# CCAMLR WG-EMM-10/11
ROSS SEA BIOREGIONALIZATION

Part I: Validation of the 2007 CCAMLR Bioregionalization Workshop Results Towards Including the Ross Sea in a Representative Network of Marine Protected Areas in the Southern Ocean

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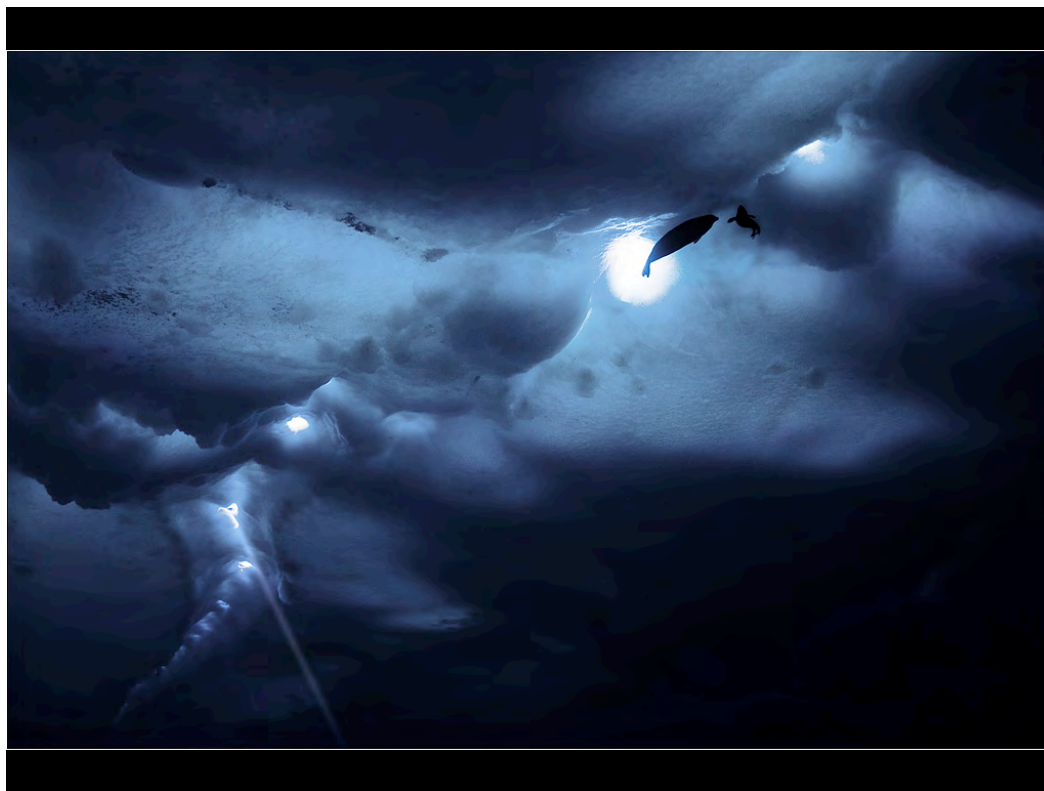
Weddell seal and pup beneath McMurdo Sound fast ice; photo J. Weller

EXECUTIVE SUMMARY

This report provides the scientific basis, validating the results of the CCAMLR Bioregionalization Workshop (2007) as well as the report of ASOC (2010), for identifying the Ross Sea as one of 11 areas deserving close scrutiny for inclusion in a network of marine protected areas. CCAMLR (2007) identified the Ross Sea as an area of high biodiversity on the basis of its high physical heterogeneity; ASOC (2010) compared characteristics of the Ross Sea to areas designated under various international agreements instituted to preserve biodiversity. The CCAMLR (2007) subsequently was endorsed in the joint meeting of CCAMLR's Scientific Committee and the Environmental Protocol's Committee on Environmental Protection (ATCM XXXII-CEP XII, Final Report, 2009). Considered herein is the Ross Sea shelf and slope, which is a smaller portion of the area identified in CCAMLR (2007) as "Ross Sea shelf".

Waters overlying the Ross Sea continental shelf and slope comprise ~2.0% of the Southern Ocean, an area inconsequential in size from a global perspective. However, as shown by this summary of information — amassed from the national research programs especially of Italy, New Zealand, United Kindgom (during the "heroic" era), and United States — the Ross Sea not inconsequential is its biodiversity nor its disproportionate contribution to world populations of many well-known iconic Antarctic species. The data and information presented herein show that the Ross Sea:

- is the most productive stretch of the Southern Ocean and contains habitat for 32% and 26%, respectively, of the world populations of Adélie and emperor penguins (summer, molting, portion of wintering habitat); 30% of the world population of Antarctic petrels, 6% of Antarctic minke whale and perhaps 50% of Ross Sea killer whale (summer foraging); and 50-72% of the South Pacific sector Weddell seal population (year round habitat).
- contains the primary habitat for subadult growth and spawning recovery of an ecologically and scientifically important, migratory, Antarctic toothfish population;
- possesses a fauna, especially its notothenioid fish, that now comprise a unique, marine example of an evolutionary radiation known as a "species flock"; its confines contain 46 endemic species of fish and invertebrates as well;
- is a region of exemplary benthic biodiversity, including >500 species first described from Ross Sea specimens, some dating back 170 years, and thus providing a baseline of species' occurrence patterns that can be used to identify ongoing changes caused by climate change;
- on the basis of projections made from current models in the Intergovernmental Panel on Climate Change array, is likely to be the last stretch of ocean on Earth, perhaps within the current century, that will support a sea-ice associated community of organisms;
- is the best studied stretch of high latitude, continental shelf ocean in the Southern Hemisphere, including its a) geologic history, geophysical characteristics, and characterization of its seafloor substrate; b) circulation; c) polynya-facilitated biogeochemical processes leading to extremely high primary production; d) benthic-pelagic coupling whereby water column production enriches the benthic community; e) diverse assemblage of benthic fauna, depending on substrate, slope, current velocities and biological interactions, and varying in age from

thousands of years to successional stages of iceberg scour events; and f) paradoxically (in today's world) low level of Ross Sea zooplankton abundance in the context of an unusually robust pelagic assemblage of numerous large fish, aerial birds, penguins, pinnipeds and whales, both toothed and baleen; and

- contains the longest, or near-longest data sets (~40-50 yrs), important to understanding effects of climate change on Antarctic marine biota: hydrography, pinniped demography, benthic community structure, toothfish prevalence variability, and penguin population change.

Owing to its low level, to date, of human impact (Halpern et al. 2008, Ainley 2010), the Ross Sea provides a valuable research opportunity to continue the concerted scientific efforts of the past 200 years to investigate, without interference from other factors (see ASOC 2010):

- climate change and its ecological effects without interference by other, direct anthropogenic impacts (indeed, climate change clearly has been altering the sea ice and oceanographic properties of the Ross Sea in a well documented fashion); and
- the dynamism inherent in both bottom-up and top-down forces that structure this foodweb.

Given, as detailed herein, the high level of endemism, the high biodiversity and the fact that several iconic species require the entire Ross Sea in order to survive and maintain their world-important populations, all of the shelf and slope, and their physical characteristics and biota, should be considered an ecological unit.

A scene from the relatively "depauperate" western (compared to the eastern) benthos of McMurdo Sound — scallops, urchins and brittle stars, including species first described from Ross Sea specimens; photo H. Kaiser.

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1. INTRODUCTION

The Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) and the Committee for Environmental Protection (CEP) have been actively discussing the development of a representative network of marine protected areas (MPAs) throughout the Southern Ocean.

As a result of CCAMLR's effort, on the basis of five physical types of data plus chlorophyll, 11 regions of the Southern Ocean were deemed to be of high habitat heterogeneity, leading to the supposition that biodiversity should be high in these regions as well (CCAMLR 2007; Figure 1). The CCAMLR report was endorsed by the CEP at the Antarctic Treaty Consultative Meeting in April 2009, and important milestones for developing a network of MPAs throughout these 11 regions by 2012 was agreed by CCAMLR in November 2009 (ATCM 2009b; SC-CAMLR 2009). Therefore, these 11 Southern Ocean regions contain the candidates for evaluation as part of the network of Antarctic marine protected areas to be established in accordance with Article VIII(2)(g) of CCAMLR and Annex V of the Environmental Protocol. Among these 11 regions, only one, identified in the CCAMLR report as the "Ross Sea shelf", constitutes a broad, shallow continental shelf, certainly a rarity in the Southern Ocean given the isostatic depression of the Antarctic land mass (see below, p. 6). Four areas contained segments of deep, narrow continental shelves; the remainder were oceanic, including some insular shelves and ridges. One of these deep-water areas, i.e. waters south of the South Orkney Islands, was recently selected to become the first large marine reserve within the network (CCAMLR Conservation Measure 91-03).
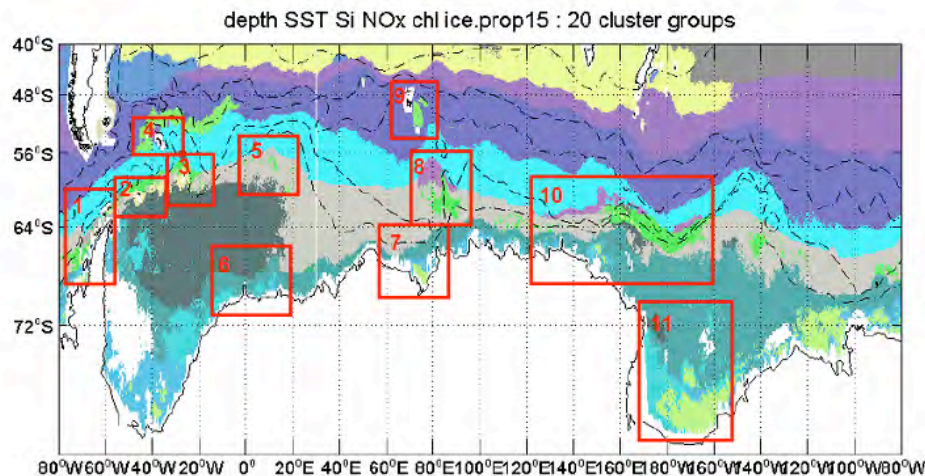
Figure 1. Secondary regionalisation agreed by the CCAMLR Bioregionalisation Workshop, analysis being based on depth, SST, silicate concentration, nitrate concentration, surface chlorophyll-*a*, and ice concentration (CCAMLR 2007). Red boxes show areas of highest heterogeneity, which have been identified by the Working Group as priority areas for identifying MPAs as part of a representative system (numbers refer to area descriptions, and are not in any order of priority): 1 = Western Antarctic Peninsula, 2 = South Orkney Islands, 3 = South Sandwich Islands, 4 = South Georgia, 5 = Maud Rise, 6 = Eastern Weddell Sea, 7 = Prydz Bay, 8 = BANZARE Bank, 9 = Kerguelen, 10 = Northern Ross Sea / East Antarctica, 11 = Ross Sea shelf.

1.1 Objective of this Report

The objective of the current document is to show that CCAMLR's bioregional selection of the Ross Sea shelf in its entirety (shelf and slope) was a valid choice on the basis not merely of *inferred* biodiversity, on the basis of high physical heterogeneity, but in terms of actual biological measures of it. The recent paper by ASOC (2010) identified the Ross Sea as comparable in biological quality among criteria used to designate important marine areas under various other international agreements.

The joint CEP/CAMLR Workshop (ATCM 2009b) endorsed the use of rigorous conservation planning in the designation of reserves, and the present document outlines the sorts of data available in regard to the Ross Sea. In addition, one quality not identified by measures of habitat heterogeneity, or biodiversity, is the extent of human impact thus far on portions of the Southern Ocean. The Ross Sea is currently the least directly anthropogenically affected marine area on Earth (Halpern et al. 2008). Moreover, it has been well researched. As detailed herein a huge amount of biological, physiological, ecological, oceanographic and climatological research has thus far been conducted in the Ross Sea, consistent with laying the groundwork for further pursuit of this scientific endeavor. A number of the mapped attributes presented and discussed in this document will be used in a subsequent document showing results of spatial conservation planning for the Ross Sea shelf and slope (Part II: Patterns of Co-Occurrence of Mesopredators in an Intact Polar Ocean Ecosystem).
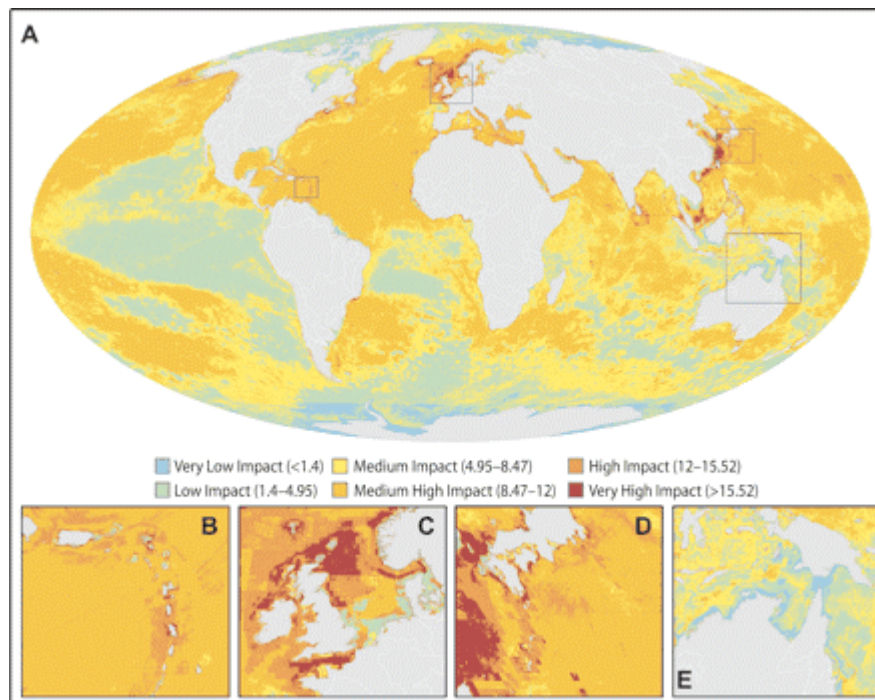

Figure 2. Image showing results of the analysis of anthropogenic impacts to the oceans as conducted by Halpern et al. (2008). These authors divided the ocean into 232 segments, and scored each on the degree to which each had been changed by 17 types of human activities. The high and low scores are indicated. The Ross Sea score was 0.1, the lowest of all; by permission, B. Halpern.

1.2. What is the Ross Sea?
As detailed in Ainley (2010), the "Ross Sea, about the size of southern Europe, is defined, following the boundary identified by Davey (2004), as the waters overlying the continental shelf and slope (3000m depth contour), including the northward projecting Pennell/Iselin Bank, from Cape Adare, Victoria Land (71° 17'S, 170° 14'E), to Cape Colbeck, Marie Byrd Land (77° 07'S, 157° 54'W; Fig. 1); see Figure 3. Some authorities view the Balleny Islands (66° 55' S, 163° 20' E) and other areas to the north as part of the Ross Sea (e.g. Waterhouse 2001, Bradford-Grieve & Fenwick 2001), but these areas, identified as "Northern Ross Sea/East Antarctica" in CCAMLR (2007; see Fig. 1), are not connected oceanographically nor geologically to the Ross Sea shelf. Rather, the Balleny Islands are the summits of deep-rising, volcanic seamounts, 200 km to the northwest of Cape Adare. The Ballenys are also faunistically different from the Ross Sea; for example, nesting there are three species of seabirds (Chinstrap penguin *Pygoscelis antarctica*, Southern Fulmar *Fulmarus glacialoides* and Cape Petrel *Daption capense)* which are considered, faunistically, as 'low Antarctic' forms and which do not nest and rarely occur over the Ross Sea shelf or slope, as defined above (see Ainley et al. 1984).

Ainley's (2010) description continues: "The Ross Sea, thus, is shaped like a right triangle, with the height being the north-south oriented Victoria Land coast and the base being the east-west Ross Ice Shelf (or Barrier), overall extending north and east, respectively from Ross Island in the southwest corner (77° 30'S, 168° 00'E). [To be more accurate, the Ross Ice Shelf covers a portion of the Ross Sea continental shelf to the south approximately equal in size to the open-water portion in the north]. The mean depth of the exposed shelf is about 500 m, although this varies widely between deep troughs and shallow banks. The shelf-break has been defined by some to occur at the level of the [outer edge of the] troughs, about 800 m, rather than the outward crest of its banks, with the slope descending to 3000 m (Smith et al. 2007); the tops of the banks at the shelf-break are in places <200 m deep. Region-wide, the Ross Sea bathymetry slopes upward from south to north (the banks) owing to the isostatic depression of the continent and southern shelf from the heavy mass of the polar ice cap." Only the Ross Sea shelf in the Antarctic, owing to its breadth and therefore release from isostatic pressure in its outer portion, has these shallow areas that are comparable to continental shelves elsewhere on Earth. Therefore, the Ross Sea alone in the Antarctic has at least physical attributes consistent with northern continental shelves, e.g. those continental shelves of the Arctic and other cold-water locations in the Northern Hemisphere. Comparable areas might be Hudson Bay, North Sea, Baltic Sea, George's Bank and so on.

"Ross Sea Surface Water (RSSW) is distinctive and, until recent glacial melting upstream, was the most saline surface water in the Southern Ocean (Jacobs et al. 2002, Jacobs & Giulivi 2009). The high salinity of RSSW is related to sea ice formation, with concomitant salt rejection as the ice forms, for much of the year (Jacobs & Comiso 1989). At the Ross Sea (Antarctic) Slope Front, Circumpolar Deep Water is upwelled and constrains RSSW to the south (Ainley & Jacobs 1981, Jacobs 1991). The central portion of the Ross Sea, from Ice Shelf front northward, due initially to frequent strong winds and subsequently to warming, becomes increasingly clear of sea ice as the season progresses, October through January. This is the Ross Sea Polynya and post polynya (Jacobs & Giulivi 1998, 1999), the largest polynya on Earth (see below).

"Biologically, the Ross Sea is divided into two components, the continental shelf

(neritic) and the continental slope (pelagic)." Defined as above, the portion of the Ross Sea free of glacier ice is 433,061 km^2 (delineated by 800 m isobath and the Ross Ice Shelf front) and 647,194 km^2 when the continental slope (to 3000 m) is included. This area comprises 2.0% of the Southern Ocean (determined to be ~32.9 million km^2; http://www.fao.org/DOCREP/003/W5911E/w5911e07.htm).
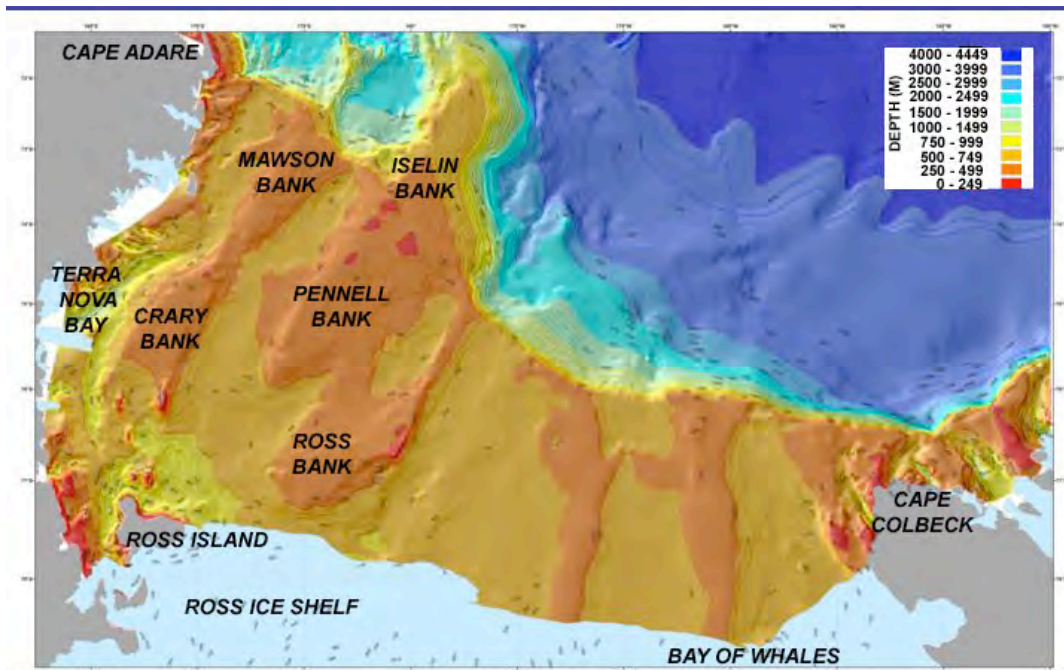

Figure 3. The Ross Sea shelf and slope as drawn by F.O. Nitsche, Lamont-Doherty Earth Observatory, using the base map of Davey (2004).

2. REVIEW: CHARACTERIZATION OF BIODIVERSITY IN THE ROSS SEA

This paper is an outcome of the international workshop on the Ross Sea held in conjunction with the International Marine Conservation Congress (IMCC), 20-22 May 2009, in Fairfax, Virginia USA (Appendix I, II).

IMCC workshop participants gave talks explaining the importance of various aspects of the physics and biota to understanding the Ross Sea ecosystem and identified data layers. Since then, these and other data layers have been accumulated and are displayed and discussed herein. Several of them are used in a conservation planning/modeling exercise that further synthesizes their overlap in time and space (Part II: Patterns of Co-Occurrence of Mesopredators in an Intact Polar Ocean Ecosystem). Ultimately, these data are the product of the national Antarctic research programs over the past 180 years, principally of Italy, New Zeland, United Kingdom (during the "heroic era" of exploration) and the United States of America.

2.1. Data layers

The following data sets are available to WG-EMM, though the requestor may be directed to other websites and use may require permission from persons originally responsible for the data:

Bathymetry: from Davey (2004).

Sediments: Anderson (1999), J. Anderson, pers. comm.; Florida State University Antarctic Marine Geology Research Facility, http://www.arf.fsu.edu

West Antarctic Ice Sheet grounding line: Anderson (1999), J. Anderson, pers.comm.

Water types: from Orsi and Wiederwohl (2009); CTD profiles (data from the Southern Ocean Database at Texas A&M University, http://wocesoatlas.tamu.edu. Also, from M. Diniman, Old Dominion University, pers. comm.

Current trajectories: Jacobs et al. (2002), Smith et al. (2007).

Sea ice: from NASA, courtesy C.L. Parkinson, pers. comm.

Climate projections of sea ice coverage, sea ice thickness, sea surface temperature from Ainley et al. (2010); J. Russell, pers. comm.

Sea ice microbial communities: proxy of sea ice persistence from CCAMLR (2007).

Chlorophyll seasonality: Smith et al. (2003); W. Smith, pers. comm.

Chlorophyll maximum: from NASA, courtesy J. Comiso, pers. comm.

Type localities of Ross Sea fish and invertebrates: J. Eastman, pers.comm; research reports of cruises by *USNS Eltanin; USCGC Edisto, North Wind, East Wind, Glacier; RRS Erebus, Mourning, Terra Nova, Discovery* (I). Verifications courtesy NZ National Museum (Te Papa), U.S. National Museum of Natural History. See Appendix IV.

Benthic sampling localities: courtesy R. Dunbar, J. Barry, W. Smith, S. Hanchet.

Faunal assemblages: Bullivant (1967), Kennett (1968), Barry et al. (2003), and Barry, pers. comm.

Scientific trawling: HMS *Discovery* (1928-1950; A. Atkinson, pers. comm.), DeWitt (1970), Takahasi & Nemoto (1984), Eastman & Hubold (1998), Sala et al. (2002), Ackley et al. (2003; J. Torres, pers.comm.), Taki et al. (2008), Donelly et al. (2004).

Antarctic toothfish distribution by size: from Hanchet et al. (2008).

Antarctic toothfish fishing effort: data courtesy CCAMLR (by permission of individual contributors from, Argentina, Republic of Korea, New Zealand, Norway, Russia, Republic of South Africa, Spain, Uruguay, UK).

Sightings of humpback, fin and blue whales: courtesy IWC (in Matsuoka et al. 2006, Sala et al. 2002).

Sightings of minke whales: courtesy D. Thiele, AnSlope cruises; D. Ainley, RISP and NBP cruises.

Sightings of beaked and killer whales: courtesy IWC, R.L. Brownell, Jr, pers.comm.; D. Thiele, Anslope cruises, D. Ainley, RISP and NBP cruises.

Sightings of crabeater, Weddell and leopard seals: courtesy D. Ainley, RISP and NPA cruises.

Satellite telemetry data of crabeater and Weddell seals: courtesy P. Boveng, J. Bengtson, US National Marine Mammal Lab.

Satellite telemetry data Weddell seals: courtesy B. Stewart, W. Testa, J. Burns.

Satellite telemetry data elephant seals: courtesy M. Hindel and D. Costa.

Sightings of albatross, penguins, petrels: courtesy D. Ainley, RISP and NBP cruises.

Satellite telemetry data emperor penguins: courtesy G.L. Kooyman.

Satellite telemetry data Adélie penguins: courtesy G. Ballard, P. Lyver, S. Olmastroni.

GLS data Adelie penguins: courtesy G. Ballard (Ballard et al. 2010).

2.2. Ross Sea Physics

2.2.1. Geology and glaciology
The Ross Sea shelf is composed of a series of southwest-northeast extending banks, the outer portions of which are <200 m deep, interspersed by troughs as deep as 700 m. These troughs were carved by glacial action during recent ice ages; they constitute the routes of "ice streams" within the larger ice sheets that at times covered most of the Ross Sea (Anderson 1999: 134-140, the source of almost all the text to follow in this section; see references within that volume). Therefore, these troughs were cut downward into the ocean bottom as is the case for canyons that project across shelves at the mouths of large rivers on the other six continents. During glacial maxima, sea level was ca. 100 m lower (Emslie et al. 2007), and so during those times the waters overlying these Ross Sea banks were even shallower than today. The continental slope is divided into two distinct physiographic portions; east of Pennell/Iselin Bank (northward-most extending bank; see Fig. 3), it is relatively gentle (2° gradient), but to the west it is much steeper, averaging 5° in the upper portion. This difference has effects on spatial variability in the upwelling of Circumpolar Deep Water along this margin.
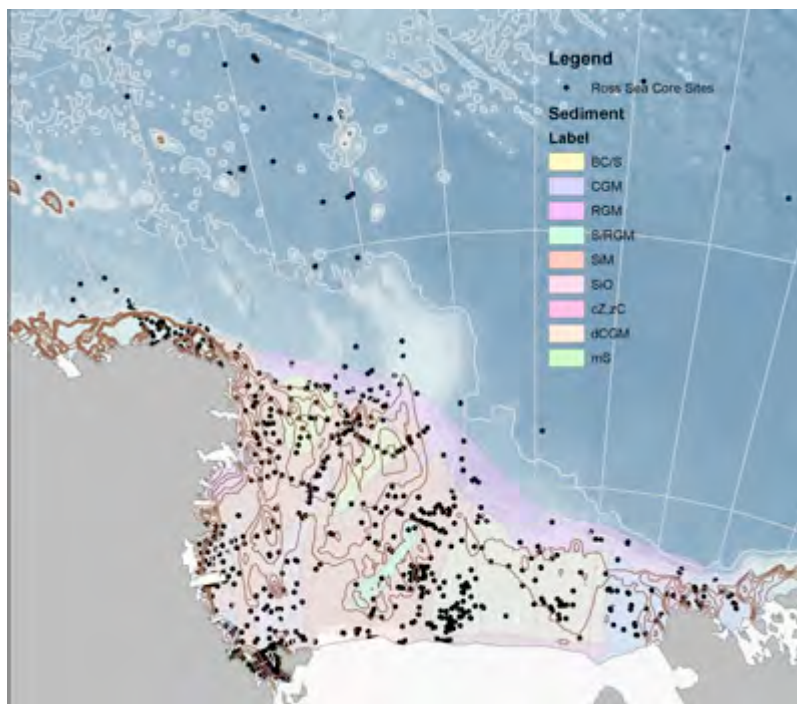

Figure 4. Sediment cores taken from the Ross Sea region over the past 50 years (indicated by dots), and the distribution of sediments as judged from those samples (from Anderson 1999): BC/S = bioclastic carbonate/sand, CGM = compound glacial marine (terrigenous silt with minor ice-rated debris), RGM = residual glacial marine (ice rafted sand), S/RGM = sand/residual glacial marine, SiM = siliceous mud, SiO = siliceous ooze, cZzC = clayey silt/silty clay, dCGM = diatomaceous compound glacial marine, mS = muddy sand. Core locations from Florida State University Antarctic Marine Geology Research Facility, http://www.arf.fsu.edu.

The sediments of the Ross Sea benthos are the most thoroughly investigated of the Antarctic continental shelves, with information coming from various coring and camera procedures conducted over the past several decades, although the effort actually began

with the James Clarke Ross Expeditions of 1841-43 (Fig. 4; Anderson 1999). The distribution of the various sediment types shown in Figure 4 reflects the relative influence of biologic, oceanographic and glacial processes. Overall, the outer shelf and slope is covered by sandy gravel, sand and muddy sand as a product of glacial-marine action. Ice-rafted, coarse sand and gravel and calcareous bioclastic material, formed from biotic processes, also covers the tops of the banks. The latter material increases from east to west along the outer shelf. Bottom currents along the shelf break and around the edges of some of the banks are relatively strong at 15-25 cm/sec. These currents affect the sorting of sand deposits (with not much silt in the high-current localities), and have great importance in affecting the distribution of benthic communities, as discussed in a later section.

The inner shelf is covered by fine-grained sediments composed of silt, sand, diatom frustules, sponge spicules, and unsorted ice-rafted debris. The concentration of biogenic material increases to the south and west across the shelf, a pattern that results from current action and to less severe sea ice in the western Ross Sea. Near-bottom currents are weak in the inner shelf, and fall below the suspension threshold, giving rise to the small particle size in these inner sediments. The thickness of these diatomaceous muds varies irregularly owing to scouring from glacial ice and icebergs (presumably when sea level was lower), as this is the deepest portion of the Ross Sea shelf (to 1000 m).

Also affecting sediment dispersal in the Ross Sea is sea ice, which regulates water column biological productivity through the admittance of sun light and, therefore, the generation of biogenic sediment (the oozes, etc.). The existence of the Ross Sea Polynya in the western Ross Sea drives much biotic production; in contrast, the eastern Ross Sea is ice covered for most of the year and much less productive, although, given that the Ross Sea is one of the most productive stretches of the Southern Ocean (see below), productivity is relatively high. This polynya and phytoplankton production will be further discussed below.

2.2.2. Water masses and circulation
The physical and chemical oceanography of the Ross Sea has been studied in considerable detail since the IGY, almost entirely during the summer when its Ross Sea Polynya expands to include much of the large continental shelf. Figure 5 shows the distribution of localities where vertical profiles of temperature and salinity have been taken according to several ocean data bases. Some ocean measurements have also been made through holes in the Ross Ice Shelf and the fast ice of McMurdo Sound. The longest Antarctic hydrographic data set comes from the Ross Sea (Jacobs 2006).

The distribution of Ross Sea water types has recently been reviewed by Orsi & Wiederwohl (2009 and Fig. 6). Three major water masses and several sub-types have been identified on the continental shelf, with Shelf Water comprising the largest volume. Most 'High Salinity' Shelf Water is generated during winter sea ice formation in coastal polynyas, best developed over the western shelf. "Ice Shelf" Water is formed by melting and freezing under the Ross Ice Shelf. Some authors now include "Low Salinity" Shelf Water in the eastern sector as part of Antarctic Surface Water, which occupies the warmed and freshened upper layers throughout the Ross Sea during the austral summer. "Modified" Circumpolar Deep Water intrudes between the Shelf and Surface waters, preferentially at some locations (Jacobs et al. 1985; Dinniman et al. 2003 and Fig. 7), and

contributes a sensible heat component to the largely wind-driven, latent heat Ross Sea Polynya.

This report defines the Ross Sea as the region landward of the 800-m isobath on the upper continental slope (see above, What is the Ross Sea?). That roughly corresponds to the mean position of the Antarctic Slope Front, which separates the warmer, abyssal deep waters from the colder shelf waters, and is the locus of a westward shelf-break current (Ainley & Jacobs 1981). On the northern side of that front, the most voluminous water mass in the Southern Ocean, Circumpolar Deep Water, can at times be found on the outer few tens of kilometers of the continental shelf when tidal excursions move the front onto the shelf. The Slope Front is also a sink where the deep and shelf waters mix to form other water masses, including the Modified Circumpolar Deep Water and Antarctic Bottom Water. Related upwelling in this area can bring nutrients and planktonic organisms into the surface layers, enhance primary production and lead to heightened densities of upper trophic-level predators (Ainley & Jacobs 1981; see below).
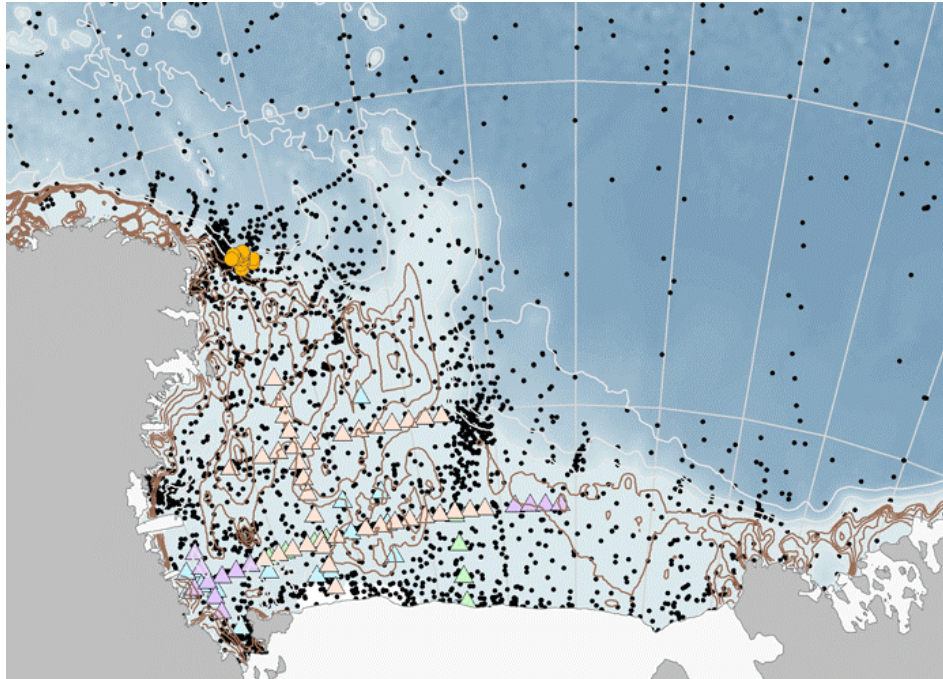

Figure 5. Distribution of vertical profiles of temperature and salinity in the Ross Sea and vicinity for the past 50 years (black dots), from the Southern Ocean Database at Texas A&M University (http://wocesoatlas.tamu.edu). The yellow dots show recent mooring locations (e.g. ROAVVERS) and the diamonds some of the repeated hydrographic stations (e.g., W. Smith, pers. comm.).
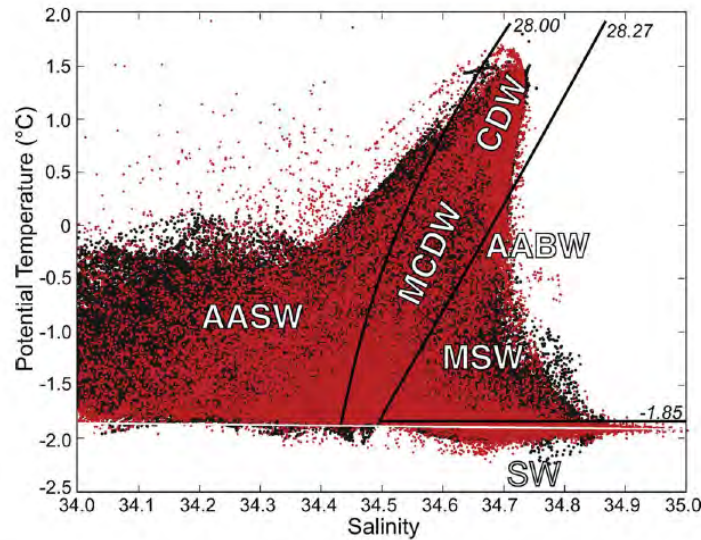
Fig. 6. Water masses on and near the Ross Sea continental shelf, as defined by their temperature/salinity characteristics, from Orsi & Wiederwohl (2009, by permission). The highly distinctive Ross Sea Shelf Water is referred to in this figure as Antarctic Surface Water (AASW).
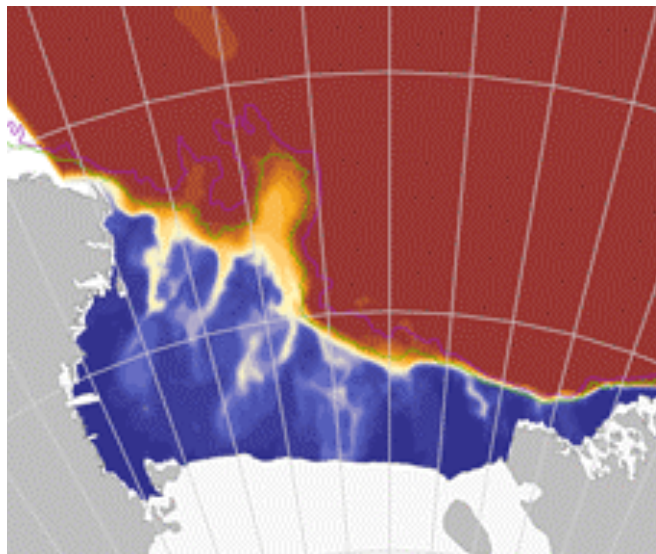

Figure 7. Modeled intrusions of Modified Circumpolar Deep Water (MCDW) at intermediate depths (red shading to orange-yellow) onto the Ross Sea continental shelf, thus displacing/ mixing with Ross Sea Shelf Water (blue); from M. Dinniman (Old Dominion University), unpubl. data. Therefore, what this figure represents are the water masses below the surface layer.

The Ross Sea's submarine banks and troughs lead to considerable spatial variability in ocean currents, and its biota (see later in this report). The circulation is largely characterized by westward flow, strongest along the Ross Ice Shelf front and continental shelf break, and northward flow along the Victoria Land coast (Fig. 8). Most of the surface circulation is driven by relatively persistent southerly winds off the Ross Ice Shelf and strong downslope flows off the Victoria Land coast in the western Ross Sea. Weak intrusions of Modified Circumpolar Deep Water are roughly aligned with the

bathymetry in models of the ocean circulation. Inflows from the east and north renew the shelf waters on a time scale less than a decade. Simulations of the movement of suspended particles in the water column have shown that, on seasonal time scales, most are not transported over great distances and remain on the shelf. Spatial variations in particle retention times could impact the standing stocks of food for upper trophic levels, as well as the transport of larvae and juvenile forms.
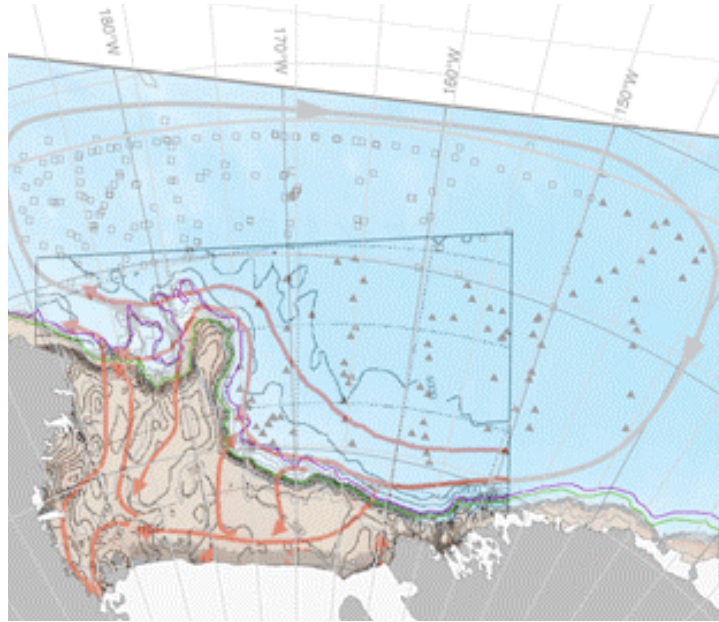

Figure 8. A composite of figures from Jacobs et al. (2002) showing the Ross Gyre north of the continental shelf, and from Smith et al. (2007) showing the general flow of currents over the shelf and slope. Symbols denote locations of hydrographic stations used to assess the patterns depicted.

The Antarctic Slope Front is extremely important to the biota of the Ross Sea, and extends along the continental shelf edge over a zone about 125 km wide. That zone includes the southern limb of the Ross Gyre (Jacobs et al. 2002), where evidence exists for slight warming over recent decades. Waters on the continental shelf, however, tend to be buffered from warming by the seasonal cooling and formation of sea ice. A more important change is steady freshening of the coastal flows, apparently due to increased melting of continental ice upstream in the Amundsen Sea to the east (Jacobs & Giulivi 2009). This will increase water column stratification and reduce vertical mixing, with potential impacts on the sea ice field and biota. The Ross Gyre also influences the circulation of sea ice in the region, and thus the life histories of penguins, fish and krill during that portion of their life history spent just to the north of the Ross Sea continental shelf.

2.2.3. Sea ice

For most of the year, much of the Ross Sea is capped by ice, except for five polynyas (Jacobs & Comiso 1989). The Ross Passage Polynya and Pennell Bank polynyas are sensible heat polynyas in the western portion of the outer Ross Sea continental slope associated with the upwelling and intrusions of MCDW (Jacobs & Comiso 1989; see Fig. 7), and polynyas important to biotic processes through past millennia (Thatje et al. 2008). Except for the west coast of the Antarctic Peninsula, where mostly sensible heat polynyas occur (e.g. Marguerite Bay), most coastal polynyas in the Southern Ocean and the remainder in the Ross Sea are largely latent heat polynyas generated by strong winds: McMurdo Sound, Terra Nova Bay and Ross Sea polynyas (Massom et al. 1998, Arrigo & van Dijken 2003). Therefore the outer Ross Sea polynyas offer high latitude examples to compare with the low latitude sensible heat polynyas of the Antarctic Peninsula.

Passive-microwave sea ice data for the Ross Sea extend back to December 1972, although the record prior to November 1978 is marred by major data gaps. From November 1978 to August 1987, the record is much improved, with data available on an every-other-day basis for most of the period; and since August 1987, the record has been further improved, with data available on a daily basis (again for most of the period).

The ice extent in the greater Ross Sea region bounded by 160° E and 130° W, the Ross Ice Shelf on the south, and the outer edge of the pack ice on the north typically reaches a maximum of approximately 4.0 x 10^6 km^2 in September (Fig. 9A). It contracts rapidly thereafter to a minimum of approximately 0.7 x 10^6 km^2 by February (Fig. 9B, C), with much variability among years for both those numbers. The ice reaches as far north as it does owing to wind in the western Ross Sea blowing strongly from the south, as well as to Ekman transport, which draws the ice offshore by its eastward movement near the ACC southern boundary. The ice is formed principally near the coast as persistent gale-force winds continually push ice offshore, forming latent heat polynyas in the process (Terra Nova Bay, Ross Sea polynyas). Due to seasonal, warming some time after the sun rises in the spring, ice formation largely ceases and is overcome by melting. The ice field then quickly recedes to cover just the eastern Ross Sea and areas along the southern Victoria Land coast (Fig. 9B, C). In years of greater than average ice recession, the ocean absorbs more thermal energy than it would otherwise, and the fall freeze-up is delayed, and vice versa for years of limited ice recession during summer (Jacobs & Comiso 1989). These seasonal patterns are summarized in Figure 10.
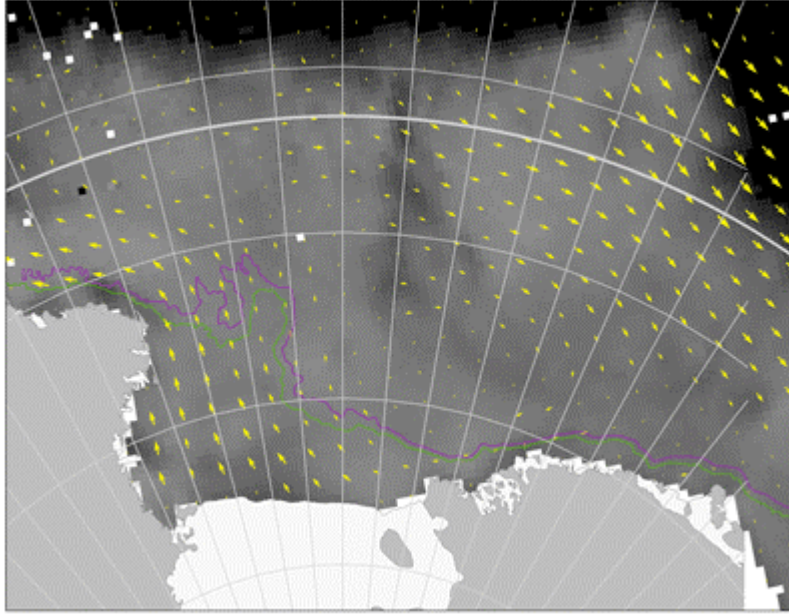
Figure 9A. Sea ice (cloudy gray) at its maximal seasonal extent, August-October depending on year. The outer edge of the ice reaches to about the southern boundary of the Antarctic Circumpolar Current. Also shown is the general circulation of the ice, as a function of winds and the flow of the Ross Gyre (data from NASA). Polynyas are apparent along the middle portion of the Ross Ice Shelf, in Terra Nova Bay (ca. 75° S), and outer shelf , vicinity of Cape Adare (ca. 71 ^{o} S). Heavy latitude line at 66.5^o is the Antarctic Circle.
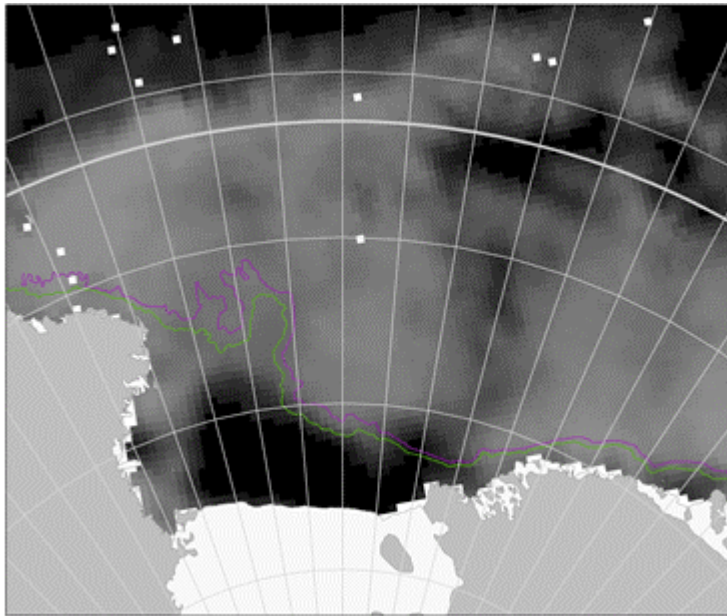

Figure 9B. Sea ice distribution (cloudy gray) in the Ross Sea region during November, with shrinkage of the ice cover occurring rapidly both at its southern boundary, as the Ross Sea polynya (at this season called a post-polynya) expands, and at its northern margin as seas begin to warm.
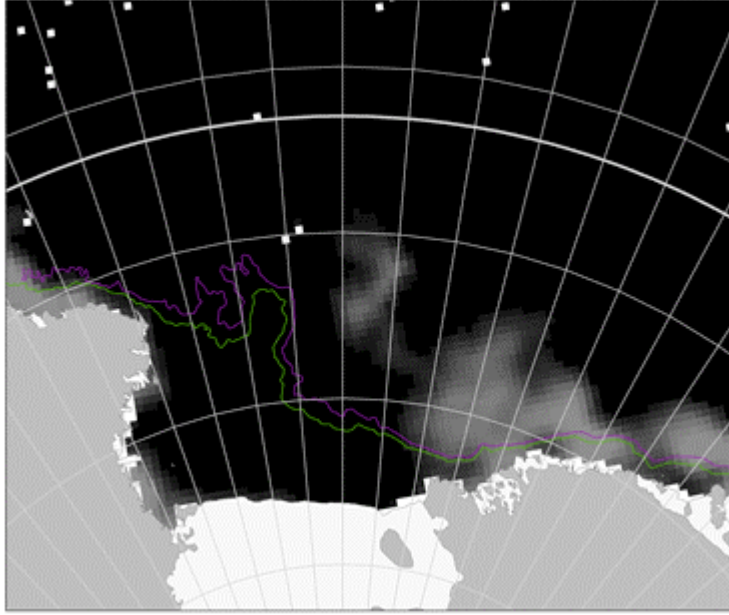
Figure 9C. Sea ice distribution in the Ross Sea region during February when it is at its minimal extent, in this case extremely so. Sea ice remains in the eastern Ross Sea and towards the Amundsen Sea, as well as just west of Cape Adare (George V Coast) and between Ross Island and Terra Nova Bay.
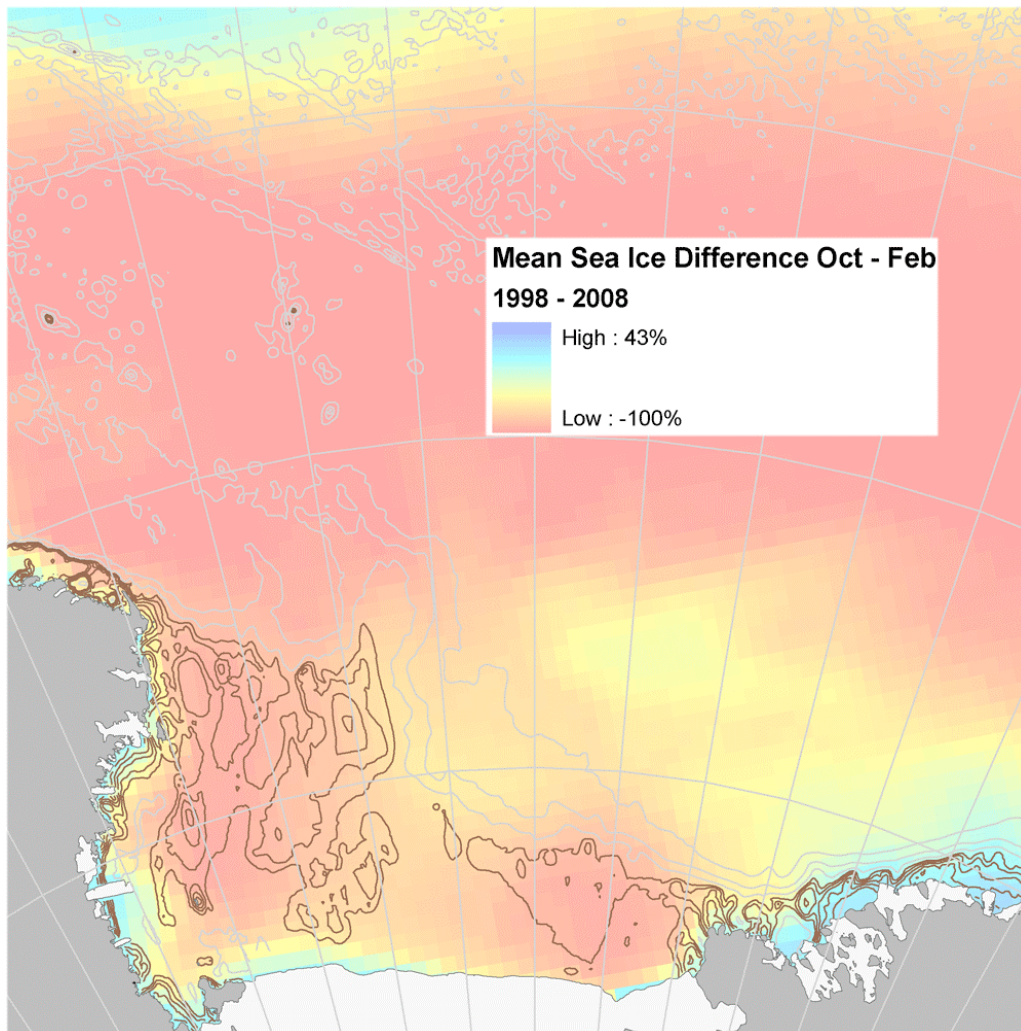
Figure 10. The mean seasonal change (October to February) in sea ice cover in the Ross Sea region (1998 – 2008). Original data from NASA.

The satellite data also allow calculation of trends in the ice cover during recent decades. Using linear least-squares fits, the Ross Sea region ice extent increased at an average rate of $12,600 \pm 1,800$ km^2/yr between November 1978 and December 2007, with every month exhibiting increased ice extent. The rates of increase ranged from a low of $7,500 \pm 5,000$ km^2/yr for the February ice extents to a high of $20,300 \pm 6,100$ km^2/yr for the October ice extents. On a yearly average basis, for 1979-2007, the Ross Sea ice extent increased at a rate of $4.8 \pm 1.6\%$/decade (updated from Cavalieri & Parkinson 2008; Fig. 11). Over the period 1979-2004, the ice-free season in much of the Ross Sea shortened, the ice retreat starting later by 29 days and the freeze starting earlier by 31 days (Parkinson 2002, Stammerjohn et al. 2008; Fig. 12). These changes are at least in part in response to increasing winds, which appear to be related in the short-term to changes in the atmospheric pressure systems involved in the Southern Annular Mode, the Antarctic ozone hole and in long-term to global warming (Thompson & Solomon 2002, Russell et al. 2006). At the same time that the sea-ice season has been lengthening and the ice extent has been growing, the Ross Sea polynyas are becoming more persistent as

well (Parkinson 2002). This is shown, at a smaller scale in Figure 10, by the greater change in ice cover near the coast.
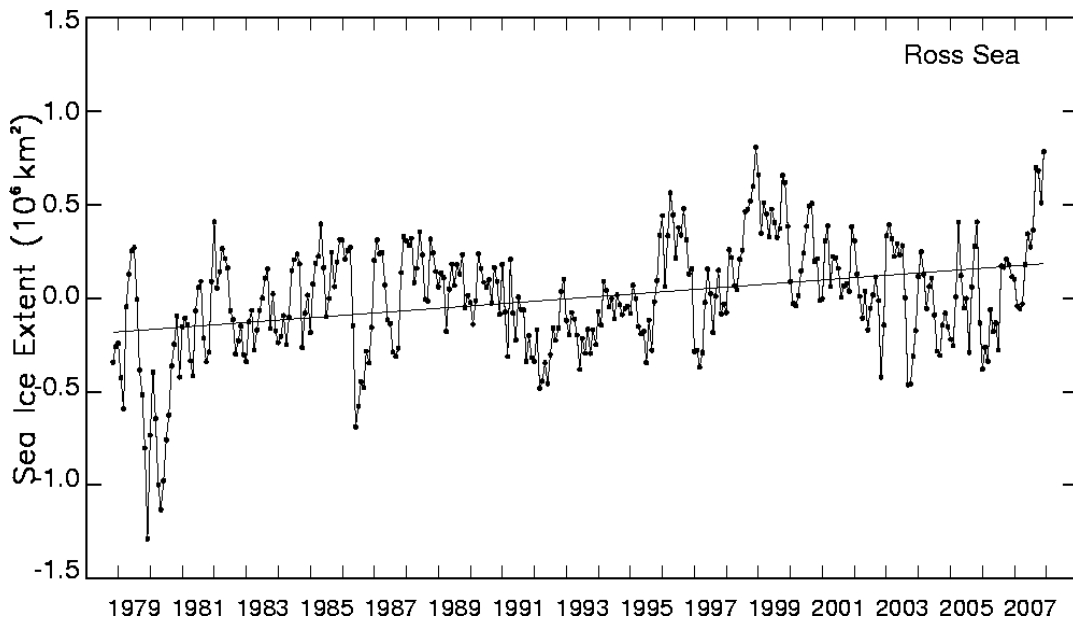

Figure 11. The trend in ice extent monthly deviations in the Ross Sea region, November 1979 – December 2007 (updated from Cavalieri & Parkinson 2008).
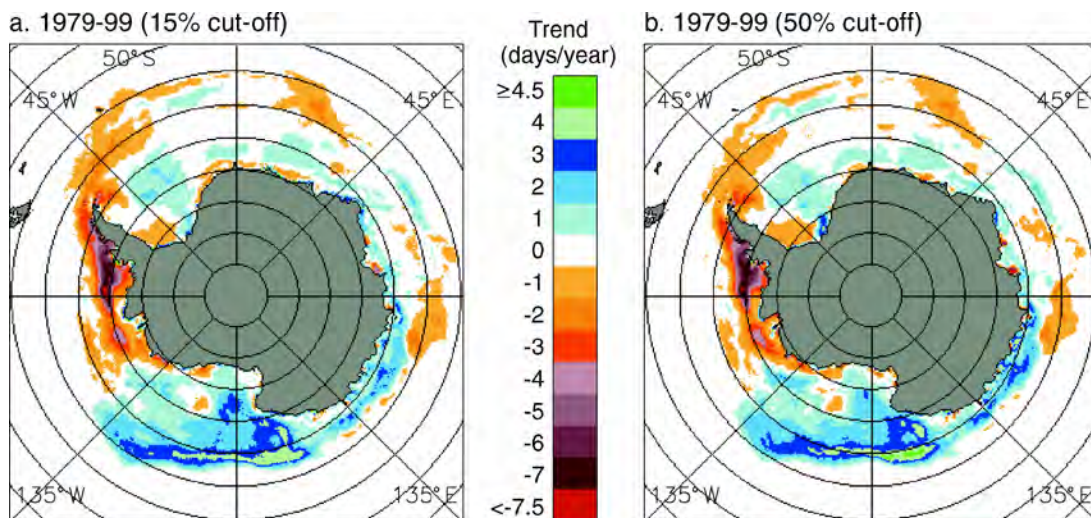
Figure 12. Image from Parkinson (2002) showing change in sea ice season for the Southern Ocean; Ross Sea is to the bottom in each image.

Placing the Ross Sea in the context of the Southern Ocean as a whole, over the period November 1978 – December 2007, the Ross Sea has had the highest rate of increase in sea ice coverage of any of five standard divisions of the Southern Ocean, although the Weddell Sea, Indian Ocean, and Western Pacific Ocean all also had slight sea ice increases; only the Bellingshausen/Amundsen Seas experienced a sea ice decrease. Overall, the Southern Ocean sea ice cover increased at an average rate of $10{,}800 \pm 2{,}500$

km^2/yr between November 1978 and December 2007, with every month showing positive values although with some of these values not being statistically significant. The Ross Sea region contributed most of this increase.

2.2.4. Climate change effects on ocean and sea ice

Global warming (in conjunction with the Antarctic Ozone Hole), already altering the oceanography and sea ice characteristics of the Ross Sea region as noted above, will continue to cause changes in the foreseeable future. Under current projections, an ensemble of climate models indicates a continuation of the poleward shift of the Southern Hemisphere westerly winds due to no recovery of the Antarctic Ozone Hole and a continued warming of Earth's lower atmosphere particularly at middle latitudes (Russell et al. 2006, Ainley et al. 2010). Early changes over the Ross Sea region include a decrease in average ice thickness by as much as 10 cm owing to increased winds, a weakening of the westerly flow due to shifts in the jet stream, and an increase in air temperatures by 1°-2° C (in the annual mean; but mostly during winter) over all locations with larger changes over the southern Ross Sea shelf. The models simulate an increase in the amount of precipitation for the Ross Sea: possibly greater than 10 cm per year, consistent with both the warming (warm air holds more water) and the incursion of more marine air.

Despite a warming ACC (Fig. 13, bottom), there is expected to be little evidence of sea ice contraction in the Ross Sea region until about 2020-2030, other than continued growth of coastal polynyas (Fig. 13, top; Fig. 14). During this time, sea ice will be disappearing rapidly throughout much of the remaining Southern Ocean, especially off East Antarctica (Fig. 13, top) and in the Antarctic Peninsula region (not shown). It would be several decades thereafter, should Earth's atmosphere continue to warm, that sea ice would disappear as well from the Ross Sea. Therefore, the Ross Sea and surrounding waters will constitute a refugium for sea ice and its dependent biotic communities for the foreseeable near future.

a)

b)
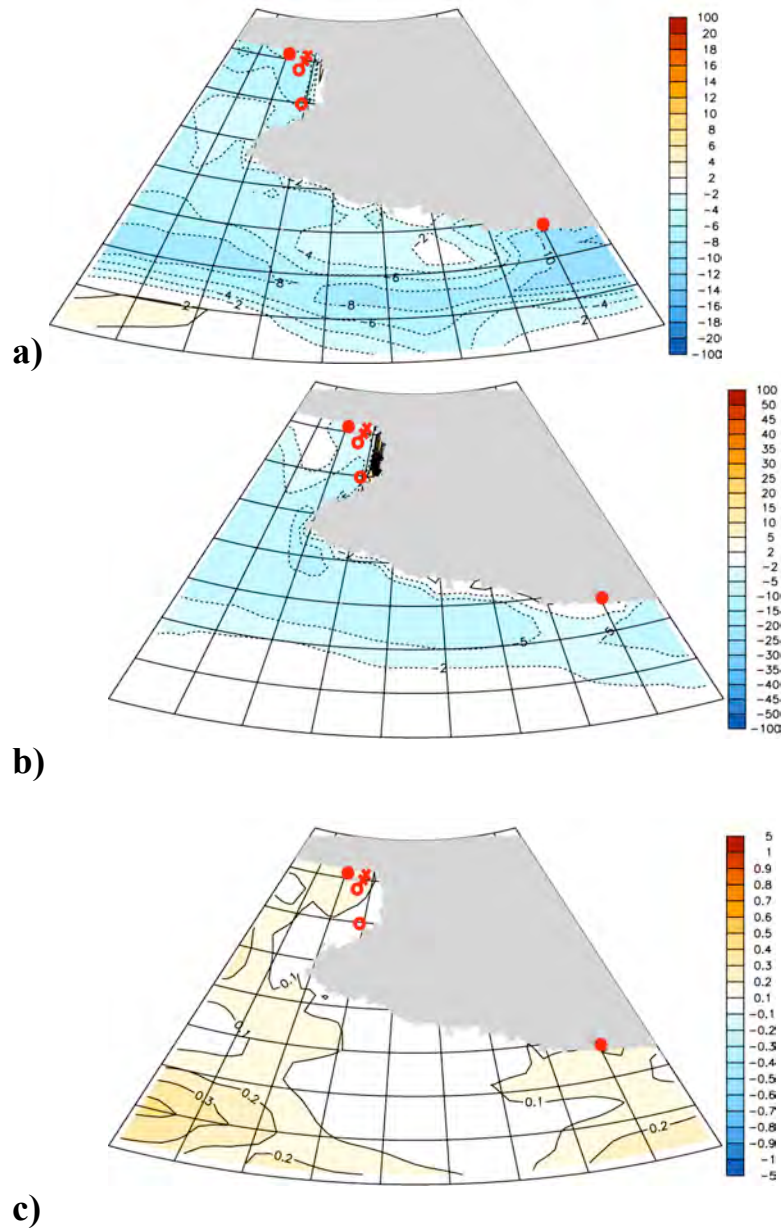
c)

Figure 13. ENSEMBLE (average of four climate models; see Fig 14): simulated change in annual mean: a) sea-ice coverage, b) sea-ice thickness (cm), and c) SST (°C, 0-100 m average) when Earth's average troposphere temperature reaches 2°C above pre-industrial CO_2 levels. Shown is Ross Sea/eastern East Antarctica, from 80°S (top) to 60°S (bottom) with grid lines every 2.5°, and from 180° (left) to 135°E (right) with grid lines every 5°. Important penguin colonies indicated clockwise around Ross Island — Cape Crozier (both Adélie and Emperor), Cape Royds, Cape Bird; Beaufort Island (both Adélie and Emperor) and Cape Washington (Emperor) north of Ross Island; and Pointe Géologie (Adélie and Emperor) is to the right. Analysis by J. Russell (in Ainley et al. 2010).
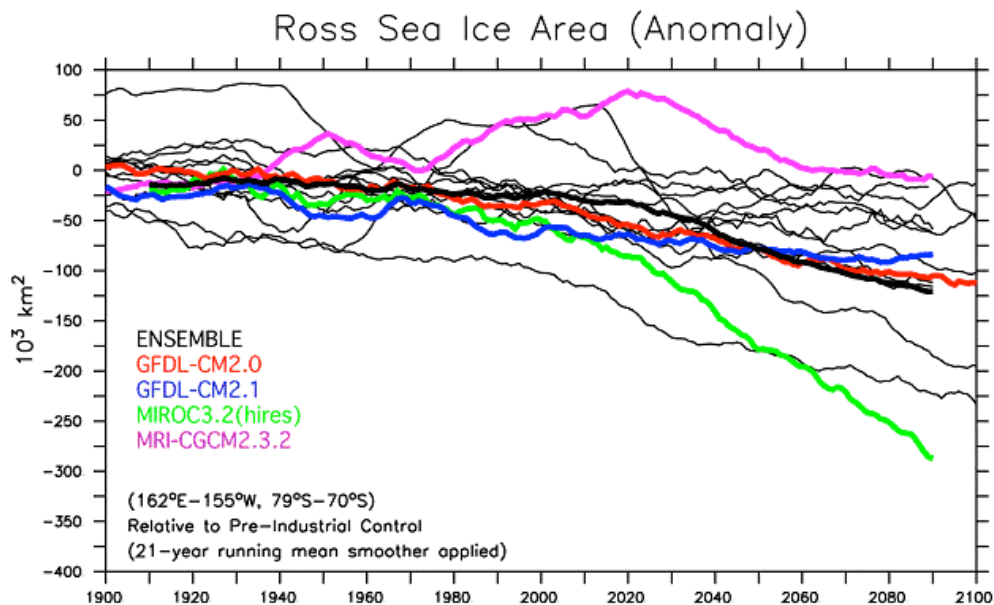
Figure 14. Results of simulations for Ross Sea sector of four climate models, plus the average of the four (ENSEMBLE), each found to simulate current conditions the best of other existing models, as Earth's average atmospheric temperature reaches 2°C above pre-industrial conditions of CO_2. Analysis by J. Russell, from Ainley et al. 2010. Note that the MRI-CGCM2.3.2 model best duplicates the pattern of sea ice increase in the Ross Sea region during the past few decades (cf. Zwalley et al. 2002; cf. Fig. 11 of current document)

2.3 Ross Sea Biology: Lower Trophic Levels

2.3.1. Sea ice microbial communities

As summarized by Smith et al. (2007), due to the large amount of sea ice present in the Ross Sea, even though the input may be small on a per meter square basis, cryophilic (sea-ice living) algae are an important source of organic matter for the food web. The dynamics of this flora are better known in the Ross Sea than anywhere else in the Southern Ocean (Arrigo 2003).

Sea Ice Microbial Communities (SIMCOs) in the Ross Sea can be divided into three categories corresponding to the major ice types observed: the (land)fast ice along Victoria Land, Marie Byrd Land and Ross Ice Shelf; the first year drifting pack ice, formed annually in the Ross Sea and Terra Nova Bay polynyas; and the multiyear ice advected into the eastern Ross Sea from the Amundsen Sea (Fig. 15). The first and second types of ice and SIMCOs are relatively rare outside of the Ross Sea region, as sea ice disappears entirely during summer in much of the remaining Souther Ocean.

While SIMCOs of the fast ice are well studied, the least-understood SIMCOs are those of the drifting pack ice, which is formed annually in the Ross Sea latent heat polynyas (see Sea Ice section). In regard to this annual ice, ice-bottom communities are formed in spring or in the northern portions of the region in winter when light levels are sufficient to initiate microbial growth as sea ice extends and thickens. As the ice melts seasonally, the microbes find their way into the water column.
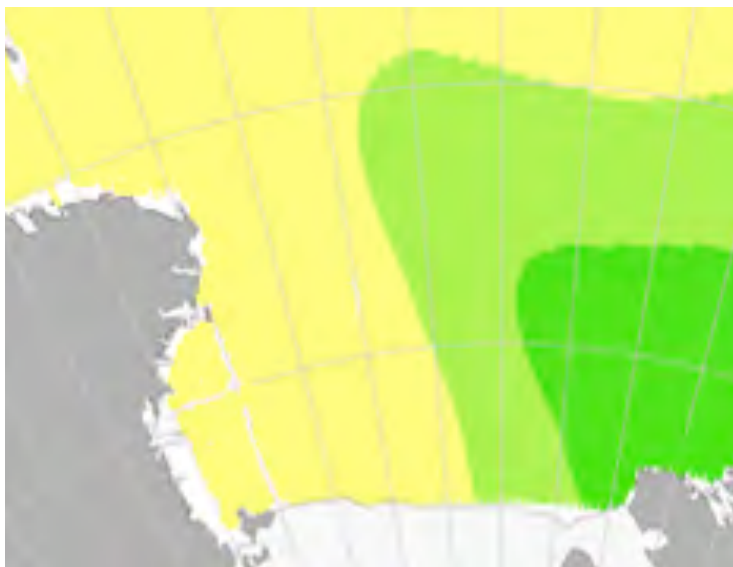
Figure 15. Simulation showing the types of ice (actually, predictability of ice presence; data from CCAMLR (2007)) and, therefore, corresponding microbial communities in the Ross Sea region. Dark green indicates heavy, multiyear ice grading into lighter colors to indicate more ephemeral, annual pack ice; along the Victoria Land coast, the white area includes significant amounts of multiyear, almost perennial fast ice and glacial ice.

The multiyear pack ice that is advected from the Amundsen Sea to the eastern Ross Sea forms one edge of the Ross Sea's Marginal Ice Zone and also has a unique sea ice microbial habitat (Ackley et al. 2003). This is just one of seven locations in the Southern Ocean where pack ice persists year round (see maps in Gloersen et al. 1992), and thus these sorts of cryophilic communities can exist. High ice deformation with thick ice and heavy snow cover generally attenuates the light, so that bottom SIMCOs are less present than otherwise in this ice. Instead, the surface flooding communities and a new habitat, internal near-surface gap layers, are the major habitats present.

2.3.2. Water column microbial dynamics

The Ross Sea is extremely productive with regard to primary production and nutrient uptake. It is the most productive stretch of the Southern Ocean, accounting for as much as 28% of all Southern Ocean primary production, certainly the result of both ice-related but mainly water column processes (Arrigo et al. 1998, 1999). Winter conditions are largely established by circulation and mixing, and in spring ice melt and solar heating increase vertical stratification and allow phytoplankton growth to proceed. Interestingly, growth in the Ross Sea seems to occur earlier than nearly everywhere else in the Southern Ocean, although the reasons for this remain unclear. In general, growth is limited by irradiance in spring and by micronutrient availability (especially iron) in summer (Arrigo et al. 2003, Smith et al. 2003: Fig. 16).
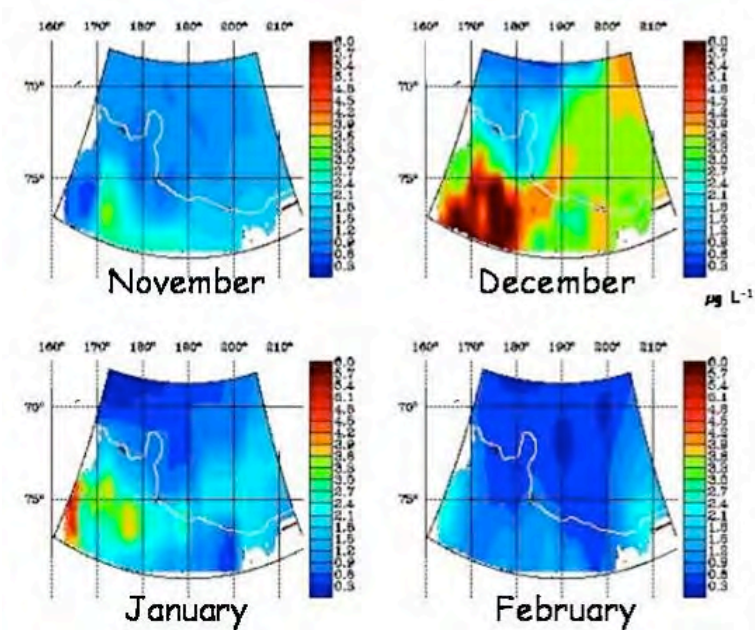
Figure 16. The seasonality of chlorophyll abundance in the Ross Sea region, 160°E to 150°W (from Smith et al. 2003). The initial spurt occurs over the western shelf in association with the Ross Sea Polynya, but spreads rapidly by December; eventually production contracts to the shallower western shelf by January and February.

Ross Sea phytoplankton has a relatively restricted biodiversity, and is driven by two functional groups: diatoms and haptophytes (especially *Phaeocystis antarctica*), each with a characteristic impact on biogeochemical cycles and food webs. Haptophytes attain extremely large biomass in spring, and growth of diatoms is generally more restricted to summer (Fig. 17). However, substantial differences occur among years, and in some years diatoms dominate in spring, and have a substantial bloom in summer that is equal in magnitude to that in spring. Physical forcing appears to be the cause of these variations. The haptophyte bloom occurs mainly in the central portion of the Ross Sea, especially that area encompassed within the Ross Sea Polynya. Though mixing and interleaving occur among the two groups, the diatom bloom coincides mainly with the marginal ice zone of the Polynya.

According to Smith et al. (2007: 99): "Bacterial biomass is low in spring, but both biomass and activity increase with the seasonal phytoplankton bloom (Ducklow et al. 2000). Microbes both in the water column and the sea ice are involved (e.g., Lizotte 2003, Garrison et al. 2006). However, biomass does not increase to the same degree as phytoplankton, suggesting that the initial biomass and activity is limited by carbon and energy sources, whereas later in the season losses due to bacterivory become important (Caron et al. 2000). This is consistent with the two-order-of-magnitude increase in microzooplankton biomass (Dennett et al. 2001), with the microzooplankton probably using bacteria as a major food source, given the paucity of smaller phytoplankton (with the exception of solitary *P. antarctica*). Bacterial cells are also larger than those from warmer waters, with average cell lengths being approximately 1 μm (Ducklow et al. 2000)."
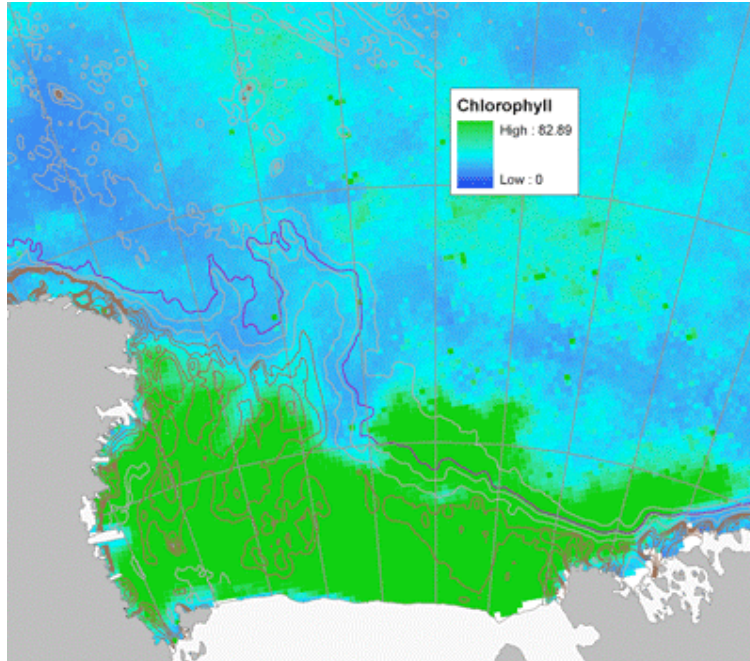
Figure 17. The overall, average distribution of chlorophyll, in mg/m^3, during summer in the Ross Sea region. Data from NASA (J. Comiso). Dark bathymetric contour represents 3000m, the lower end of the slope.

As also noted in Smith et al. (2007: 100), and important to enrichment of the benthos, especially of the banks: "In many areas of the ocean and Antarctic, the export of organic matter to depth (in this case 500 m) is tightly coupled, as passive sinking of phytoplankton and phytodetritus is relatively rapid (of the order of 10 m per day), and so sinking of particles can deliver particulate organic carbon (POC) to 500 m within days to a few weeks (Lohrenz et al. 1992, Fischer et al. 1988, Smith & Dunbar 1998). In the Ross Sea, the maximum in phytoplankton biomass and flux can be, however, separated by up to 4.5 months. The production peak [Dec] is due to the seasonal bloom of [the dominant haptophyte] *P. antarctica*, whereas the flux maximum is much broader, occurs in May (winter), and is mediated by the pteropod *Limacina helicina* (Collier et al. 2000). Given that the yearly production is approximately 100 g C/m^2, and the January–June flux is approximately 3.5 g C/m^2, this suggests that the Ross Sea is neither highly retentive nor characterized by high rates of export relative to production (Grebmeier & Barry 2007; see below, Overall Benthic Community Patterns), but the timing of flux is unusual and may influence benthic growth and survival."

In summary, phytoplankton and microbial standing stocks are highly seasonal, and inversely related to macronutrient concentrations, but also are greatly influenced by the concentration, distribution and inputs of iron (Smith et al. 2007, and references therein). Lower trophic level biodiversity is relatively restricted, but has substantial impacts on upper trophic level processes. Circulation also strongly influences seasonal particle retention times and the biological impacts, as well as the vertical inputs of materials. Therefore the biophysical interactions on the Ross Sea continental shelf are critical to the determination of the region's food web structure and biogeochemical cycles.

2.4 Ross Sea Biology: Benthic Communities

On the basis of its invertebrate fauna, the Ross Sea is considered to be a biodiversity "hotspot" (Clarke & Johnston 2003). Certainly this must have to do with the very high habitat diversity as detailed above (and acknowledged by CCAMLR (2007)): shallow shelf with deep troughs bordering shallow banks, a complexity of water types, and a complexity of circulation and water flow rates in part determined by topography. The first biological samples were taken 170 years ago by the James Clark Ross expeditions, with sampling continued by most expeditions through the International Geophysical Year and the International Polar Year. As a result, the type locality of about 500 animals is located in the Ross Sea, including more than 400 benthic invertebrates (Fig. 18, Appendix IV). These records of species occurence patterns provide a baseline for detecting underway and future changes in faunal patterns caused by climate change. The Antarctic Treaty places special attention on type localities (ASOC 2010).
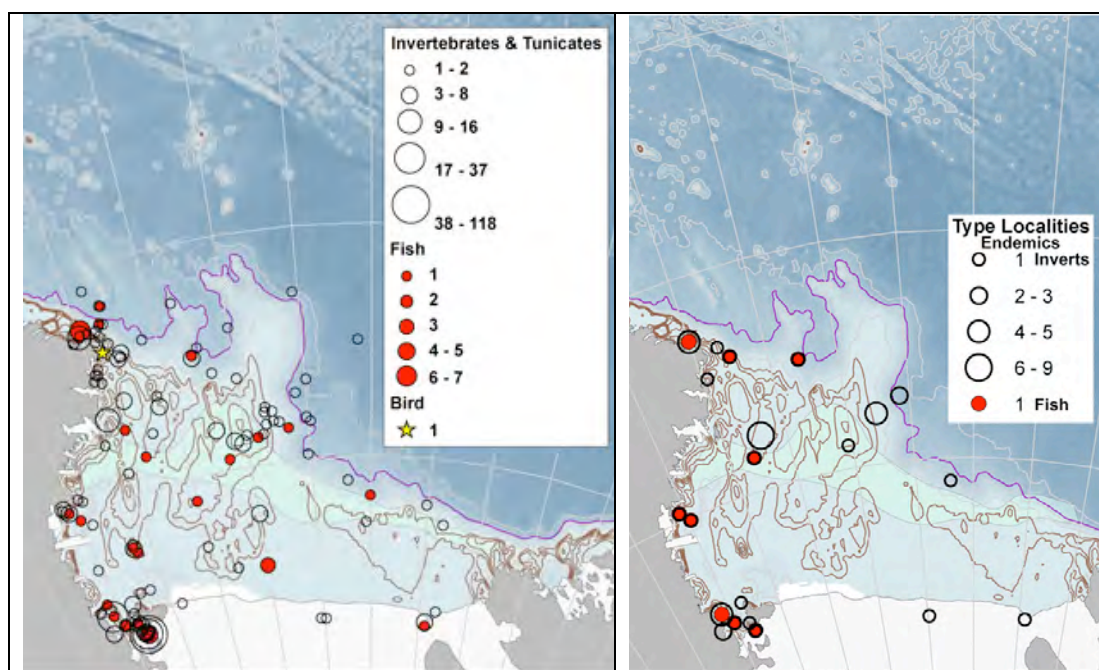

Figure 18. Left panel: the type localities of organisms first described from Ross Sea specimens (see Appendix IV). Shown also is the zone (pale aqua shading over the outer shelf) in which the outer edge of past ice sheets were grounded, indicating that during glacial maxima the northwest Ross Sea was a refuge where continental shelf organisms could continue to persist, as the ice sheets scoured the shelf everywhere else (see Geology and glaciology, above). Sediment analysis indicated that this area in the northwestern shelf during glacial maxima was covered by sea ice as it is today, but that a polynya existed here, as it also does today (see also Section 2.2.3, above). Right panel: the break down of type localities for species found only in the Ross Sea.

2.4.1. Overall pattern of benthic communities

Benthic faunal communities inhabiting the continental shelf and upper slope of the Ross Sea comprise a diverse and specialized assemblage with close taxonomic ties to the circum-Antarctic shelf fauna. Several archetypically Antarctic taxa, such as serolid isopods, are abundant in the Ross Sea. Owing to larval dispersal as zooplankton, most Ross Sea invertebrate taxa are distributed around the entire continent.
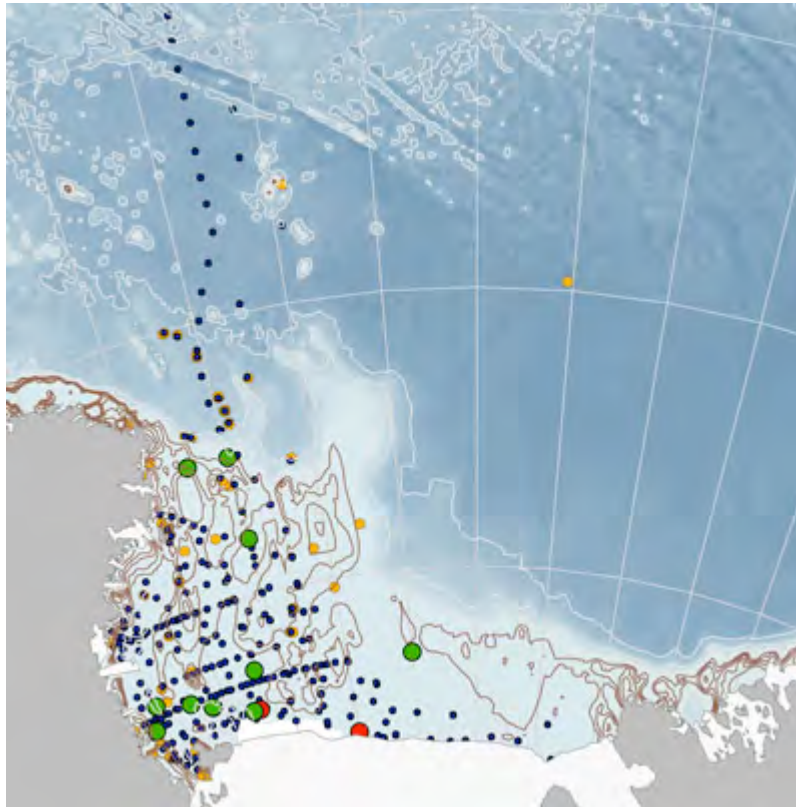
Figure 19. The distribution of sampling to investigate benthic faunal components in the Ross Sea region: blue dots, benthic camera stations (ROAVERRS, *R/V Tangaroa* IPY); yellow dots, bottom grabs; green and red dots, multi-year sediment trap moorings (ROAVERRS, W. Smith).

The general distribution of benthic fauna throughout the Ross Sea has been intensively researched, perhaps more so than any other Antarctic continental shelf (Fig. 19). According to Bradford-Grieve & Fenwick (2001) ~1500 benthic grabs have been made in the Ross Sea region, including areas north of the Ross Sea shelf. The distributions of communities and species assemblages have been viewed in several ways. Bullivant (1967), on the basis of species composition as deduced from bottom grab samples, described three major faunal zones/assemblages (Fig. 20: deep shelf mixed, deep shelf mud bottom, Pennell bank; and two coastal assemblages: Victoria Land and McMurdo Sound shelf. Kennett (1968), concentrating just on foraminifera, plotted the distribution of high species richness, which more or less corresponded with the outer two zones (deep shelf, Pennell Bank) of Bullivant (1967; Fig. 20).
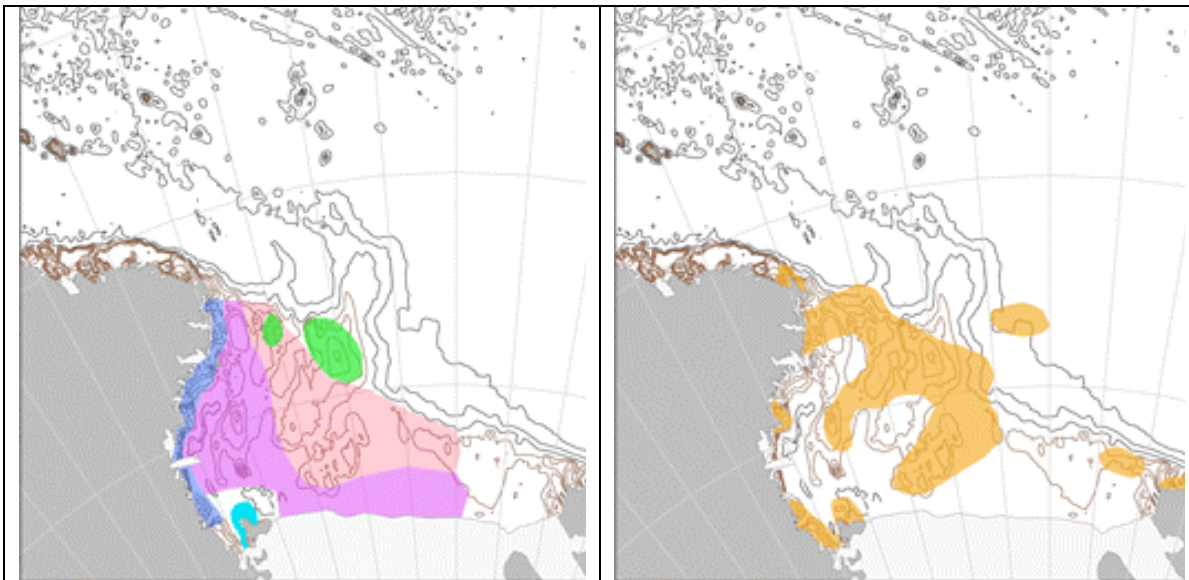
Figure 20. Left, the faunal assemblages described by Bullivant (1967): green, Pennell Bank; pink, deep shelf mixed; purple, deep shelf mud; blue, Victoria Land coastal; aquamarine, McMurdo Sound. Right, areas of high foraminifera species richness as described by Kennett (1968).

Using the newer technology of remote cameras, and a far more dense survey grid than available from bottom grabs, Barry et al. (2003) quantified benthic communities on the basis of functional groups (Figs. 21, 22). Variation in faunal composition was found to be linked more closely to seafloor habitat and sediment characteristics than to the position, size, and timing of ice cover or primary productivity near the sea surface. This is consistent with the biotic flux as described above, i.e. a dense rain of sedimentation equivalent everywhere over the shelf (see Section 2.3.2: Water column microbial dynamics).

The abundance and biomass of benthic fauna, dominated mainly by bryozoans, siliceous sponges, cnidarians and annelid worms, generally declines with depth, shifting from an assemblage of shallow-living, filter- and suspension-feeding taxa, to a deeper-dwelling group dominated by deposit feeders. The differential existence of the shallow-living group is consistent with the short duration of sinking as a function of depth, that is the benthic-pelagic coupling is stronger over the shallow banks (see Section 2.3.2: Water column microbial dynamics). Cluster analyses identified 5 major faunal-habitat associations. The "Suspension Feeder, Rich" (SFR) zone occurs mainly on the current-swept crests of shallow seafloor ridges where high abundances of bryozoans, hydroids, and sponges are typical. This appears to be the least common community, as it was detected only at three sites; Ross, Crary and Pennell banks. A "Suspension Feeder, Poor" (SFP) assemblage was found on shallow banks (but not ridge crests) and had a similar faunal composition, but lower overall abundance and distinctly lower bryozoan abundance. A "Mixed Slope Assemblage" (MSA) was typified by suspension- and filter-feeding taxa and dominated mid-slope depths. Deeper stations with lower current speeds and an increased percentage of deposit-feeding taxa represented an "Ophiuroid-Worm Assemblage" (OWA) composed mainly of ophiuroids and maldanid polychaetes. In the deepest basins, especially in the south, the "Depauperate Basin Assemblage" (DBA) was similar to the OWA, but with far lower overall faunal densities.
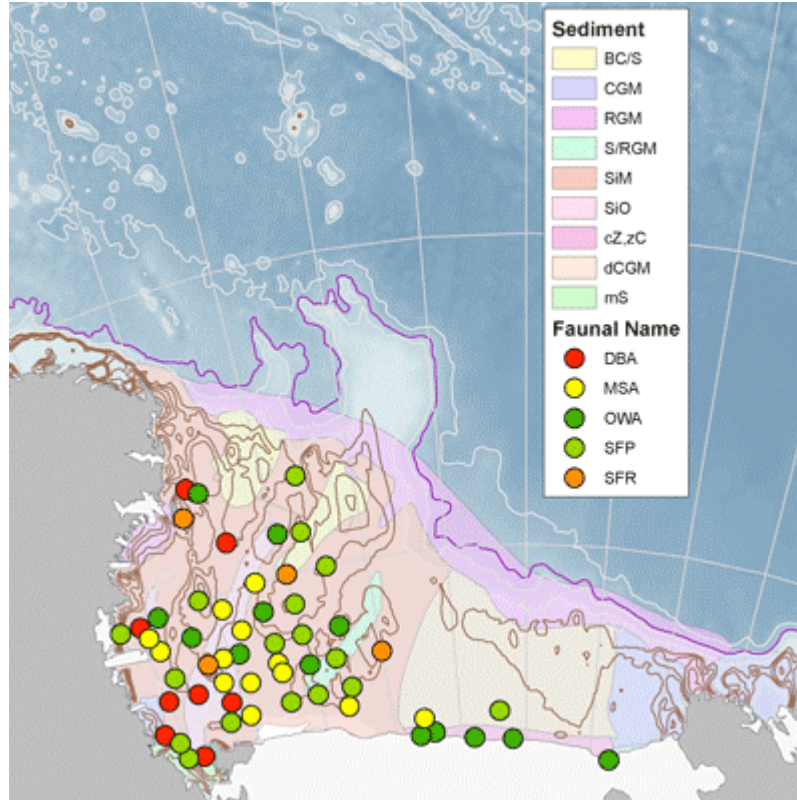
Figure 21. The distribution of five benthic communities as defined by functional groups of species (from Barry et al. 2003). Faunal communities: DBA = depauperate basin association, MSA = mixed slope assemblage, OWA = ophiuroid/worm association, SFP = suspension feeders (poor), SFR = suspension feeders (rich). Sediments from Anderson (1999; see Fig. 4): BC/S = bioclastic carbonate/sand, CGM = compound glacial marine (terrigenous silt with minor ice-rated debris), RGM = residual glacial marine (ice rafted sand), S/RGM = sand/residual glacial marine, SiM = siliceous mud, SiO = siliceous ooze, cZzC = clayey silt/silty clay, dCGM = diatomaceous compound glacial marine, mS = muddy sand.

Barry et al. (2003) had little coverage of the outer shelf. Therefore, combining the distribution of benthic assemblages apparent in Barry et al. (2003) with those mapped by Bullivant (1967) and Kennett (1968), who had relatively few sampling points (but more on the outer shelf) compared to the camera stations of Barry et al. (2003) and a sketchy knowledge of bottom topography and sediment distribution, a more integrated view of benthic communities appears (Fig. 22). Certainly this proposed distribution could stand validation by future sampling. Nevertheless, it combines Bullivant's species-based assemblages with the functional groups detailed by Barry et al. The latter's MSA and OWA comprise B&D's "deep shelf mixed" assemblage; DBA and SFP communities comprise B&D's "deep shelf mud" assemblage; but the rather rare SFR of Barry et al. (2003) remains by itself. Whether of not SFR coincides with B&D's "Pennell Bank" assemblage remains to be seen. Barry et al. (2003) did not sample the northern, most shallow portion of the shelf, although 3 of 4 of the sites where they found SFR were bordering this habitat. Similarly, the distribution of foraminifera species richness, when viewed with the better known benthic topography of today, might look like that shown also in Figure 22.
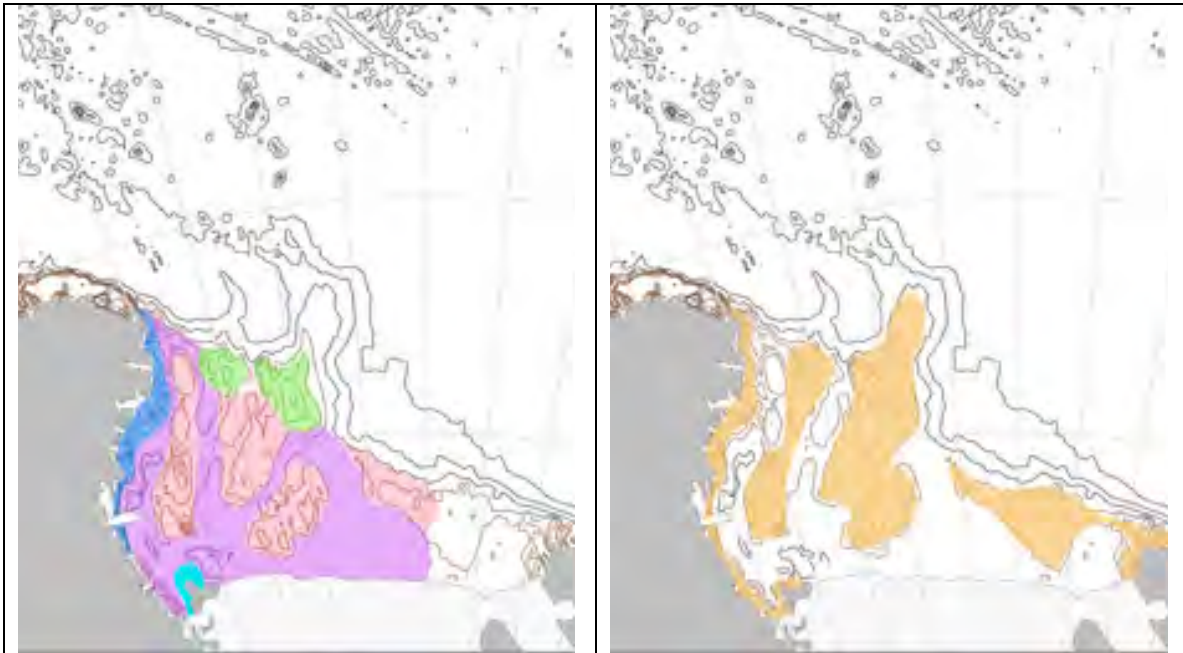
Figure 22. Left, possible distribution of Ross Sea benthic communities, combing Bullivant (1967) and Barry et al. (2003). Bullivant had relatively fewer sample points (bottom grabs) and lacked the benefit of the detailed topography now known (Fig. 3). As shown here, for example, Barry et al.'s DBA and SFP communities are combined into Bullivant's "Deep shelf mud" assemblage. Right panel, a depiction of Kennett's (1968) proposed distribution of high foraminifera species richness using the bathymetry and sediment types now but not then known. As in Fig. 20, green, Pennell Bank; pink, deep shelf mixed; purple, deep shelf mud; blue, Victoria Land coastal; aquamarine, McMurdo Sound; beige (right panel), areas of high foraminifera species richness.

The benthos of the Ross Sea depends nutritionally on sinking organic debris derived from the flux from disintegrating sea ice, but more so from the intense phytoplankton blooms that occur seasonally, but episodically, in three regional polynyas (Ross Sea, Terra Nova Bay, McMurdo Sound polynyas; Chiantore et al. 1998; see Water column microbial dynamics, above). Although life on the Antarctic continental shelves is undoubtedly coupled to upper ocean production, the strength of pelagic-benthic coupling is weaker than reported, and as expected, for the very shallow Arctic shelves (Grebmeier & Barry 1991). In addition, polynyas that "feed" the Ross Sea benthos appear to be more "retentive" (i.e., much primary production is recycled in the water column rather than exported to the seabed) than "exportive", due to the average greater depth of the continental shelf than found in the Arctic. Nevertheless, year-to-year variation in the magnitude of both surface production and export to the seabed has detectable effects on the Ross Sea benthos, more so than elsewhere on the continental shelf of Antarctica where shelves are characteristically deeper. Consequently, pelagic-benthic coupling, though obscure in space, is evident over temporal scales, through changes in the magnitude of sinking organic debris, even though it is redistributed by lateral advection and bathymetric effects. Finally, the benthic communities do provide habitat, and refuge, for mid-water organisms, such as fish (Eastman & Barry 2002).

2.4.2. Characterization of nearshore bottom communities

The shallow benthos of the western Ross Sea, the "Victorialand and McMurdo Sound coastal assemblages"of Bullivant (1967), is actually composed of a patch-work of finely defined species assemblages (see Fig. 23), rather than being homogeneous carpets that stretch over large areas. The Ross Sea appears to be somewhat special; it is more productive than the Weddell Sea, which has little by way of shallow near-shore habitat (it is covered by ice), while the Antarctic Peninsula and northern insular shelves are subject to a different climate. Nevertheless, the Ross Sea communities share some basic characteristics with other Antarctic coastal ecosystems, as a consequence of their shared evolutionary history. The benthic fauna of the Ross Sea does not show particularly high levels of endemism, and some groups (like molluscs) show affinities with other distant Antarctic areas like the Weddell Sea (see for instance, Clarke & Johnston 2003). Yet locational differences are found in the depth distributions of individual species, as well as in their abundance, and consequently in their role in ecosystem functioning. Shell crushing predators are functionally absent from these communities and echinoderms typically play important roles in benthic food webs as predators, scavengers and omnivores.
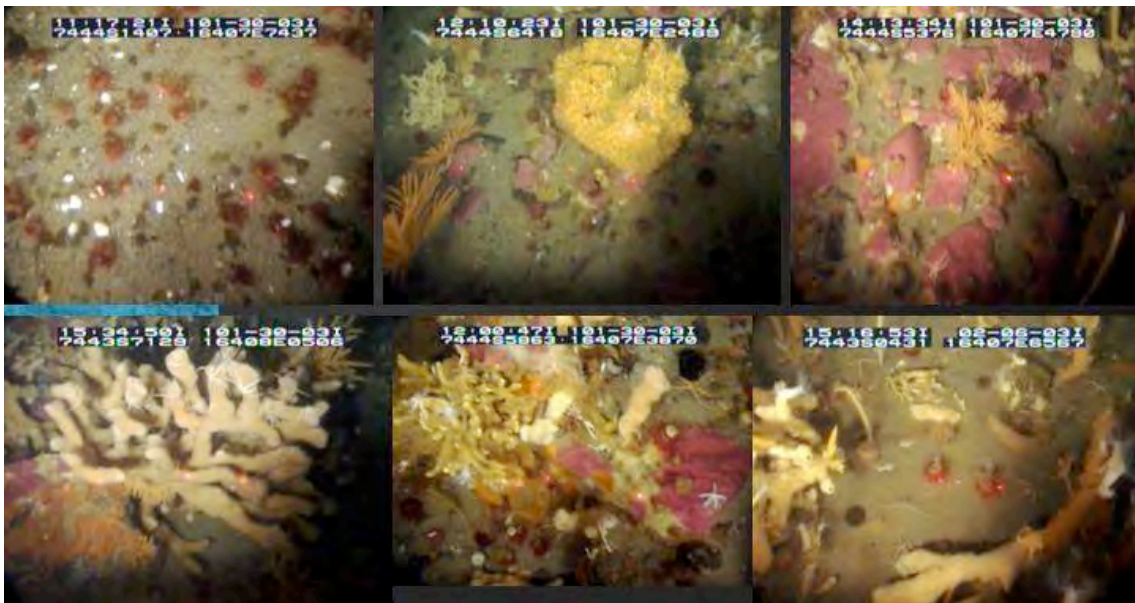

Figure 23. An example of the great variability in community composition over short spatial scales in Terra Nova Bay. Source: S. Thrush, NIWA; approximately 1- m^2 plots.

The spatial heterogeneity in communities and the strong variation in forcing functions along the coast emphasize the potential for non-linear responses to changes in environmental forcing or trophic links. What this means is that species assemblages vary greatly over short distances. The longest time series of benthic community change in the Antarctic, a record extending since the late 1960s, has been compiled for several communities in McMurdo Sound. It is one of the longest of any biotic time series in the entire Antarctic (Dayton 1989, Conlan et al. in press).

2.5. Ross Sea Biology: Middle Trophic Levels

2.5.1. Zooplankton

Despite the importance of zooplankton in the food web and biogeochemical cycles of the Ross Sea, little is known about the seasonal or interannual abundance and distribution of zooplankton or the factors that control community dynamics. In fact, among its major players, the zooplankton appear to be the least known component of the food web, at least in terms of abundance, with sampling effort respectable (Fig. 24) but in no way as intense as the Scotia Sea or East Antarctica. There is a clear separation in middle trophic level faunal groups as a function of shelf vs. deep waters (Fig. 25); such a demarcation is much more obvious in the Ross Sea with its very wide shelf and relatively shallow depths compared to other Antarctic continental shelves. The relative lack of regular sampling is in stark contrast to the taxonomic work that has been carried out, with about 500 species of copepods, amphipods and euphausiids first described from Ross Sea specimens (Appendix IV).
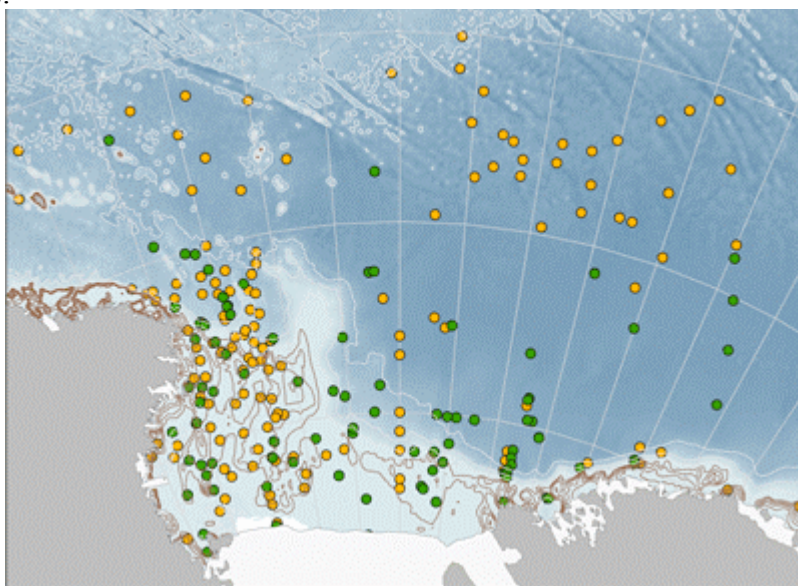

Figure 24. A summary of scientific trawling to sample middle trophic level organisms: yellow, mid-water trawls targeting zooplankton, including those undertaken by HMS *Discovery* (1928-1950), Sala et al. (2002), Taki et al. (2008), and the APIS project (see Ackley et al. 2003 for a summary); green, trawls targeting fish, including DeWitt (1970), Takahasi & Nemoto (1984), Eastman & Hubold (1998), and Donelly et al. (2004).

A comparison of Antarctic shelf regions indicate that zooplankton biomass is highest in waters west of the Antarctic Peninsula, an order of magnitude lower in the Ross and Weddell seas, and another order of magnitude lower elsewhere. Indeed, mean density of krill in the Scotia Sea is 49.3 tonnes/km^2 while in the Pacific region it is just 7.6 tonne/km^2 (Nicol et al. 2000). Moreover, the zooplankton biomass of the Ross Sea is dominated by smaller zooplankton, such as copepods, rather than the larger krill (Deibel & Daly 2007). Since the Ross Sea is very productive, it is not known why zooplankton biomass is lower than along the Antarctic Peninsula or whether it appears that way due to limited sampling. It could be related to intense predation pressure given the unusually high densities of top trophic level species (Ainley et al. 2006a, b; Ainley 2007). It could well be that the Ross Sea demonstrates a large scale trophic cascade (see definition and

review in Baum & Worm 2009): high upper level predator foraging depletes the middle trophic level, which in turn results in lower grazing pressure on phytoplankton (and thus high phytoplankton and chlorophyll concentrations). This is inferred by the lack of grazing pressure measured by Arrigo et al. (2003) and is important to considering the Ross Sea shelf and slope as an ecological unit.
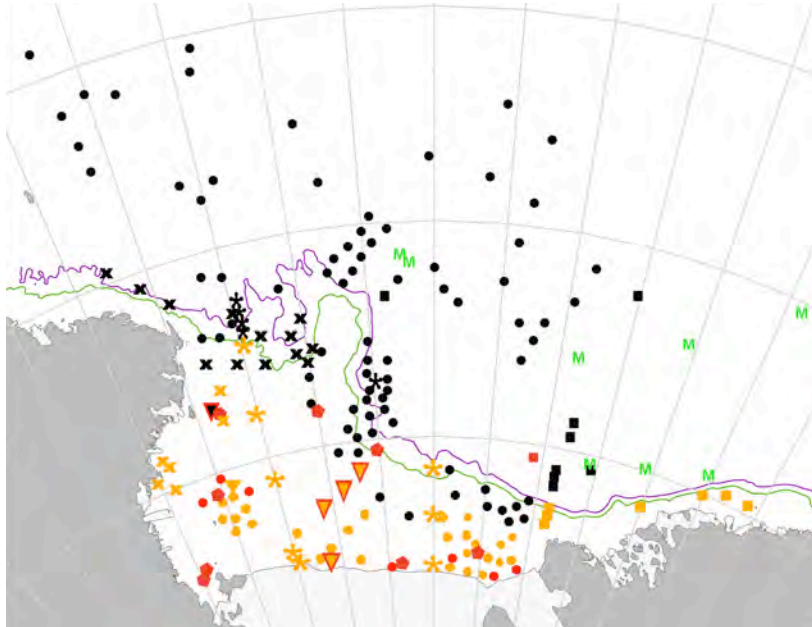

Figure 25. Spatial patterns of middle trophic species, presence - absence: *E. superba* (black symbols), *E. crystallorophias* (yellow), *Pleuragramma antarcticum* (red), and myctophid fish (green). The studies used to derive this map were: Ichii et al. 1998 (circles, "predominant" in minke whale stomachs); Torres and Quetin in Ackley et al. 2003 (squares, diver surveys and net tows); DeWitt & Hopkins (1977, triangles, silverfish stomachs); Sala et al. 2002 (x's, net tows); Taki et al. 2008 (asterisks, trawls); Ainley et al. (1984, pentagons, bird stomach samples); Donnelly et al. (2004, green "m's", trawls).

Based on vertical nets and double oblique trawls taken in February, zooplankton in McMurdo Sound, on the inner shelf, is dominated by copepods (primarily *Metridia gerlachei, Calanoides acutus, Oncaea curvata, Oithona similis*) and pteropods (*Limacina helicina, Clione limacina*). Crystal krill, *Euphausia crystallorophias*, is observed at low abundances, but may be underestimated if associated with sea ice; or may have been eaten earlier in the season (or driven to the bottom) by numerous predators (see above, Ainley et al. 2006a). Copepods, pteropods, and crystal krill also are relatively abundant in Terra Nova Bay and other waters overlying the Ross Sea continental shelf. Antarctic krill *E. superba* is almost completely absent on the inner Ross Sea shelf, where it is replaced by the smaller crystal krill (Fig. 25). In contrast, Antarctic krill occur over the outer shelf, especially over the continental slope in regions of upwelled and intruded modified Circumpolar Deep Water (Fig. 26). Acoustic surveys over several years between November and January detected swarms at an average depth of 30 m. However, another study using net tows between December and February observed both krill species primarily between 100 – 400 m (Taki et al. 2008), possibly a response to the increasing

risk of predation during summer. Reported densities of Antarctic krill range up to 1,896 individuals/m^3 along the slope; the smaller crystal krill have been observed up to 4705 individuals/m^3 (Sala et al. 2002) over the shelf (Fig. 26). Antarctic krill in the Ross Sea region are most abundant along the western shelf break, either side of Pennell Bank (Figs. 25, 26). This is the area where the slope is steepest, and where CDW upwells and intrudes southward by way of deep troughs (Figs. 3, 7, 26).
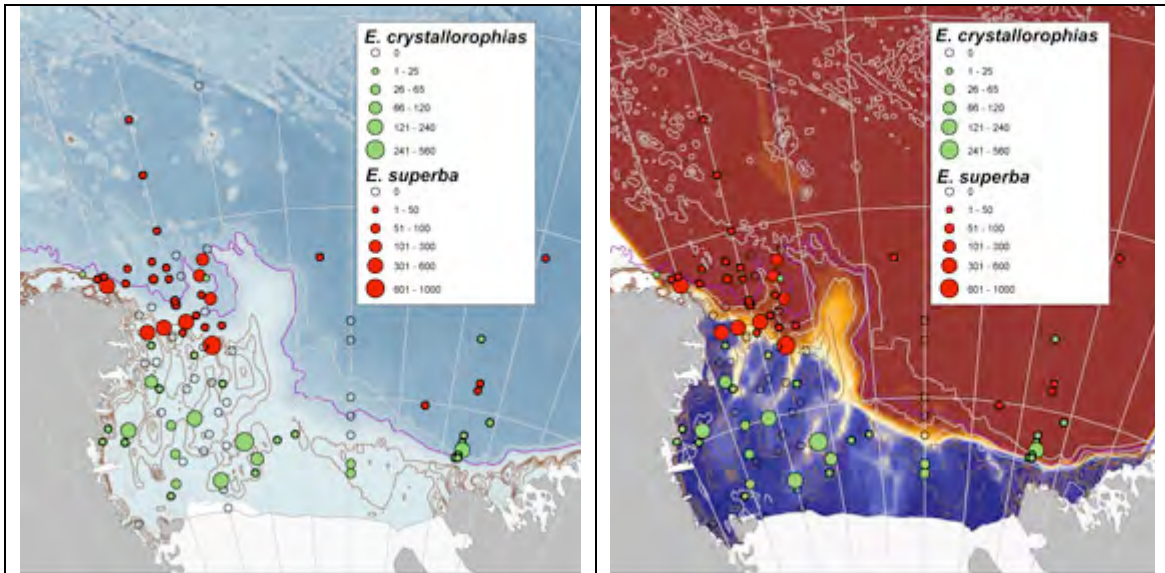

Figure 26. Left panel, the abundance of krill, in g/1000 m3: green, *E. crystallorophias;* red, *E. superba*; right panel, the abundance of krill compared to intrusion of Circumpolar Deep Water (CDW) onto the outer shelf. Data from Sala et al. (2002), Parker and Torres (unpubl. APIS data), and Taki et al. (2008); units standardized among studies by using conversion factors provided by L. Parker and J. Torres: g/1000 m^3 vs individuals/1000 m^3 for krill caught in the eastern Ross Sea and off Marie Byrd Land. CDW data from Dinniman, Hofmann and Smith, unpubl. (see Fig. 7).

The pteropod, *L. helicina*, also may be an important prey for fish and as a grazer on phytoplankton, including diatoms and *Phaeocystis,* copepods, and microzooplankton. In addition, these pteropods play an important role in biogeochemical cycles (see Water column microbial dynamics), contributing to the carbon and carbonate flux through production of fecal pellets and mucous flocs and rapid sinking of aragonite shells of dead individuals. *L. helicina* has been reported to account for 63% of the zooplankton community in McMurdo Sound and have populations ranging from 1 – 1,398 individuals m^{-3} in Terra Nova Bay, where pteropods were a major component of the flux at the end of the growing season. Given the connection of pteropods with *Phaeocystis*, their distribution might best be depicted by the December bloom shown in Figure 17; more surveys though are needed.

2.5.2. Fish
The Ross Sea fish fauna consists of 16 families and 95 species and, although the fauna is reasonably well known from a taxonomic perspective (Table 1), on the basis of appreciable scientific sampling (Fig. 24), new species and new records are still coming to light, some as by-catch from the new longline fishery for *Dissostichus*. The most speciose taxa are notothenioids (a perch-like group), liparids (snailfishes) and zoarcids (eelpouts;

Eastman 2005), with the four families of notothenioids alone accounting for 64% (61/95) of species diversity in the Ross Sea. Higher taxonomic diversity is restricted and species diversity is low in comparison to other shelf areas in the world, because a number of prime fish habitats do not exist in the Ross Sea — intertidal zones, shallow rocky reefs and estuaries. Glacial, pack and anchor ice further restrict the availability of shallow water to organisms (Eastman 1993).

Table 1. The most abundant notothenioids and non-notothenioids in the Ross Sea fish community; benthic fish biomass and biomass density is 22-fold and 3-14 fold, respectively, greater than pelagic (mid-water) fish. References: a) DeWitt 1970, b) Eastman & Hubbold 1999, and c) Donnelly et al. 2004.

Community	Species
Benthic shelf	
Inshore	*Trematomus bernacchii, T. newnesi, Pagothenia borchgrevinki*
Offshore	*T. scotti, T. eulepidotus, T. loennbergii, Bathydraco marri, Prionodraco evansii, Dolloidraco longedoralis*
Benthic slope	*Chionobathyus, Pogonophryne, Macrourids* (grenadiers)
Mid-water shelf	*Pleugramma*
Western Ross Sea (a)	By number 92%
	By weight 97%
Eastern Ross Sea (c)	By number 91%
	By weight 77%
Mid-water slope (c)	Myctophids (*Electrona, Gymnoscopelis*), Bathylagids (*Bathylagus*), Gonostomatids (*Cyclothone*), Paralepidids (*Notolepis*)

In the Ross Sea, high diversity sites, such as sponge spicule mats and bryozoan debris fields, have at least an order of magnitude lower fish diversity (10–15 species) than tropical coral reefs (Eastman & Hubold 1999). However, benthic trawl sampling in the western Ross Sea indicates that notothenioids dominate species diversity (77%), abundance (92%) and biomass (91%) — a degree of dominance unparalleled in any other marine ecosystem (Eastman 2005). The most abundant benthic shelf species are *Trematomus scotti, T. eulepidotus, T. loennbergii, Bathydraco marri, Prionodraco evansii* and *Dolloidraco longedorsalis* (Eastman & Hubold 1999). On the slope notothenioids and macrourids (grenadiers) are the dominant groups. Benthic fish biomass is considerably higher than that of pelagic fish and peaks at 400–500 m depths. *Pleuragramma antarcticum* is the dominant mid-water species in shelf waters by number; in slope waters it is replaced by mesopelagic oceanic species such as myctophids (lanternfishes; DeWitt 1970, Donnelly et al. 2004).

The dominance of notothenioids is the result of the historic absence of competition from other fish groups that allowed them to exploit new habitats and trophic regimes. They occupy an array of pelagic, cryopelagic, epibenthic and benthic habitats at various depths on the shelf and slope. Diversification in 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 (Eastman 1993). Although neutral buoyancy is found in only a few nototheniids, some, *Dissostichus mawsoni* and *Pleuragramma antarcticum* for example, are abundant and ecologically important in the Ross Sea, as the top piscine predator (adults occupying the niche of sharks) and the primary forage fish, respectively (La Mesa et al. 2004) (See Fig. 27). While *D. mawsoni* is nowhere near to being numerically significant, its ecological role as a top predator is likely immense (Eastman 1993, La Mesa et al. 2004).

Figure 27. The main fish and their depth-defined habitats in the coastal portion of the Ross Sea shelf; only three species occur in the water column, while all of the remainder are associated with the bottom as adults; courtesy A. DeVries.

2.6 Ross Sea Biology: Top Trophic Levels

2.6.1. Squid
The colossal squid *Mesonychoteuthis hamiltoni* occurs in waters north of the Ross Sea shelf, including those overlying the continental slope. It is an important predator of toothfish and likely once was prey for sperm whales (long since decimated from waters north of the Ross Sea). However, we know almost nothing about this predator (Rosa & Seibel 2010). Other, smaller and at times near-surface dwelling squid are important prey for birds and seals over the shelf, especially *Psychroteuthis glacialis* and *Gonatus antarcticus* (Ainley et al. 1984, Skinner & Klages 1994). Little is known about the diet of these squid, but presumably it is composed of small fish and zooplankton.

2.6.2. Antarctic toothfish

The Antarctic toothfish, *D. mawsoni*, is a neutrally buoyant (as adult, >100 cm), large-sized nototheniid with a large population occurring in the Ross Sea (see Fig 28). Knowledge of its life history is scanty, and totally unknown is its ecological role when in the supposed planktonic and small juvenile portions of its life cycle. What little is known comes mostly from studies in McMurdo Sound, and from the recent fishery. Neither eggs nor larvae have been found. Certainly its ecological role changes as it grows from tiny first life stages to gargantuan size (140 kg, 2+ m) as adults, thus from being ostensibly prey as small individuals ultimately to become the only large piscine predator in the High Antarctic water column as an adult.
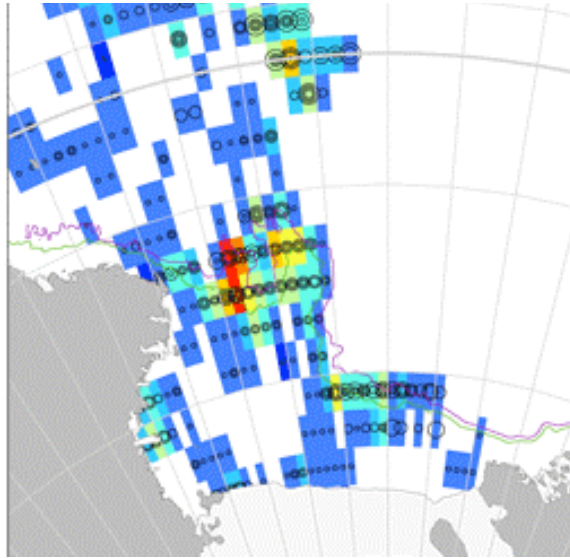

Figure 28. Distribution of the total biomass of toothfish taken from CCAMLR Fishery Area 88, 1997-2007. "Hotness" of color indicates level of take, from blue, aquamarine, yellow, orange, to red, and therefore indicating the importance of the Ross Sea slope to these fish. Circles (size and intensity) indicate fish caught per hooks set. Data from CCAMLR.

Over the past 35 years about 4,500 toothfish have been weighed, measured and tagged in McMurdo Sound. This is likely the longest time series available in the Southern Ocean on occurrence patterns of a fish and one of the longest time series of any Antarctic biological data. Many large adults have been caught in this sampling regime. The occurrence of these larger fish under the southern Ross Sea ice thus does not fit with the pattern of fish caught in the longline fishery, which now catches only small fish, on average, in the southern shelf waters (Hanchet et al. 2008, Brooks & Ashford 2008; Fig. 28). Fifteen recaptures have been recovered at the McMurdo fishing site and a few by commercial fishers at distances of up to 800 km from McMurdo (Petrov & Tatarnikov 2010). From the recapture studies, growth of young fish is apparently rapid but that of subadults and adults relatively slow: length increased 2-3 cm per year and weight one kilogram per year among subadults.
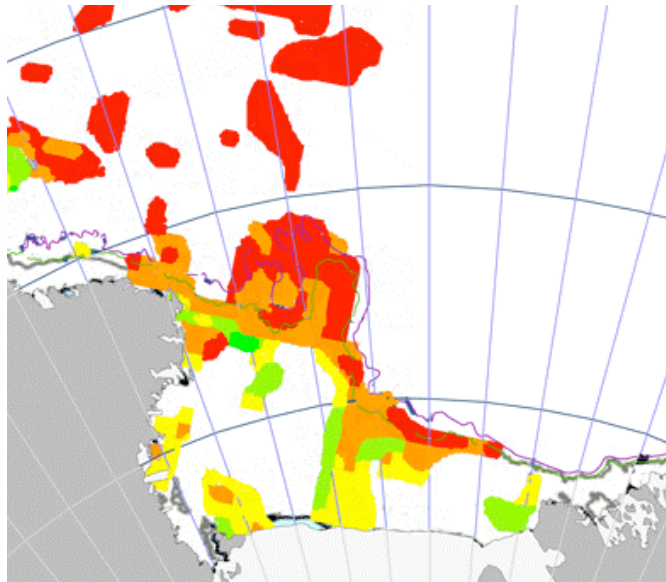
Figure 29. The distribution, on average, of Antarctic toothfish, by size class (TL), as taken in the CCAMLR Area 88 fishery: green 40-80 cm, yellow 80-100 cm, orange 100-120 cm, red >120 cm (redrawn from Hanchet et al. 2008).

2.6.3. Cetaceans

Historical analysis indicates that the cetacean fauna of the Ross Sea shelf is likely much the same as it was when James Clark Ross provided the first observations in 1841-43 (Ainley 2010). In numerical order it is composed of Antarctic minke whales (*Balaenoptera bonaerensis*; fish, krill predator), Ross Sea (or type-C) killer whales (*Orca orcinus*; fish predator), Arnoux's beaked whales (*Berardius arnouxii*; likely main prey toothfish, macrourid fish, if diet is similar to beaked whales elsewhere; Brownell & Ainley 2010), and type-B killer whales (seal predator; Pitman & Ensor 2003). It lacks now only blue whales (*Balaenoptera musculus intermedia*), at least in the numbers that existed before industrial whaling (Ainley 2010; Figs. 30, 31). Currently, the cetacean fauna is numerically dominated by about 21,000 minke whales and perhaps as many as 3000 killer whales (T. Branch *in* Ainley 2010; Ainley 1985). Most of the killer whales are the "Ross Sea" resident fish-eating type; there are perhaps just a few dozen type-Bs, the apex predator in this system, although type-As (minke whale predator) could occur along the slope. The Ross Sea slope lost its blue, and a few fin whales, during the 1920s; minke whales seem likely to have filled the void (Ainley 2010). Blue whales seem to have been totally absent for decades, but in the past 10 years increasing but still sparse numbers have been seen, particularly over the outer shelf (Fig. 30). Other than a very few fin whales, no species of cetaceans other than the above are known to have occurred in waters of the Ross Sea shelf or slope. The current distribution of large cetaceans in the Ross Sea region exhibits the classic latitudinal segregation summarized by Laws (1977), north to south: humpback (*Megaptera novaeangliae*), fin, blue, minke (cf. Figs. 31, 32; see Matsuoka et al. 2006 for occurrence patterns in areas farther to the north of what is shown in Fig. 30).
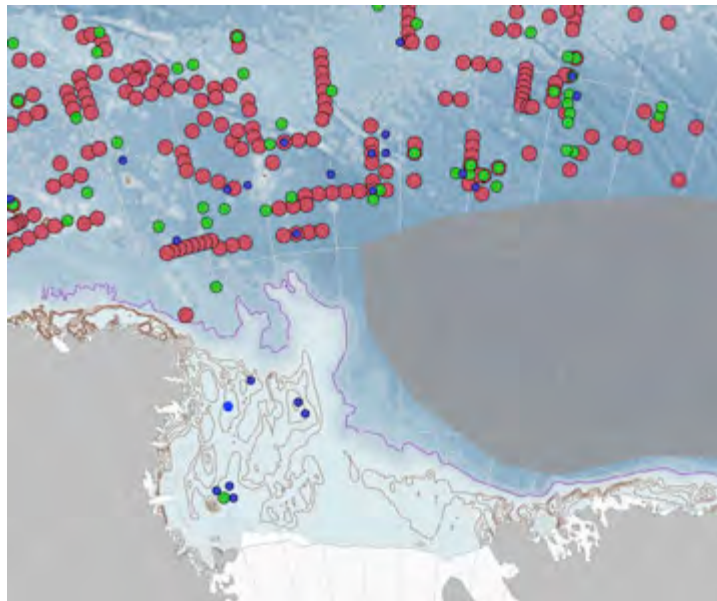
Figure 30. IWC sighting data of humpback (red), fin (green) and blue whales (blue), 1987-88 to 2004-05 summers; data plotted from Matsuoka et al. (2006), Sala et al. (2002). The gray area in the east indicates where IWC survey vessels rarely venture owing to the persistent sea ice.
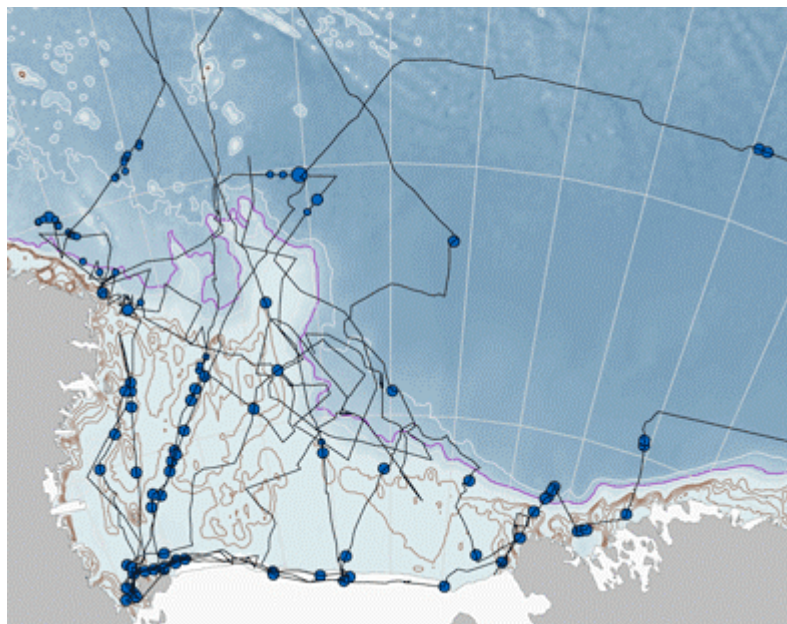

Figure 31. Antarctic minke whale sightings from surveys during RISP (1976-79), AnSlope (2004) and NBP94 cruises, which covered the entire Ross Sea,and waters to the north during December to March. Note concentration of sightings along the western Slope (shelf break) Front, as well as in the extreme western and eastern Ross Seas. Whales were seen within the pack ice of the latter two areas, which constitue the marginal ice zone of the Ross Sea Polynya (see Karnovsky et al. 2007).

Intensive surveys of cetaceans on the entire Ross Sea shelf and slope, including both open and ice-covered waters, were conducted during 1976-1981, mostly during hydrographic cruises as part of the Ross Ice Shelf Project (RISP; Fig. 31). During this time, industrial whaling was targeting minke whales (ultimately taking about 15,000 from IWC Area V, which includes the Ross Sea and waters off George V Coast). However, as

these whales occur well into the pack ice, a portion of the population persisted from which the regional population could well have since recovered (industrial whaling ended in 1986; see references and discussion in Ainley 2010). Most recent surveys have been conducted by IWC, of which Antarctic Slope Front (AnSlope) surveys were a part.

As far as anyone knows, all cetaceans exit the Ross Sea during winter. On the basis of the summer RISP and AnSlope surveys, it is clear that the minke whale is the primary baleen whale present, and it mainly frequents the marginal ice zone (MIZ) that rings the Ross Sea Polynya and post-polynya, and waters overlying the shelf break especially in the western Ross Sea (cf. Figs. 9B, 31). Relatively few whales frequent waters in the central portion of the shelf, from the Ice Shelf outward, though individuals may transit the area. This pattern is confirmed by records of minke whales taken more recently by the Japanese Whaling Agency (Ichii et al. 1998). Of particular importance to whales is the MIZ along the Victoria Land and Marie Byrd Land coasts, as well as along the Slope Front (Karnovsky et al. 2007).
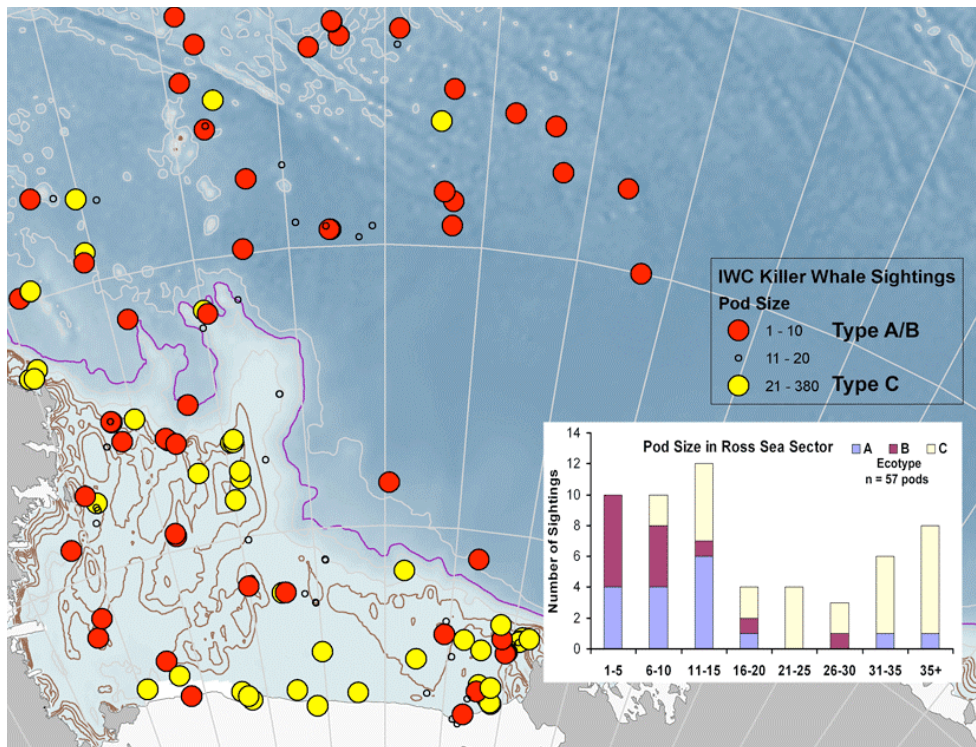

Figure 32. Sighings of killer whales in the Ross Sea sector based on IWC cruises. Ecotypes separated on the basis of pod size as reported in Pitman & Ensor (2003), with data augmented by sightings around Ross Island (Ainley et al. 2006a, 2009; n = 57 pods).

The other major cetacean species of the Ross Sea is the killer whale, especially the type-C or Ross Sea killer whale. The latter was recently determined to be a species separate from other killer whale forms (Morin et al. 2010). A few thousand killer whales, including all types, were estimated to exist in waters overlying the shelf and slope (Ainley 1985; Fig. 32). Over the shelf and slope, the numbers are dominated by the Ross Sea killer whale as inferred from the large pod size that characterizes this species (Pitman & Ensor 2003, Fig. 32). The ratio of Ross Sea (C) to type-B killer whale over the

shelf is about 50:1 (Ainley et al. 2009). It appears that Ross Sea killer whales are found, during summer, to frequent mainly the shelf and particularly the banks.

The third major species, another toothed whale, Arnoux's beaked whale, is also found mainly over the continental shelf in this region. The concentration of sightings in the southwestern corner likely is an artifact of search effort, i.e. beaked whales seen from and in the vicinity of shore stations (Fig. 33). Beaked whales are very wary of vessels, and thus are difficult to census at sea.
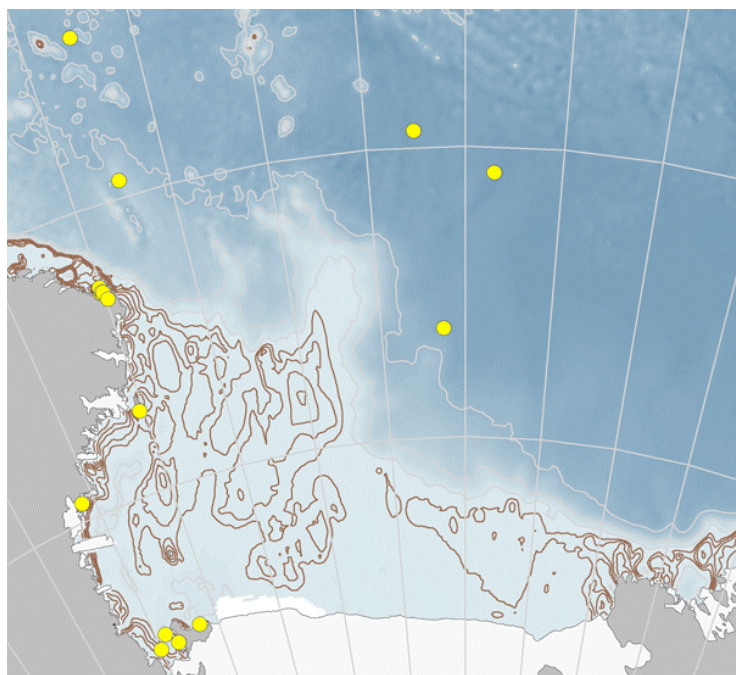

Figure 33. Arnoux's beaked whale sightings from IWC data base, as well as sightings from Ross Island shores (Ainley, Ballard, pers. obs.) and vicinity of Terra Nova Bay (G. Lauriano, pers. obs.)**.**

2.6.4. Seals
The four species of Antarctic pack ice seals, the crabeater (*Lobodon carcinophagus),* leopard (*Hydruga leptonyx),* Ross (*Omatophoca rossii*) and Weddell (*Leptonychotes weddellii),* all occupy the Ross sea region during some part of the year. The life histories of these species are sufficiently different that each uses the various ecosystem components in different ways.

2.6.4.1. *Ross Seal.* This species was first described from a specimen collected just north of the Ross Sea slope by the J.C. Ross expedition. It is rather transient in the system, and mostly occurs in pelagic waters; on rare occasions it is sighted over the Ross Sea slope (Ainley 1985, estimated perhaps 5000 can be found in that habitat). The Ross seal requires large ice floes that remain stable for several weeks, which they occupy for pupping and molting in the late spring and early summer; these floes are found in the eastern Ross Sea and Amundsen Sea (see Fig. 9, 10). Ross seals are known to move north of the pack, often beyond 60° S, during much of the year. The species feeds principally on squid (Laws 1984, Skinner & Klages 1994, Siniff et al. 2009).

2.6.4.2. *Crabeater seal.* The crabeater is the most abundant seal in the Ross Sea; surveys during 1976-79 estimated about 204,000 within the confines of shelf and slope waters (Ainley 1985; Fig. 34). Erickson & Hanson (1990) estimated 1.2M in the Southern Ocean sector 160° E-130° W, which includes the Ross Sea. This species is dependent on relatively small ice floes for breeding, pupping and molting in the austral spring. It is found in the outer edges of the pack ice, but more so along the shelf break depending on pack ice characteristics (Fig. 34). Therefore, when the Ross Sea pack ice disappears seasonally, except along its western and eastern margins, Ross Sea crabeater seals must move east or west to remain associated with sea ice (Figs. 9, 10). It preys almost exclusively on krill (Laws 1984), but in the Ross Sea presumably this includes both Antarctic krill and crystal krill given the seals' occurrence over both the shelf and slope of the Ross Sea (cf. Figs. 26, 34).
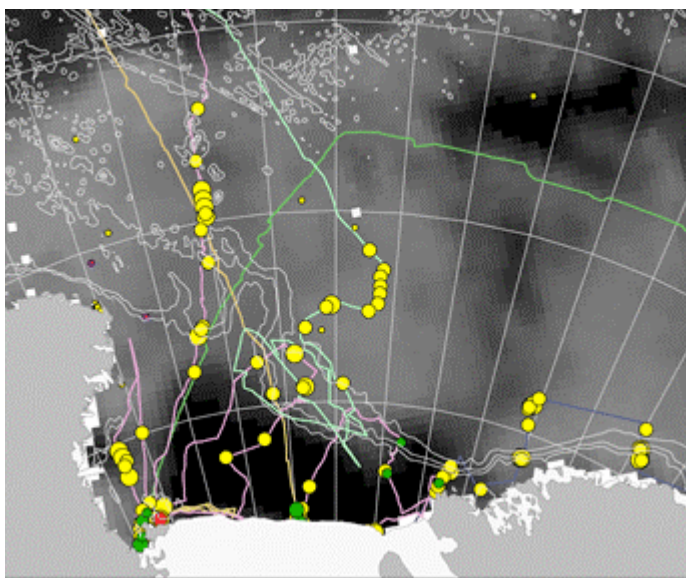

Figure 34. Sightings of crabeater (yellow), Weddell (green) and leopard (red) seals during December. Data collected December-February during cruises of the RISP project, 1976-1979, and during NBP94 (cruise tracks indicated by lines). Owing to dense ice concentrations, ships often did not approach the coast close enough to encounter most Weddell and leopard seals.

The species' distribution patterns are shown as well in Figure 35. Generally, crabeater seals tagged with satellite transmitters mostly over the shelfbreak off Marie Byrd Land in February (minimal pack ice extent; Antarctic Pack Ice Seal program: J. Bengtson, P. Boveng, unpubl. data), remained in waters over the outer shelf and shelf break (Antarctic Slope Front) to a great degree, moving west seasonally with the growing sea ice field (Fig. 9) during the succeeding months.

2.6.4.3. *Leopard seal*. This species is often found in coastal areas during summer, and preys upon young crabeater and Weddell seals at the time of weaning, as well as on penguins, both adults and fledglings. They also feed on krill and fish. During the winter they move out into the pack ice north of the Ross Sea, presumably into the area frequented by crabeater seals and penguins. On the basis of surveys conducted during

1976-79, almost 8000 were estimated for the Ross Sea (Ainley 1985); Erickson & Hanson (1990) estimated 55,000 in the 160° E-130° W sector of the Southern Ocean.
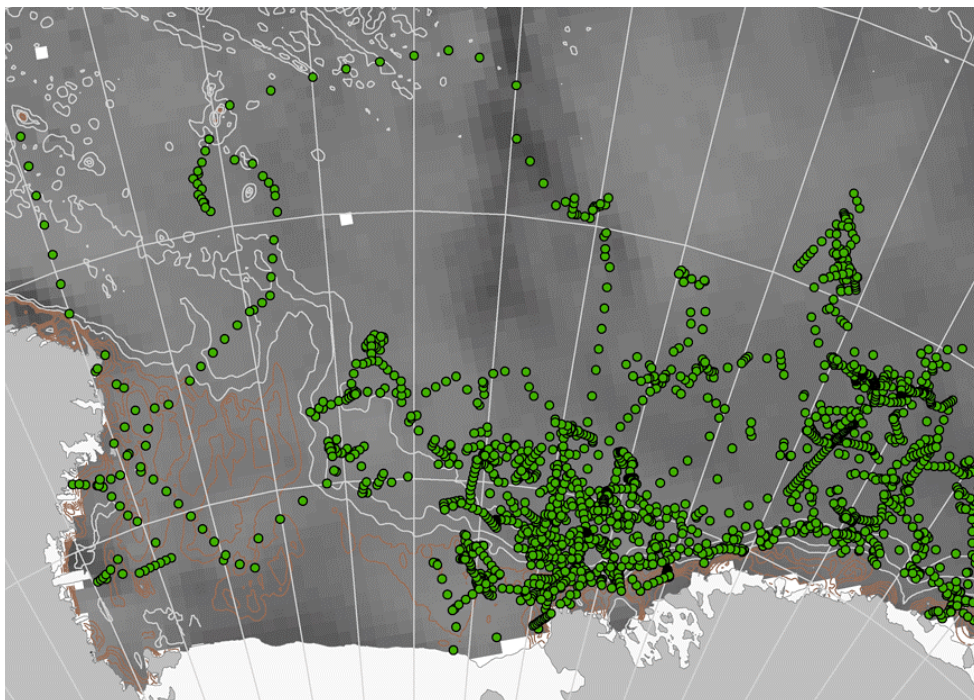

Figure 35. Tracks of crabeater seals tagged with satellite transmitters in February along the shelf break off Marie Byrd Land (J. Bengtson, P. Boveng, unpubl. data).

2.6.4.4. *Weddell Seal*. The Weddell is the only seal species that can be considered a permanent resident of the Ross Sea. It occupies the fast ice areas for pupping and breeding activities (see Fig. 36). During the breeding season both adult males and females mostly fast, thus lose significant weight, which must be recovered before the next pupping season. To recover condition, these seals move out into waters overlying the Ross Sea shelf after the breeding season, as do the juveniles produced, as deduced from studies of Weddell seals satellite tagged along the coast of southern Victoria Land (Fig. 34, 36). This is true, too, of Weddell seals tagged in the vicinity of Cape Colbeck, Marie Byrd Land, although their specific breeding haulout remains unknown. Those seals remained over the shelf, and to some degree the shelfbreak, throughout the winter.

A population of 30,000-50,000 Weddell seals have been estimated for the shelf and slope of the Ross Sea (Stirling 1969, Ainley 1985). That portion of the population associated with breeding haulouts was estimated to be >10,000 (but many sites not censused; Siniff & Ainley 2008). Erickson & Hanson (1990) estimated 68,000 within the 160° E-130° W sector. Therefore, to say the least, a very sizeable proportion of that population must occur within the Ross Sea, i.e. 50-72%. Weddell seals are disappearing along the eastern margin of the Pacific sector as the sea ice disappears, something that is not a factor yet in the Ross Sea (Siniff et al. 2009; see Climate change, above). An isolated, genetically distinct population occurs at tide cracks around White Island in extreme southern McMurdo Sound (Gelatt et al. 2009).

The main species on which Weddell seals are known to prey include the Antarctic silverfish and Antarctic toothfish (Ainley & Siniff 2009). The relative dietary importance

of these species is not yet well understood, but existing satellite tracking data show that some individuals move to the same areas where the commercial toothfish fishery occurs, i.e. along the Ross Sea slope (cf. Figs. 28, 36). Unfortunately, no tagging data exist for the breeding populations that exist in northern Victoria Land and which would be expected to exploit the outer western shelf and slope (complementary to Cape Colbeck populations in the eastern portion of the Ross Sea).
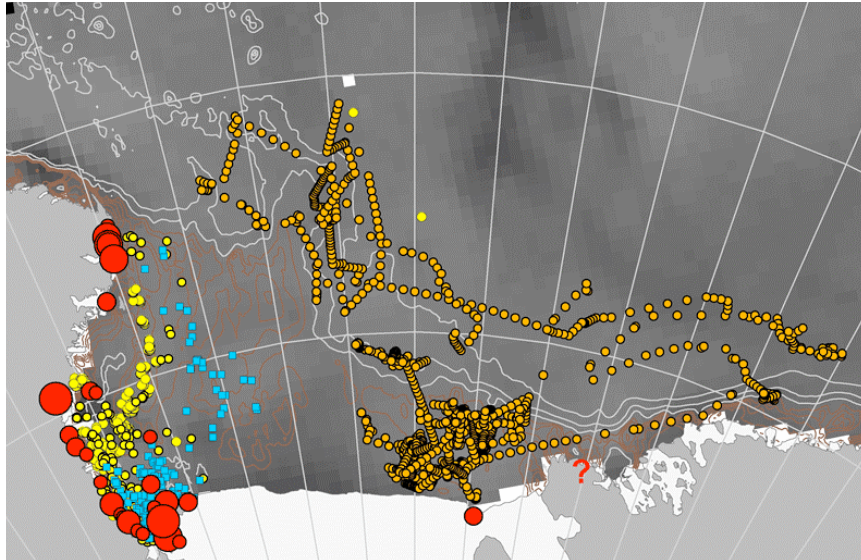

Figure 36. The known pupping locations of Weddell seals in the Ross Sea (red dots, graded in size by number of animals); the question mark at Cape Colbeck, King Edward VII Peninsula indicates no surveys available from Marie Byrd Land though without doubt the species breeds there. Also shown are satellite positions during winter of animals tagged in southern McMurdo Sound: pups (yellow) and adult females (blue); data from B. Stewart, W. Testa, J. Burns. Winter movements of Weddell seals tagged in February off Marie Byrd Land shown in gold (J. Bengtson, P. Boveng, unpubl. data); attachment locations are at the extreme eastern end of the position streams, the seals having subsequently moved west into waters overlying the Ross Sea shelf and slope in accord with the westward growth of sea ice as the season progressed.

2.6.5. Seabirds

2.6.5.1. *Petrels and Albatrosses*. Incredibly abundant in the waters of the Ross Sea, especially along the continental slope, are snow (*Pagadroma nivea*) and Antarctic (*Thalassoica antarctica*) petrels (Fig. 37). It is estimated that about 1M snow petrels and 5.5M Antarctic petrels frequent the waters of the shelf and slope at any given time during summer; therefore, at least 30% of the world population of Antarctic petrels, as judged from at-sea surveys, are found in the Ross Sea (cf. van Franeker et al. 1999). The Ross Sea (Antarctic) Slope Front is especially important for Antarctic petrels. Most of the breeding locations of both of these species are unknown, as they nest on the snow-free tops of nunataks and mountains often 100s of kilometers inland from the coast, e.g. the Fosdick Mountains of Marie Byrd Land. The snow petrel is rarely found very far from pack ice; both species roost on icebergs grounded near the Ross Sea shelf break (outer Pennell Bank).
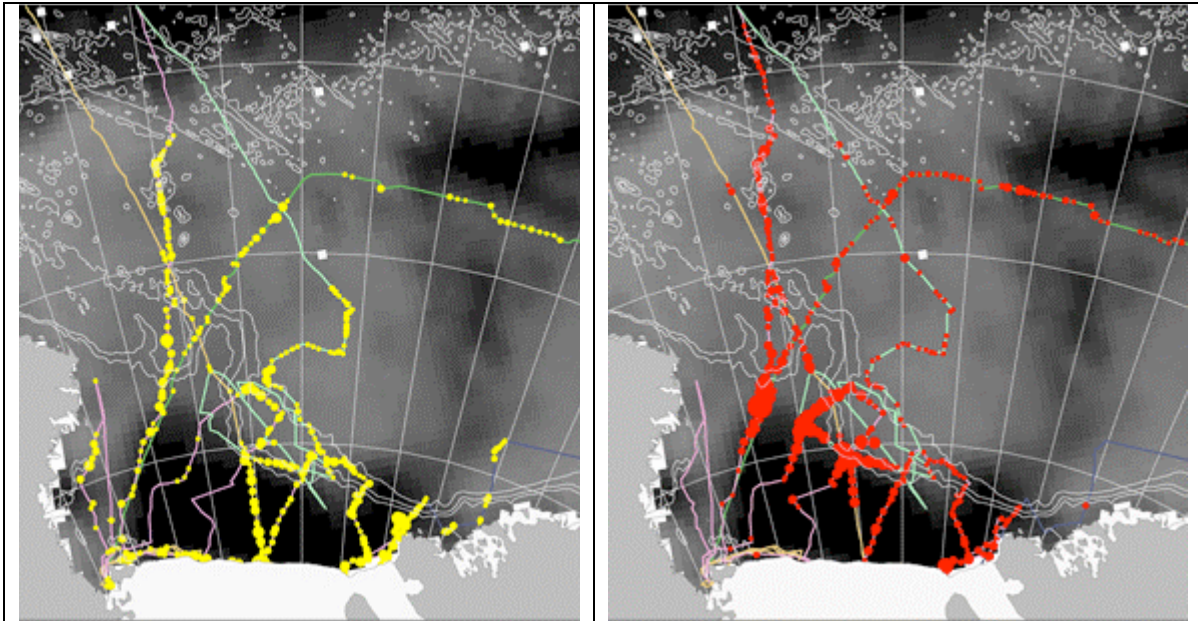
Figure 37. Sightings of snow (yellow) and Antarctic (red) petrels in the Ross Sea region during surveys as part of RISP (1976-79) and NBP94 (1994) cruises, and as discussed in Ainley et al. (1985, 1994). Cruise tracks indicated by lines; largest symbols represent 400 birds.

Albatrosses do not occur in waters over the Ross Sea shelf, but to some degree do so over the slope, especially light-mantled sooty albatross (*Phoebetria palpebrata*; Fig. 38). In that area, these birds feed on krill (Ainley et al. 1984). The sooty albatrosses that frequent the Ross Sea slope waters most likely nest at New Zealand sub-Antarctic islands (e.g. Campbell I.) and Macquarie Island, hence their concentration in the western third of the study area (Fig. 38). Southern Giant Petrels (*Macronectes giganteus*) once frequented waters overlying the Ross Sea shelf (Ainley et al. 1984) but no longer do so (Ainley, pers. obs.), their breeding populations having decreased at sites well to the north of the Ross Sea, e.g. Macquarie Island (Patterson et al. 2008).
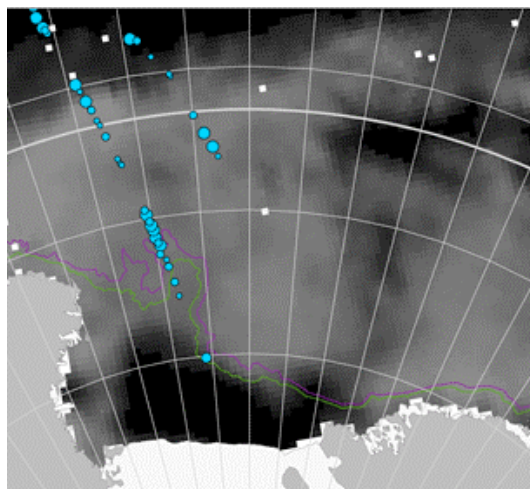

Figure 38. Albatross sightings (all species combined), made during RISP and NBP94 cruises during the 1970-early 1980s. The largest circle represents three birds. Those seen over the slope are almost entirely light-mantled sooty albatross (Ainley et al. 1984); see Fig. 37 for cruise tracks.

2.6.5.2. *Penguins.* Penguins are found in association with the marginal ice zone and the Antarctic Slope Front in the Ross Sea region during early summer (Fig. 39). The importance of the Slope Front is especially important to the emperor penguin during this time. Very few penguins frequent the ice-free, post-polynya waters in the south central Ross Sea or the pack-ice covered waters well north of the Ross Sea during summer.
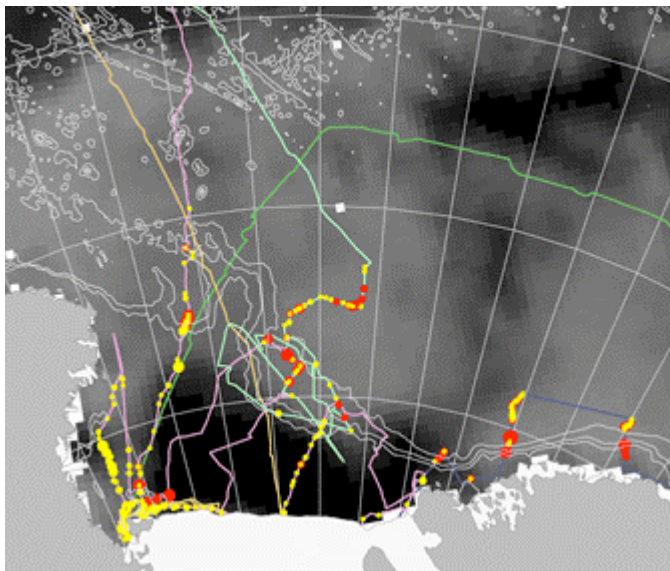

Figure 39. Sightings of emperor (red) and Adélie (yellow) penguins during summer during RISP and NBP94 cruises. Largest symbols are 25 birds; cruise tracks indicated by lines. Most of the survey was done during December-January when Adélies are associated with coastal breeding colonies, but Emperors are not.

An estimated 78,850 pairs of emperor penguins and 1,050,300 of Adélie penguins nest at 8 and 26 colonies bordering the Ross Sea (Woehler 1993, and updates); this represents 26 and 38% of the world populations, respectively. Including non-breeders (number approximately equal to the number of breeding pairs, i.e. 1/3 of the population), the Ross Sea penguin population is about 4.1M individuals. The at-sea distribution of Adelie penguins during summer is constrained by chick provisioning duties (Figs. 40, 41). Therefore, a "halo" of high penguin density is found in association with each colony or group of colonies; the size of the halo, as worked out for Adelie penguins, is a function of colony size, the boundary growing larger as colony size grows (Ballance et al. 2009). The foraging of emperor in winter is affected by day light, and it is likely that southern Ross Sea emperors must travel north to the Slope Front where at least twilight exists (Ainley & Ballard ms). Thus the sizes of "halos" for them would be affected by factors in addition to prey depletion which is the factor that most affects Adélie penguin foraging extent. Moreover, owing to their deep diving, emperor penguins foraging should be viewed as a volume rather than a surface extent. The research to delineate that volume as a function of colony size has not been carried out. During surveys of seabirds at sea (Figs. 39), cruise tracks barely intersected the large number of penguins foraging from colonies in the northwestern Ross Sea and therefore, incorrectly, the numbers of penguins depicted there is low.
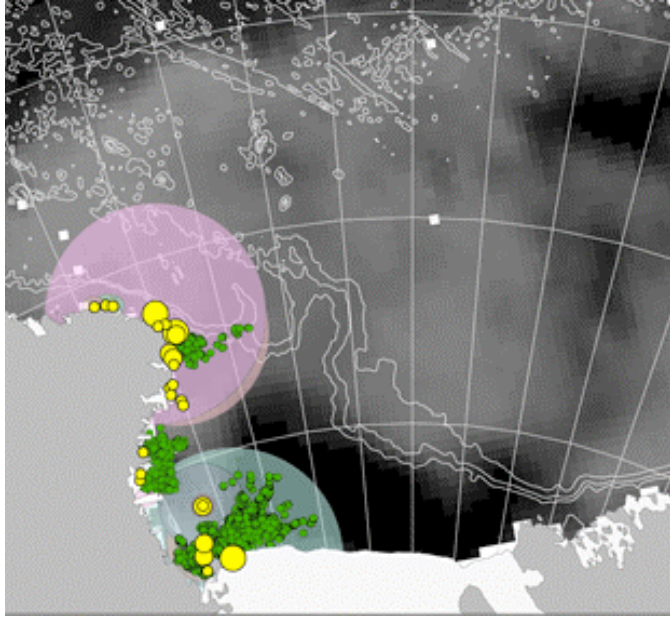
Figure 40. Foraging tracks (determined by satellite) of Adélie penguins breeding at three locations: Ross Island, Terra Nova Bay and Cape Hallett. These and other colonies are shown by yellow symbols, the sizes of which are proportional to colony size. The transparent colored halos indicate zones of foraging as a function of colony size for the colonies at which tracking studies have been completed (see Ballance et al. 2009). The halo for Terra Nova Bay is exactly the size of the area covered by foraging tracks and therefore is obscured; data from S. Olmastroni, P. Lyver, D. Ainley/G. Ballard.
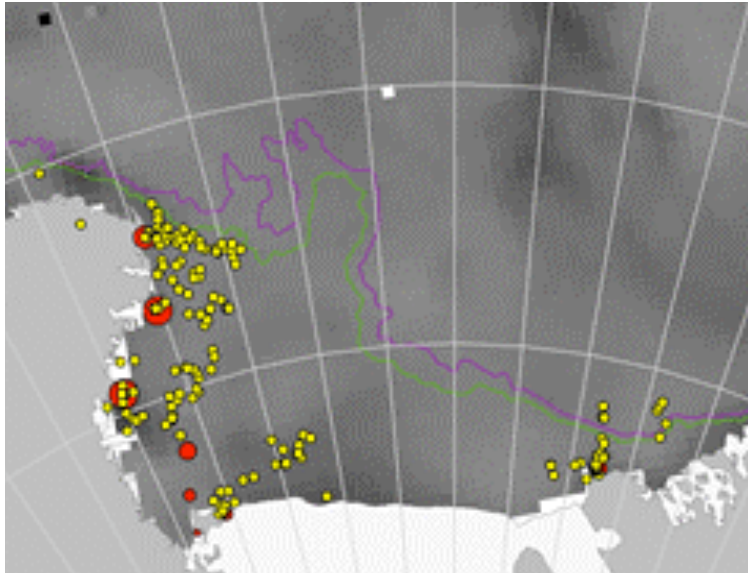
Figure 41. Foraging tracks (determined by satellite) of emperor penguins during spring (daylight available, hence no need to travel north to light; Ainley & Ballard ms) for those breeding at five locations: Cape Colbeck (Marie Byrd Land), Ross Island, Cape Washington, Coulman Island and Cape Roget. All known colonies are shown by red symbol, the size of which is proportional to colony size; data from G.L.Kooyman. During mid-winter birds from southern colonies may have to travel north to twilight during June-July (Ainley & Ballard ms).

After breeding, Adelie and emperor penguins must forage voraciously to regain condition before fasting for a few weeks, at which time they molt all their feathers. The Antarctic Slope Front appears to be particularly important for this activity (Fig. 42). Large numbers of penguins, both species, can be found molting during January and February, residing on ice floes in the pack ice that still remains in waters of the eastern Ross Sea and farther to the east (see Figs. 9, 10).
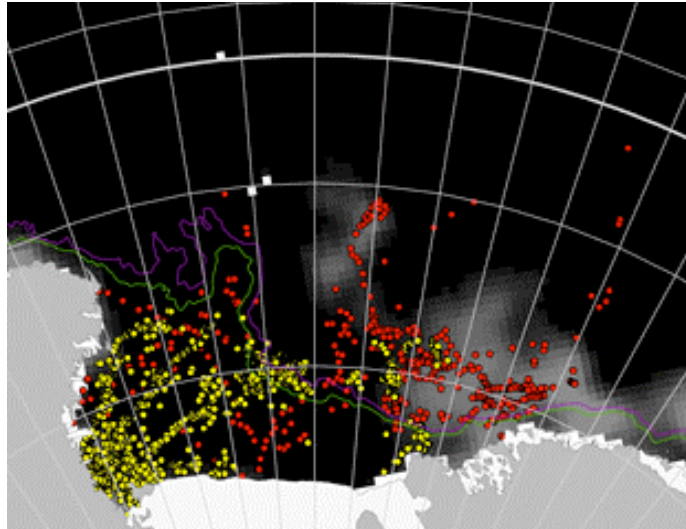

Figure 42. The summer-autumn movements of penguins: Adélie penguins (yellow) after completing breeding on Ross Island, just before their annual molt in February (data from D. Ainley/G. Ballard); and the pre- and post-molt foraging movements of emperor penguins (red), tagged at colonies and in the pack ice off Marie Byrd Land (data from G.L. Kooyman). Not shown (no data) are the movements of Adélie penguins from northern Victoria Land colonies, which may occupy the seeming void of penguins along the shelfbreak west of Pennell Bank. Heavy latitude line indicates Antarctic Circle.

After molting, Marie Byrd Land emperor penguins move a short distance and Victoria Land emperor penguins, occurring then off Marie Byrd Land, begin to slowly move back towards nesting colonies, where they will begin breeding in March-April (pair formation; Figs. 41, 42). At that time, Adélie penguins move with the pack ice, remaining in waters overlying the Slope Front for as long as ice conditions and the availability of light allow (Ballard et al. 2010). As light disappears, they move northward in the pack ice to the vicinity of the Antarctic Circle, eventually occupying ice floes entrained in the ice movements of the Ross Gyre (Fig. 43, cf. Fig. 9A).
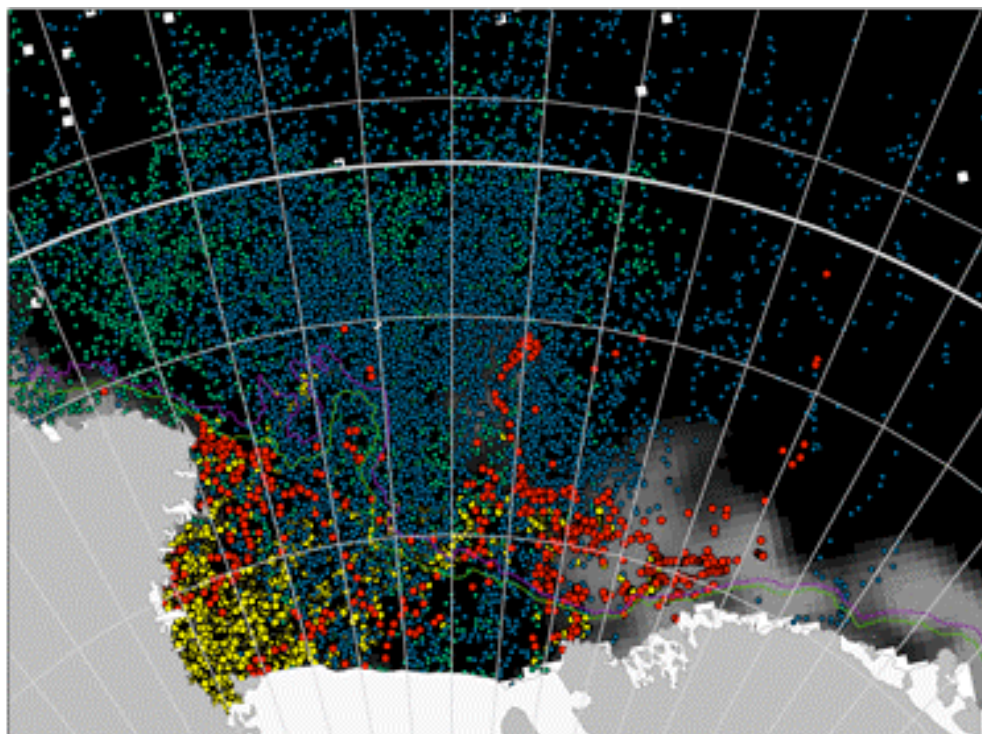
Figure 43. Summary of Ross Sea penguin movements. Red dots: foraging movements of Victoria Land and Marie Byrd Land emperor penguins throughout their annual cycle; yellow dots: foraging of Victoria Land Adelie penguins during summer (no data for Cape Adare and vicinity colonies); blue (July) and green (August) dots indicate positions of wintering Adélie penguins from Ross Island (at that time of year emperors are associated with breeding colonies; see Ballard et al. 2010 for further summary of these winter data). Had data been available for Adélie penguins nesting in northern Victoria Land, certainly there would be dense yellow dots in the waters out from Cape Adare and vicinity. Heavy latitude line designates the Antarctic Circle.

3.1 SUMMARY OF BIOTIC AND BIODIVERSITY PATTERNS

A visual inspection of the distribution patterns of various aspects of the Ross Sea fauna as detailed in the previous section reveals some common patterns: the shelf and slope comprise a unit, although connections among the more mobile fauna with the seamount-studded waters to the north are also apparent. These patterns are summarized in Table 2, and many of these distributions will be used in Part II, which contains results ofdistribution modeling and systematic conservation prioritization, delineating patters of species richness and relative importance.

Also evident in this document are the patterns of benthic diversity and community distribution. Five broadly defined communities were identified, with the most spatially confined being the Pennell Bank, McMurdo Sound and Victoria Land coast communities. The diversity of the Ross Sea benthic communities are exemplary (Clarke & Johnston 2003). The Pennell Bank community is adjacent to the highly productive Slope (shelf break) Front and is also shallow enough that at least dim sunlight likely can penetrate to certain portions. Like the McMurdo and Victoria Land communities, sharply-defined bathymetry accelerates currents, thus bringing a continual supply of particulate food sources. At least 40 invertebrates are endemic to the Ross Sea, and about 450 species

were first described from Ross Sea specimens. These type species and their type localities offer important gauges of any changes to the biota due to climate or other forces.

Table 2. Summary of the occurrence patterns, especially of mobile organisms, as revealed in the maps contained in this report; in each case the areas are shown where a species or faunal group is most abundant or concentrates its activities.

	Shelf	Shelfbreak, outer shelf	Slope	Seamounts, deep ocean	In text source
Antarctic krill		X	X		Figs. 25-26
Crystal krill	X	X			Figs. 25-26
Demersal nototheniid fish	X	X	X		Figs. 27, 29, Table 1
Macrourid fish			X	X	Table 1
Antarctic silverfish	X	X			Figs. 25, 27, Table 1
Myctophid fish			X	X	Fig. 25, Table 1
Antarctic toothfish	X	X	X	X	Figs. 28,29
Minke whale	X	X	X		Fig. 31
Blue whale		X	X		Fig. 30
Killer whale	X	X	X		Fig. 32
Arnoux's beaked whale	X	X	X		Fig. 33
Crabeater seal	X	X	X	X	Figs. 34, 35
Weddell seal	X	X	X		Figs. 34, 36
Snow petrel	X	X	X		Figs. 37
Antarctic petrel		X	X		Figs. 37
Albatross, esp. light-mantled sooty			X	X	Fig. 38
Emperor penguin			X	X	Figs. 39, 43
Breeding foraging	X	X			Fig. 41
Molting			X	X	Fig. 42
Adélie penguin					Fig. 39, 43
Breeding foraging	X	X	X		Figs. 40, 42
Molting, wintering			X	X	Fig. 43

The biodiversity and evolutionary significance of the Ross Sea shelf and slope are also exemplary in other ways. Of the 95 fish species found in the Ross Sea (Gon & Heemstra 1990), forty were first described from specimens taken from these waters, i.e. the Ross Sea is the type locality of these species (Appendix IV). Seven are endemic to the Ross Sea, found nowhere else among Antarctic areas so far surveyed. That total is not huge compared to warmer waters, but the relatively low species diversity should not lead to dismissal of the fauna as uninteresting in comparison to the speciose faunas of tropical lakes, rivers and coral reefs. Numbers of species are not paramount but, when considering the High Antarctic shelf, the nature of the fish diversity overshadows the numbers. Indeed, the isolated waters of the shelf form a unique evolutionary site where the

abundance, biomass, and morphological and ecological diversity of the dominant notothenioid fishes overshadow the relatively small number of species. This is most logically understood in a historical and evolutionary context (Eastman 1993, 2005; Near 2004, Eakin et al. 2009). The unique evolution of buoyancy and blood antifreezes appear to have had major effect on the radiation.

The radiations of other High Antarctic groups, including lobodontine seals (Deméré et al. 2003, Fyler et al. 2005) and some lineages of bryozoans, pycnogonids, echinoderms, amphipods and isopods, provide additional evidence that Ross Sea is a noteworthy evolutionary locality (Brandt 1999, 2000; Brandt et al. 2007), as noted above (Appendix IV). In addition there are three recently diverged species of killer whales in the Ross Sea, including the recently recognized Ross Sea killer whale, a smaller form that feeds in dense pack ice on fish (LeDuc et al. 2008, Morin et al. 2010). A unique genotype of the Adélie penguin, and one of Weddell seal, is also found only in the Ross Sea (Roeder et al. 2001, Gelatt et al. 2009).

The patterns discussed herein, and illustrated in the figures, indicate that important components of the Ross Sea upper trophic level fauna require the entire Ross Sea shelf and slope to complete their annual cycle. In the case of the penguins, most of which nest along Victoria Land, the Slope Front in the eastern Ross Sea is required after breeding in order to recover condition, molt, prepare (fatten) for winter in the case of Adelies or move back towards breeding sites in the case of emperors. In the case of toothfish, they require the shelf apparently to mature and the slope, i.e. the Antarctic Slope Front, in order to fatten for spawing. Finally, the Weddell seal, which feeds little during the spring breeding haul-out, require the entire shelf and slope to recover condition and fatten for the next pupping and breeding season.

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Appendix I: IMCC Ross Sea Symposium, 21 May 2009, Fairfax Virginia USA

	MORNING SESSION	**FAIRFAX MARRIOTT**
830	David Ainley	Introduction: Why are we here?
850	Claire Parkinson	Ross Sea sea ice
910	Walker Smith, Eileen Hofmann	Circulation, hydrography, phytoplankton
940	Steve Ackley/Mike Lizotte	Sea Ice microbial communities
1000	BREAK	
1020	Stacy Kim, S Thrush, M Chiantore, Marino Vacchi, J Barry	Benthic-pelagic coupling
1040	Jim Barry, Jacqueline Grebmeier	Overview of benthic communities
1100	Simon Thrush, M Chiantore, S Kim, J Barry	Nearshore bottom communities
1120	Kendra Daly	Pelagic zooplankton
1140	Joe Eastman, M Vacchi, A DeVries	Ross Sea fish fauna
1200	LUNCH	
1250	Mariachiara Chiantore, M Vacchi, A Devries, S Thrush	Benthic community/fish interactions
1310	Art DeVries, J Eastman	The Antarctic Toothfish
1330	Don Siniff, B Garrott, J Rotella	Pack ice seals
1350	Jay Rotella, B Garrott, D Siniff	Weddell seal demography
1410	Silvia Omastroni, D Ainley	Seabirds
1430	David Ainley, R Brownell	Cetaceans
1445	Further discussions	Everyone
	AFTERNOON SESSION	**GEORGE MASON UNIVERSITY**
1630	John Weller	Welcome
1635	John Weller	Slide show, and talk
1655	Peter Young	Ross Sea movie clips

1710	Joe Eastman	The Ross Sea Past: evolution
1730	Joellen Russell	The Ross Sea Future
1810	Sylvia Earle	Ross Sea from a global perspective
1830	Jim Barnes	Ross Sea biopolitics
1750	David Ainley	Workshop Review

Appendix II: WORKSHOP PARTICIPANTS
Steve Ackley, University of Texas – San Antonio
David Ainley, H.T. Harvey & Associates
Tosca Ballerini, Old Dominion University
James Barnes, Antarctic & Southern Ocean Coalition
Robert Brownell, National Marine Fisheries Service, Monterey
Ed Butler, Antarctica New Zealand
James Barry, Monterey Bay Aquarium Research Institute
Riccardo Cattaneo-Vietti, Università di Genova, Genoa
Mariachiara Chiantore, Università di Genova, Genoa
Claire Christian, Antarctic & Southern Ocean Coalition
Colleen Corrigan, UN Environmental Program, Cambridge
Kendra Daly, University of South Florida
Art DeVries, University of Illinois-Urbana
Sylvia Earle, National Geographic Society
Joseph Eastman, Ohio University
Robert Hofman, Marine Mammal Commission (retired)
Stacy Kim, Moss Landing Marine Laboratories
Roberta Marinelli, Office of Polar Programs, NSF
Silvia Olmastroni, Università di Siena, Siena, Italy
Claire Parkinson, NASA Goddard Space Flight Center
Polly Penhale, Office of Polar Programs, NSF
Jay Rotella, Montana State University
Joellen Russell, University of Arizona
Don Siniff, University of Minnesota
Lucia Simion, Paris, France
Walker Smith, Virginia Institute of Marine Science
Simon Thrush, NIWA / Università di Genova
Sue Vang, Office of Polar Programs, NSF
John Weller, Boulder CO
Peter Young, Christchurch NZ

Subsequent modeling:
Dennis Songsjomjit, PRBO Conservation Science

In the afternoon at GMU, about 50 persons additional to those above attended the workshop.

Invited, but regrets, owing to schedule conflicts: Kevin Arrigo, Stanford University; Janet Bradford-Grieve, NIWA-NZ; John Croxall, BirdLife International; Vonda Cummings, NIWA-NZ; Susie Grant, BAS; Stan Jacobs, Lamont-Doherty; Jane Lubchenko, NOAA; Matt Pinkerton, NIWA-NZ; Peter Thomas, US Marine Mammal Commission; Kristina Gjerde, UNEP

To view the Ross Sea imagery presented at the workshop and IMCC registration area by John Weller and Peter Young, go to: www.lastocean.com

Appendix III: ACKNOWLEDGEMENTS

Appendix IV. A summary of species first described from Ross Sea specimens, type localities being given special recognition by the Antarctic Treaty (ASOC 2010). Sources: US National Museum of Natural History, National Institute of Water & Atmosphere (NZ); NZ DSIRO Bulletins 142, 147, 151, 167, 176, 186, 198, 206; NIWA Biodiversity Memoir 108; scientific reports of the UK "Erebus and Terror" Expeditions, "Discovery Expedition", "Terra Nova Expedition", "Nimrod" and "Morning" Expeditions. All checked against the World Registry of Marine Species (WoRMS). Upon request a detailed species breakdown is available of the actual localities that went into drafting of Figure 18. Not included are the yet-to-be named 48 benthic isopod species from Terra Nova Bay vicinity referred to in Choudhury & Brandt (2009).

VERTEBRATES/CHORDATES

	BIRDS	Stercorariidae	1
	FISHES	Melanocetidae	1
		Liparidae	8
		Zoarcidae	1
		Nototheniidae	13
		Artedidraconidae	8
		Bathydraconidae	3
		Channichthyidae	6
	CHORDATA	Tunicata	5
	HEMICHORDATA	Cephalodiscidae	2

INVERTEBRATES

	ANNELIDA	Polychaeta	40
		Myzostominae	2
		Tubificidae	2
		Hirundinaea	1
	ARTHROPODA	Chelicerata, Pycnogonida	32
	MAXILLOPODA	Ascothoracida	1
		Copepoda	17
		Tantulocarida	2
	MALACOSTRACA	Amphipoda	37
		Cumacea	8
		Euphausidae	1
		Isopoda	21
		Leptonathiidae	2
		Mysidae	7
	OSTRACODA	Halocyprididae	1
		Philomedidae	2
		Podocopa	1
	BRACHIOPODA		1
	BRYOZOA	Cylindroleberididae	16
	CNIDARIA		22
	COELENTERATA	Actiniae	1
		Iophonidae	1
		Coelosphaeridae	1
		Niphatidae	2
	CTENOPHORA		1
	ECHINODERMATA	Ophiuroidaea	9

	Ophiuridae	7
	Asteroidea	7
	Holotharcoidea	2
	Crinoidea	1
MOLLUSCA	Amphineura	1
	Aplacofora	5
	Bivalvia	3
	Gastropoda	47
	Lamellibranchiata	7
	Nudibranchiata	9
	Octopoda	1
NEMATODA		14
NEMERTINA		2
PORIPHERA		30
CALCAREOUS PORIFERA		16
FORAMINIFERA		3