Collins, Smith
12:00: Lunch
13:00: GROUP DISCUSSION --- The practical side of LTERs
E.g., Models of management
Data management
Outreach
Networking: what is required?
Obligations: Head PI, other PIs
15:00: Break
15:30: GROUP DISCUSSION --- Scales of sampling --- Ainley
18:00: Dinner

DAY 3

08:30: Large scale forcing in the Ross Sea --- Comiso, Beardsley
09:00: GROUP DISCUSSION --- Overarching themes for a potential LTER studying ACE
10:00: Break
10:30: Concluding remarks --- Penhale
11:30: Goodbye, and thank you!!
12:00: Lunch
13:00: Organizing committee and rapporteurs meet to outline Workshop Report
14:30: Adjourn

APPENDIX B:**ATTENDEES**

Participant	Specialty	Institution	Address	Contact
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