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"The Scientific Committee considered a review of the Ross Sea marine
ecosystem and agreed that the region had experienced relatively little
commercial exploitation, had a long history of scientific exploration,
and constituted a unique natural location to study the effects of
climate change on ecosystem processes."  SC-CAMLR-XXI Para 3.11, Oct
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THE ROSS SEA, ANTARCTICA, WHERE ALL ECOSYSTEM PROCESSES STILL REMAIN FOR STUDY

CCAMLR document number: WG-EMM-02/60

1.0 SUMMARY

The Ross Sea is a well-defined embayment of Antarctica about the size of southern Europe, bounded by Victoria Land to the west; King Edward VII Peninsula, Marie Byrd Land, to the east; the Ross Ice Shelf to the south; and the Southern Ocean, Pacific Sector, to the north. Its waters are composed of two related biotic systems: the Ross Sea Shelf Ecosystem (RSShelfE) and the Ross Sea Slope Ecosystem (RSSlopeE). The RSShelfE is the last Large Marine Ecosystem on Earth (except the Weddell Sea) that has escaped direct anthropogenic alteration; the RSSlopeE, similar to all of Earth's other marine ecosystems, has lost its large baleen whales but otherwise is intact. A huge multidisciplinary, international scientific effort has been invested in studies of the geology, physics and biology of the Ross Sea over the past 45 years. In particular the activities of the US, NZ and Italian Antarctic programs have been a model of international scientific cooperation and collaboration. The successful result is an incredible wealth of knowledge, including long-term biological data sets, not available anywhere else in the Antarctic, which has documented clear signals of climate forcing, as well as top-down influences not confused by human exploitation or activity. Ironically, much remains unknown about how these ecosystems function. The Ross Sea is off limits to mineral extraction, but pressures on its biological resources are growing. The economic value of the resources should be weighed against the value of the system as a unique scientific resource. The Ross Sea represents an unparalleled natural laboratory in which the results of different fishery management strategies can be modeled in the context of short-term and decadal variation in biological populations, with these models applied elsewhere in the Southern Ocean and the World.

2.0 BACKGROUND

The Ross Sea Shelf Ecosystem (RSShelfE) is one of the few remaining Large Marine Ecosystems (LME; *sensu* Sherman et al. 1990, 1993) where human influences have been minimal. Therefore, neither top-down nor bottom-up forcing mechanisms have been compromised. The RSShelfE may be the last LME on Earth (except perhaps the Weddell Sea) where this is the case. Other than a recent, and at present small-scale experimental fishery for Antarctic toothfish (or cod *Dissostichus mawsoni*) on the shelf (589 mt in 2000; Smith 2001, Waterhouse 2001) and, for the past 14 years, a scientific take of minke whales (*Balaenoptera bonarensis*) mostly along the continental slope (Ross Sea Slope

Ecosystem, 80 whales/yr; Ichii et al.1998 Brown & Brownell 2001), there has been no direct human influence: no oil spills or other significant pollution, no gill netting nor trawling with associated ‘by-catch’, and no over-exploitation of forage- or upper-level fish by industrial fisheries. Moreover, no top-trophic predator populations have been decimated by the introduction of feral animals. Finally, to no appreciable degree had the great whales nor various commercially exploited pinniped species ever frequented RSShelfE waters and, therefore, their demise in all the other oceans and seas of the World has been neutral to this particular LME.

On the other hand, the RSShelfE has not been ignored scientifically. Its marine geology is as well known as most other continental shelves. This is the result of decades of research during which myriads of sediment cores and seismic profiles have been obtained. In part this effort has been stimulated by interest in climate change and the history of the West Antarctic Ice Sheet, which during the last glacial maximum had overlain the entire Ross Embayment (now only half; e.g. Stuiver et al. 1981, Anderson 2000). The basic RSShelfE physical oceanography has been well investigated beginning in the 1960s through *R/V Eltanin* surveys and later projects such as RISP (Ross Ice Shelf Project), WOCE (World Ocean Circulation Experiment) and JGOFS (Joint Geophysical Ocean Flux Study); included has been ample work on small-scale current patterns and sea-ice dynamics (e.g., Barry 1988, Jacobs & Comiso 1989, Jacobs & Giulivi 1998, Jacobs et al. 2002, Diniman et al. ms). Biogeophysical processes that contribute to sediment histories have been well researched, too, e.g. such projects as ROAVERRS (Research on Ocean and Atmospheric Variability and Ecosystem Response in the Ross Sea). Much has been learned about primary productivity (studies by S. El Sayed, O. Holm-Hanson, W. Smith and ROAVERRS over 3 decades; e.g. Smith & Sakshaug 1990, Arrigo et al. 1998), and the ecology of its fast ice epontic microalgae and microbial communities is better known than anywhere in the Antarctic (studies by C. Sullivan and colleagues, e.g. Ackley & Sullivan 1994, Arrigo et al. 1994, Fritsen et al. 1994, Garrison et al. 1986, Grossi et al. 1987). Organisms in the top-trophic levels are well known: its baleen whales (Ainley 1985, Ichii et al. 1998, Branch & Butterworth 2001), seals (Testa & Siniff 1987, Testa et al. 1990; and the Antarctic Pack Ice Seals project, APIS), and birds (e.g., Ainley et al. 1983, 1984, 1998, 2003a,b). The presence of a distinct, fish-eating *Orca* species or subspecies is in the process of being described (R.Pitman, pers. comm.), and a research program on *D. mawsoni* in McMurdo Sound has operated for about 30 yrs (deVries and colleagues; Eastman 1993). Data sets are developed enough that decadal and interannual variability has been identified in the physics (Jacobs & Giulivi 1998, Jacobs et al. 2002), the benthic communities (Dayton 1989) and the highest trophic levels (Testa et al. 1992, Wilson et al. 2001, Cameron 2001).

3.0 DESCRIPTION OF THE ROSS SEA

The area of interest occurs south of and shallower than the 3000 m isobath, which is the dividing line between the lower continental slope and the deep ocean. This boundary extends from 69^o S, 170^o E (off Cape Adare, Victoria Land) to 76^o S, 155^o W (off King Edward VII Peninsula, Marie Byrd Land). Included is a northward jog of the isobath, around Iselin Bank, to about 69^o S, 175^o W. This region, which is about 598,000 km^2, includes the continental slope (500-3000 m, RSSlopeE) and the continental shelf (RSShelfE) of the Ross Sea (Fig. 1). Ichii et al. (1998) as well included both the slope and the shelf in their definition of “Ross Sea.”

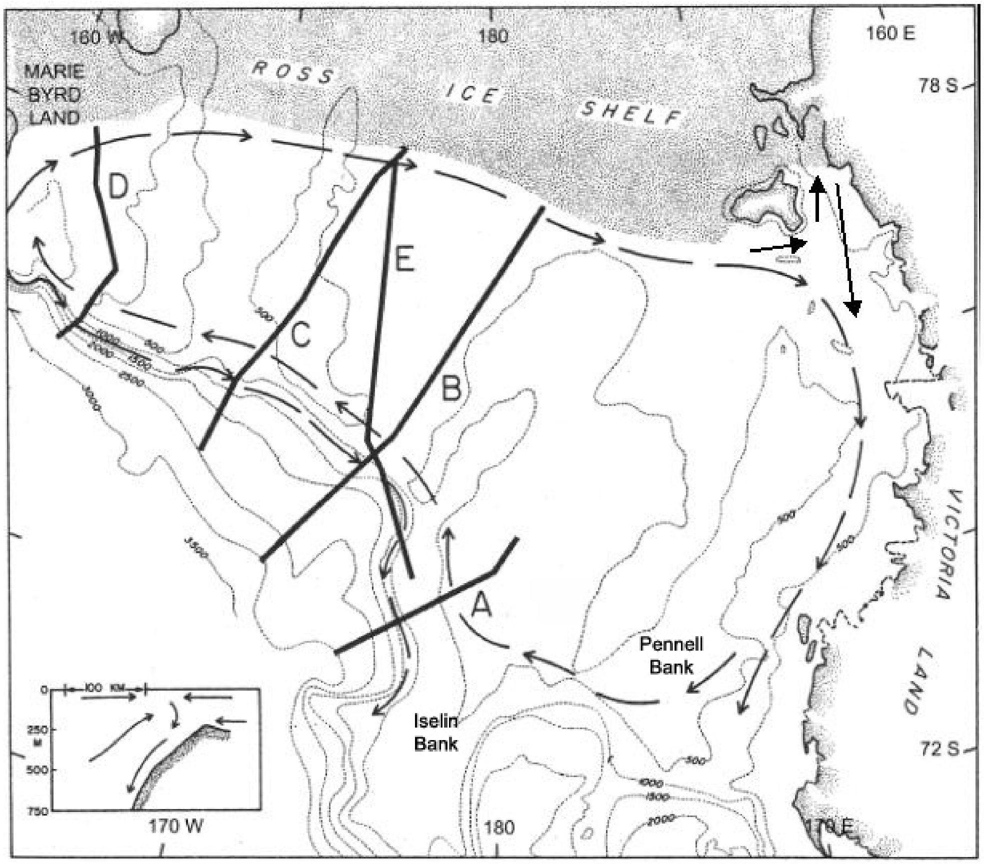

Figure 1. The Ross Sea showing horizontal and vertical (insert) circulation at the surface. Transect lines C & D are referred to in Figure 6. Figure redrawn from Ainley & Jacobs (1981).

3.0.1 ***Physical attributes***. Oceanographically, the Ross Sea is well defined. A general clockwise (anticyclonic), sluggish circulation is evident within the confines of the 500 m isobath (Ainley & Jacobs 1981, Dinniman et al. in press; Fig. 1). Along the shelfbreak this current opposes the East Wind Drift (Klepikov & Grigoryev 1966, Jacobs et al. 1970), which encircles the continent south of the Antarctic Circumpolar Current (ACC; which is westerly). The waters overlying the shelf are referred to as High Salinity Shelf Water (HSSW), or Ross Sea Shelf Water (RSSW) (Ainley & Jacobs 1981, Diniman et al. in press). The high salinity is derived from sea-ice formation (and salt rejection) that persists for much of the year, as well as the long residence time of water within the Ross Sea (ca. 4 years; Jacobs & Giulivi 1998).

A Shelfbreak Front exists along the outer shelf margin (Ainley & Jacobs 1981: Fig 1, insert). This is caused by the upwelling of warmer Circumpolar Deep Water (CDW) as it moves south to then be deflected upward (and downward) when it meets the continental slope. Some CDW, where it meets one of the four NW-SE bearing trenches of the shelf, flows well south of the shelfbreak (Jacobs & Giulivi 1998). Therefore, there is a strong oceanographic connection between the RSSlopeE and RSShelfE.

Throughout most of the year, ca. 8 mo and except for several polynyas, the Ross Sea is covered by sea ice. In fact, at maximal extent this ice extends well north of the Ross Sea reaching the southern boundary of the warmer ACC (Fig 2). Maximal ice extent in the Pacific Sector of the Southern Ocean is reached in August-September, but well before then the Ross Sea is covered (by April). In October, the sea ice begins to recede rapidly. It reaches minimal extent in February. At that time, the Ross Sea is clear of sea ice except for a narrow band along the southern Victoria Land coast and in the eastern Ross Sea (Fig 2, right panel). In fact, there is some interannual variability in the degree to which the sea ice disappears; in years of greatest winter extent much more sea ice remains in the subsequent February and *vice versa* (Jacobs & Comiso 1989, Jacobs & Giulivi 1998). In effect, reliably safe access into the Ross Sea by ships, other than icebreakers, is possible only during January and February.

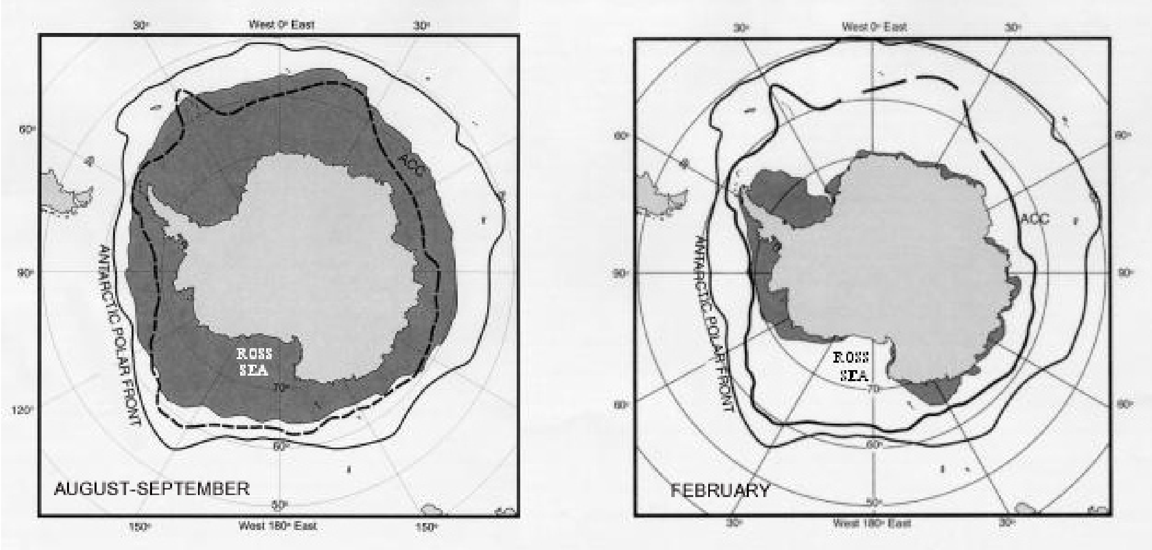

Figure 2. The seasonal change in sea-ice extent in the Southern Ocean; figure drawn from Gloerson et al. 1992.

Important components of the Ross Sea ecosystems are several polynyas (Jacobs & Comiso 1989, Arrigo et al. 1998). These are areas of persistently open water or loose pack ice within the larger region covered by sea ice. Two of them, the large Ross Sea polynya (along the front of the Ross Ice Shelf) and the Terra Nova Bay polynya (off middle Victoria Land), are the latent-heat type formed in response to persistent, strong winds and the heat generated by the continual freezing of sea water (the newly-formed ice being continually swept away). The other two are sensible-heat polynyas formed by the upwelling of warm CDW at the shelfbreak. The largest of these, the Ross Passage Polynya, is just off Cape Adare, Victoria Land; the other is at the northern end of Pennell Bank (Figs 1, 3). These polynyas allow both early access of the southern Ross Sea by ships and access to the food web by air-breathing top predators. They are also closely involved in the life cycle of important middle-trophic level species (crystal krill).

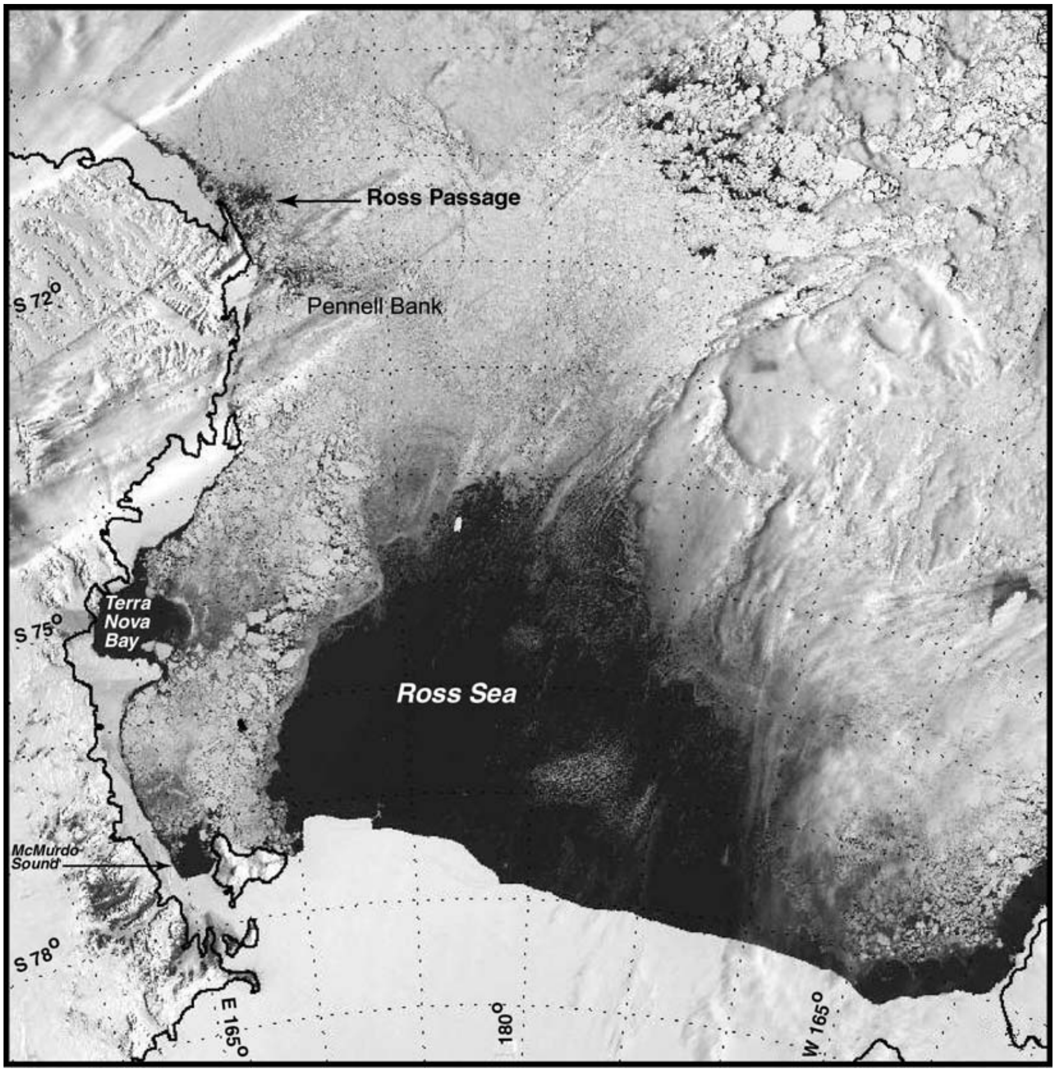

Figure 3. Satellite image showing important polynyas in the Ross Sea. This image was taken in November, after the Ross Sea polynya had tripled its winter size. Ross Passage and Pennell Bank polynyas are of the sensible-heat type; Ross Sea and Terra Nova Bay are latent-heat polynyas.

3.0.2 *Biological attributes*. Measures of primary productivity and plankton standing stocks indicate the Ross Sea to be the richest stretch of water of comparable size in the entire Southern Ocean (Arrigo et al. 1998, 2001). Confirming this is the richness of benthic communities, which depend largely on the ‘rain’ of biotic particles from the surface (Dayton 1990). Little research has been conducted on the abundance and distribution of the important mid-trophic level forage species (crystal krill, *Euphausia crystallorophias*; and Antarctic silverfish, *Pleuragramma antarcticum*), but the numbers of their top-trophic level predators also confirm the richness of the food web. About 38% of the world population of Adélie penguins (*Pygoscelis adeliae*; 940,000 of 2.5 M pairs) and 26% of emperor penguins (*Aptenodytes forsteri*: 52,000 of 197,000 pairs) nest along Ross Sea shores (Woehler 1993). Of these Ross Sea populations, 93% of emperor penguins (year round) and 39% of Adélie penguins (during summer) feed within the waters of the RSShelfE; the remainder feed in the RSSlopeE. Several millions of Antarctic petrels (*Thalassoica antarctica*) feed within the RSSlopeE during summer, this being one of the greatest concentrations of this species anywhere in the Southern Ocean (Ainley et al. 1984, van Franeker et al. 1999). Some of these petrels are known to nest in Marie Byrd Land; but the nesting locations of the majority are not known. The unknown sites could be spread throughout all of West Antarctica, as the species nests in the talus of nunataks and mountain tops hundreds of kilometers inland (van Franeker et al. 1999); almost all inland sites known have been discovered inadvertently by geologists seeking clues to other scientific questions. Similarly, among seals, Ross Sea numbers contribute the following to Pacific Sector populations at least as of the most recent surveys during the 1970s and early 1980s (cf. Stirling 1969, Gilbert & Erickson 1977, Ainley 1985): 45% of Weddell seals (*Leptonychotes weddellii*; 32,000 individuals), 11% of leopard seals (*Hydrurga leptonyx*; 8,000), and 12% of crabeater seals (*Lobodon carcinophagus*; 205,000). The difference in proportions is related to the fact that the latter two species are much more pelagic (off shelf) than the neritic (continental shelf) Weddell seal. Finally, on the order of 14,300 minke whales and 3,500 killer whales (*Orca orcinus*) were estimated to occur annually within the RSShelfE during the same time period (Butterworth & Best 1982, Ainley 1985). What the numbers of minke whales and their killer whale predators are now in the Ross Sea, the minke whales having declined Antarctic wide (Branch & Butterworth 2001), remains to be determined.

These predators occur during summer where their food is most abundant. Essentially, this is along the shelf break (RSSlopeE) and along the edges of what earlier in the year had been the Ross Sea Polynya (Fig 4). Within the polynya, a dense bloom of the colonial flagellate *Phaeocystis antarctica* begins to develop each year as soon as the sun rises. As a result of large clumps and long chains containing huge numbers of individual cells, this alga can withstand the intense downward mixing caused by the strong winds and turbulence characteristic of the polynya. However, the gummy globs are avoided by grazers. However, along the polynya edges, where sea ice shelters the waters and allow stratification of the water column, single-cell diatoms bloom. These diatoms are much more the preferred food of grazing zooplankton. Therefore, a robust food web develops.

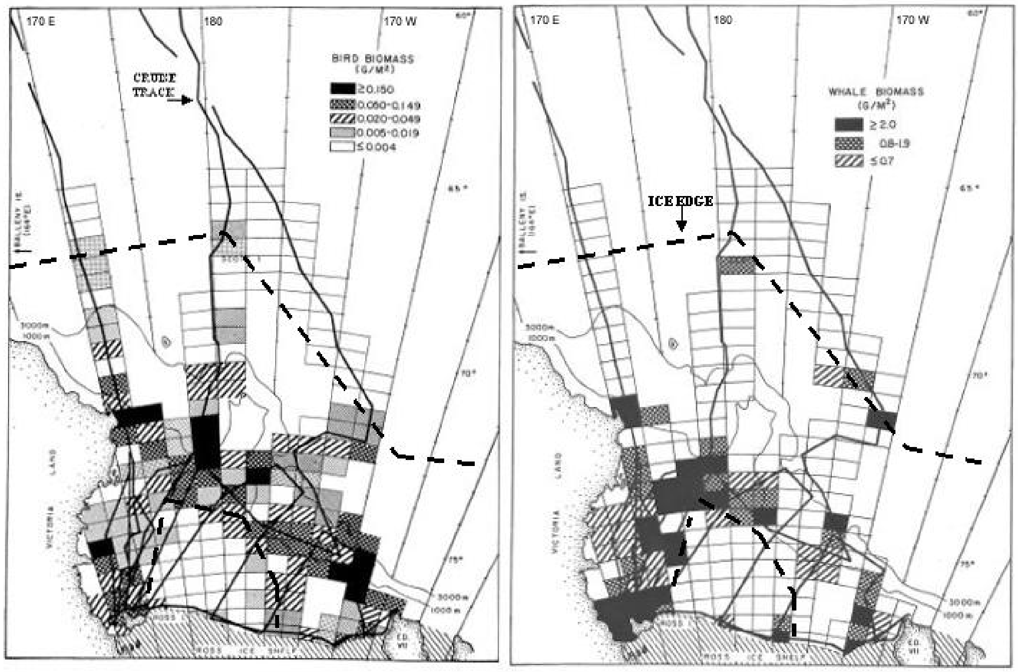

Figure 4. Distribution of seabirds and cetaceans in the Ross Sea during December. Correspondence with the Shelfbreak Front (RSSlopeE) and the marginal ice zones are clear; large-scale ice edges shown by heavy dashed lines. Comparison to Figure 3 reveals the lack of top-level organisms in the Ross Sea Polynya, which is dominated by *Phaeocystis* blooms.

Obviously, the Ross Sea's top-trophic predators are remarkably well known. Then, too, the Ross Sea is well defined and the research of several nations has been productive since the Antarctic Treaty went into effect. In fact, the emperor and Adélie penguin, as well as Weddell seal populations have been researched, at first sporadically, since the dawn of Antarctic scientific study 100 years ago. What is lacking in our understanding of the RSShelfE (and continental shelf ecosystems elsewhere in the Southern Ocean) is the coupling between lower and upper trophic components. In other words, how does the abundance and availability of middle-trophic level organisms respond to climate factors that, in turn, affect upper-trophic level populations, and *vice versa*? The two main middle-trophic-level species in the RSShelfE are the Antarctic silverfish and crystal krill (e.g., DeWitt 1970, Eastman 1993, Hopkins 1987, Pakhomov & Perissinotto 1997, Hubbold & Hagen 1997; Fig. 5). In Antarctic neritic waters these two species are the principle prey of all top-trophic species —Adélie and emperor penguins, Weddell seals, minke whales and Antarctic toothfish (Ainley et al. 1998, 2003a; Burns et al. 1998, Cherel & Kooyman 1998, Davis et al. 1999, Eastman 1985; Ichii et al. 1990, 1998; Laws 1984, Plötz et al. 1991). A soon-to-be-described 'new' killer whale preys on the toothfish and possibly silverfish. The Weddell seal preys on toothfish as well (Testa et al. 1985).

To illustrate the importance of crystal krill and silverfish, about 75% of Antarctica's 2.5 million Adélie penguin breeding pairs prey mainly (80-95% of diet) on these two organisms; the remaining penguins — owing to colony location (e.g., northern Antarctic Peninsula, n.w. Victoria Land) — forage in waters over the shelfbreak where they mostly eat Antarctic krill (*E. superba*; 24 studies summarized in Ainley 2002). A huge amount of effort and literature, appropriately, has addressed the life history of Antarctic krill (e.g., Marr 1962, El Sayed 1994, and subsequent work). In contrast, owing to the difficulties of marine research in coastal, ice-bound seas, relatively little is known about the life history of silverfish and crystal krill. Indeed, although CK may be the single major consumer of phytoplankton in neritic waters (Pakhomov & Perissinotto 1997), major points of its life history were not described until the mid-1980s (Ikeda 1986; O'Brien 1987a,b; Siegel 1987; Brinton & Townsend 1991) and others remain unknown.

Also obvious is the simplicity of the RSShelfE (Fig 5). The latter figure outlines what may typify the major trophic connections in the RSShelfE, although many important interactions remain unknown. The silverfish and crystal krill are central, and interspecific competition for these organisms by upper trophic level predators is likely. The decrease or increase of any major species would likely elicit a demographic response in one of the others. Investigations of Adélie penguin foraging currently underway around Ross Island indicate that these birds either deplete their prey or force it to become unavailable (through predator avoidance) during the period of penguin chick provisioning when foraging is most intense: 1) a switch from one major prey item (crystal krill) to another (silverfish), 2) increasing foraging distance from colonies, 3) increasing foraging depth, and 4) increasing foraging time with food loads successively decreasing as well. Moreover, penguins from the largest colony, by their density, apparently exclude from their foraging area those penguins from other colonies nearby (Ainley et al. 1998, 2000, 2003b; Ballard et al. 2002). During the chick provisioning period, hundreds of minke whales and killer whales also forage within the penguin foraging areas.

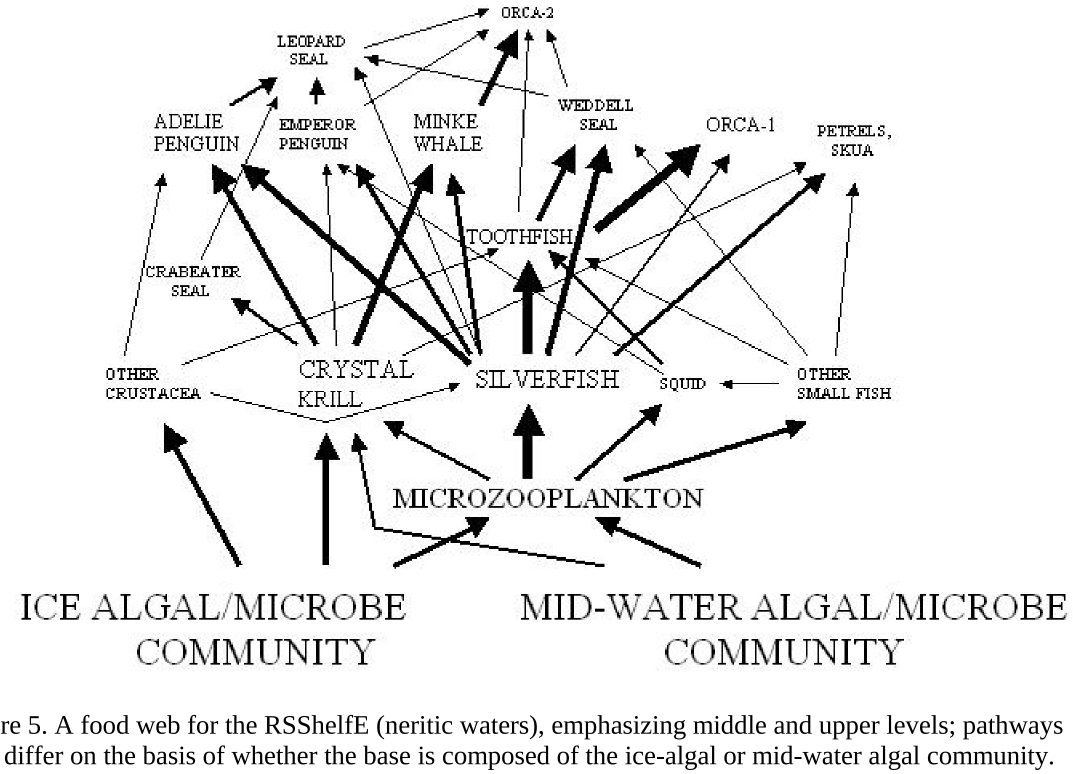

Figure 5. A food web for the RSShelfE (neritic waters), emphasizing middle and upper levels; pathways may differ on the basis of whether the base is composed of the ice-algal or mid-water algal community.

Prey depletion has also been observed among Weddell seals in McMurdo Sound. These seals prey on toothfish during early spring, but apparently deplete these fish within breath-holding distance of the breeding areas where the seals concentrate. This was shown by variation in human fishing success as a function of distance from seal haul outs (Testa et al. 1985). After depleting the toothfish, the seals turn to smaller prey, such as silverfish. Like all trophic interactions, other factors, too, may be involved in their persistence. For instance, confounding interpretation of these results is the lack of information on the movements of both the silverfish and the toothfish, independent of predator avoidance.

The RSSlopeE is another matter. There the dominant middle-trophic species is the Antarctic krill. As noted above, the natural history and role in food webs of *E. superba* is relatively well known. It has been the subject of intense research for 80 years, although not much effort has been expended on it in the RSSlopeE. Important to Antarctic krill is the vertical movement of water along the shelf break (Fig 6). This species sheds its eggs in this region, depending on the upwelling to assist the upward migration of larvae. Besides this krill species, also important to upper trophic levels in the RSSlopeE, and elsewhere in deep waters of the Southern Ocean, are myctophid fish (Ainley et al. 1984, 1992). A provisional food web for these waters is presented in Ainley & DeMaster (1990).

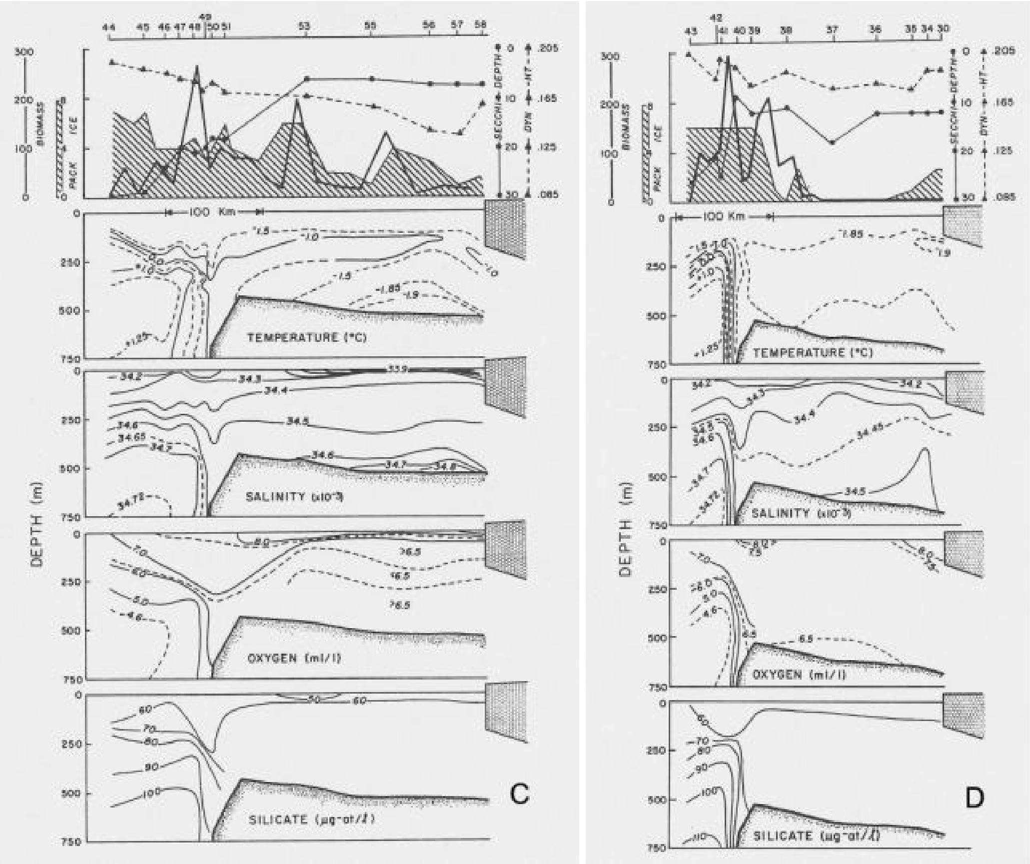

Figure 6. Section north-south across the Ross Sea (see Fig 1). Illustrated is the Shelfbreak Front (RSSlopeE), where high densities of predators (in this case birds) feed principally on Antarctic krill. Drawings from Ainley & Jacobs 1981.

4.0 UNIQUE SCIENTIFIC VALUES

Nowhere else on Earth, other than the Weddell Sea, do we still have a natural laboratory in which can be observed a neritic marine ecosystem that has not been significantly affected by commercial fisheries or other human activity. Unlike other parts of the Southern Ocean, consistently collected data sets are long enough in the Ross Sea that clear patterns of decadal and interannual variability have been identified in the physics, the benthic communities, and the highest trophic levels. In such a well-defined but appreciably large system, these data sets have few parallels elsewhere in the Southern Ocean or even elsewhere on Earth. Questions remaining in regard to factors explaining identified trends in these ecosystem components will not be satisfactorily answered if exploitation of biological resources continues or expands in the Ross Sea. Decades of effort and expense will be lost, and like elsewhere the climate-effect signal will be submerged by anthropogenic forces.

Thanks to long-term collections of data, decadal and ENSO-scale fluctuations in the weather, oceanography and sea-ice patterns of the Ross Sea have become apparent (Jacobs & Giulivi 1998, Jacobs et al. 2002, Ainley et al. ms). Within that context, periodic surveys along permanent transect lines in McMurdo Sound, begun by a series of researchers in the U.S. Antarctic Program (USAP) in the late 1960s, have identified a major shift in the composition of benthic communities that occurred during the late 1970s (Dayton 1989, 1990). The shift apparently is related to the formation of anchor ice. No such data have been gathered elsewhere in the Southern Ocean. Why the frequency of years of anchor ice formation has changed is not yet known.

The New Zealand Antarctic Program (NZAP) has monitored the size of Adélie penguin colonies on Ross Island annually since 1959 (Taylor & Wilson 1990). This data set is almost two decades longer than analogous ones elsewhere in the Antarctic (Woehler et al. 1999) and compares with any chronicle of seabird population change anywhere in the world. During the 1970s and especially the 1980s (to the present) the populations have been growing noticeably. Part of the variability (30%) in annual population size is related to sea-ice extent during winter (Wilson et al. 2001), but much more effort is required to understand the remaining factors affecting population change. Likely involved are changes in the formation and decay of sea ice and polynyas (Ainley et al. ms). Within that context, the only existing demographic study of this species was completed by USAP researchers on Ross Island penguin populations during the 1970s, and a comparable study by USAP and NZAP is presently underway.

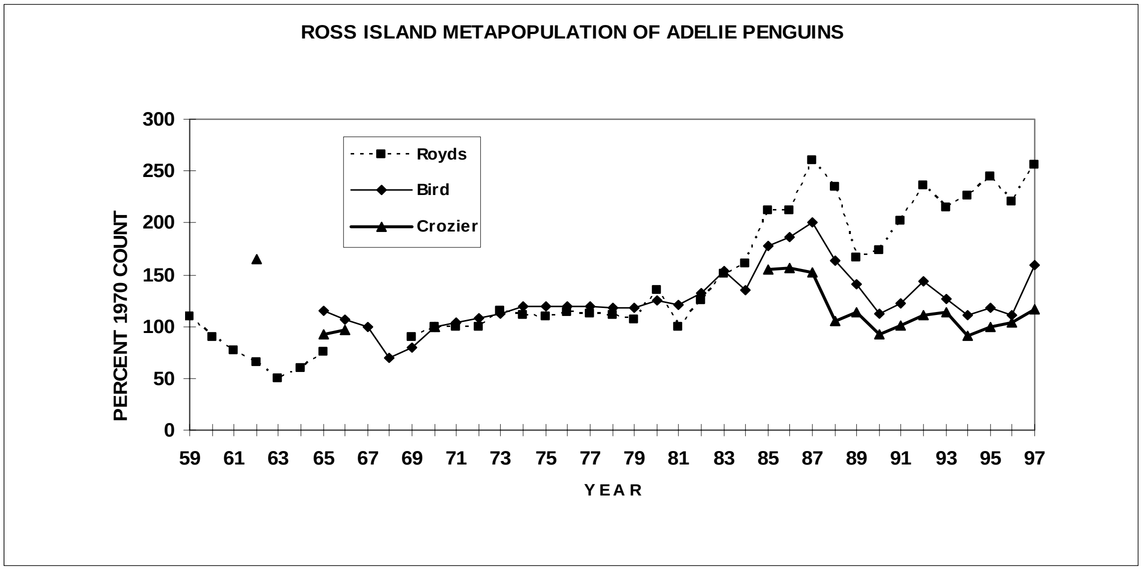

Figure 7. Trends in Adélie penguin colony size on Ross Island, 1959-1997. The NZAP continues to census these colonies annually (number of breeding pair) using aerial photography. Data from Wilson et al. (2001).

Finally, one of the longest demographic studies of a pinniped population anywhere, that of Weddell seals, has been underway, first by NZAP and subsequently by USAP, in McMurdo Sound since the late 1960s (Stirling 1971, Testa & Siniff 1987, Testa et al. 1991, Cameron 2001). Initially, a take of seals to provide food for dogs was allowed but has since been stopped (early 1980s) by agreement under the Antarctic Treaty. This population showed some major fluctuations in pups born and estimated adults in the early 1970's (Fig. 8) but it size has remained relatively consistent since the mid 1980s. Why the population has become less variable remains to be determined; climate and food-web factors could well be involved.

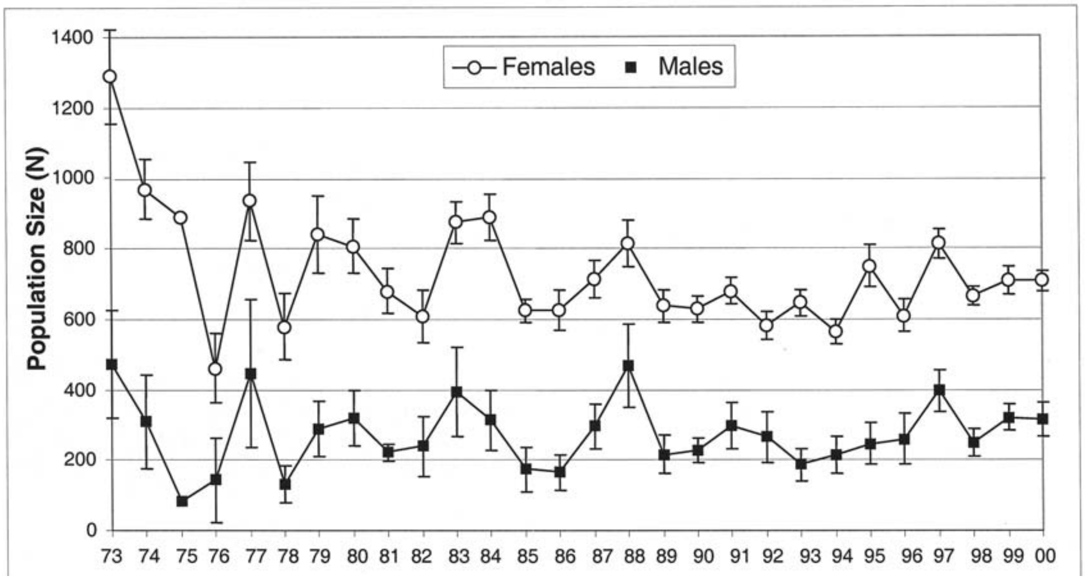

Figure 8. Jolly-Seber population abundance estimates ($\hat{N}$) for female and male Weddell seals in Erebus Bay, McMurdo Sound. Error bars are two standard errors. 1975 estimates are from an aerial count; as such they have no error bars (Cameron 2001).

5.0 COMPETING SCIENTIFIC AND ECONOMIC INTERESTS

5.0.1 *Antarctic toothfish*. A fishery for Antarctic toothfish (or cod) has been developing in the RSShelfE during the past few years (Smith 2001, Waterhouse 2001). The potential of this fishing to affect the Ross Sea ecosystems are profound.

Studies in McMurdo Sound, in which over 5,000 toothfish have been caught, measured and tagged since the 1960s, reveal this to be a cornerstone species in the Antarctic icthyofauna (Eastman 1985). Eastman characterizes this fish (along with its close relative, the Patagonian toothfish *Dissostichus elonginoides*), as “the largest notothenioids and probably the most important piscine predators in the water column of the Southern Ocean” (p. 77). The Antarctic toothfish reaches 163 cm total length and 60-70 kg. Its growth is very slow (cm/yr) and it reaches decades in age. Apparently, it spawns only every other year (DeVries, pers. com.). Recently, toothfish tagged in McMurdo Sound were caught near Cape Adare, 800 km to the north of McMurdo Sound. Therefore, the Ross Sea toothfish population travels widely. This species preys heavily on silverfish, as do most other top predators of the RSShelfE (Fig. 5). In turn, it is a major food of Weddell seals and killer whales (see above).

Researchers working among the Aleutian Islands (North Pacific) have hypothesized that commercial fishing, principally for walleye pollock (*Theragra calcogramma*; currently the largest fishery in the world), a trophically central species, has so altered the food web that killer whales are preying on sea otters, which is not the norm (Estes et al. 1998). One result is that the reduction in sea otters has led to a cascade of effects through benthic communities. Normally, sea otters control the populations of invertebrates that graze on sea weeds. Without the otters and, subsequently, without sea weeds, entire reef-dwelling fish communities have been negatively affected. This is an example of what could take place in the Ross Sea if the abundance of Antarctic toothfish is significantly altered. Weddell seals and killer whales either would have to decline and/or increase their predation of other prey, including the whales taking more of the seals.

In that regard, the closely related Patagonian toothfish appears to have been severely overexploited virtually everywhere that an industrial fishery has developed (Waterhouse 2001). Over-exploitation is easily accomplished given the very slow reproductive rates of these fish and, once accomplished, leads to the fishery moving to new areas. In the face of a growing commercial fishery for Antarctic toothfish, the RSShelfE food web is in jeopardy of grave alteration (Table 1). It is commendable that the fishing in the Ross Sea thus far has been controlled and done with a sub-aim of acquiring more information on the toothfish (Smith 2001). Any plans to increase fishing activity, however, must be viewed with repercussions to ecosystem processes also in mind.

Table 1. The following is a summary of the Ross Sea Antarctic toothfish take to date (unknown is the take by unlicensed boats). Data from CCAMLR.

2001/2002: Subarea 88.1, Conservation Measure 235/XX; Catch limit: 2508 mt (2337 south of 65S; 171 mt north 65S; 10 vessels notified (NZ – 4, Russia – 3, South Africa – 2, Japan – 1)
Subarea 88.2, CM 236/XX; Catch limit: 250 mt, all south of 65S; 7 vessels notified (NZ – 3, Russia – 1, S. Africa – 2, Japan – 1)
2000/2001: Subarea 88.1, CM 210/XIX; Catch limit: 2064 mt (175 mt north of 65S; 1889 south of 65S); Actual catch: 658 mt (66 mt north of 65S; 592 mt south of 65S), by NZ, South Africa and Uruguay
Subarea 88.2, CM 211/XIX; Catch limit: 250 mt, all south of 65S; Actual catch: 0
1999/2000: Subarea 88.1, CM 190/XVIII; Catch limit: 2090 mt (175 mt north 65S; 1915 mt south 65S); Actual catch: 745 mt south of 65S by NZ (originally the EC and Chile intended to fish here)
Subarea 88.2, CM 191/XVIII; Catch limit: 250 mt all south of 65S; Actual catch: 0 (originally Chile and EC intended to fish here)
1998/1999: Subarea 88.1, CM 169/XVII; Catch limit: 2281 mt (271 mt north of 65S; 2010 mt south of 65S); Actual catch: 296 mt all south of 65S by NZ
Subarea 88.2, closed
1997/1998: Subarea 88.1, CM 143/XVI; Catch limit: 1510 mt (338 mt north of 65S; 1172 mt south of 65S); Actual catch: 39 mt all south of 65S by NZ
Subarea 88.2, CM 139/XVI; Catch limit: 63 mt (25 mt north of 65S; 38 mt south of 65S); Actual: 0
1996/1997: Subarea 88.1, CM 115/XV; Catch limit: 1980 mt; Actual: 1 mt
Subarea 88.2, CM 115/XV; Catch limit: 1980 mt; Actual: 0

5.0.2 ***Minke whale***. This species was exploited heavily in the Southern Ocean during the 1970s and 1980s but the take ceased under an International Whaling Commission (IWC) moratorium. The take of the minke whale grew progressively as the other, larger baleen whales were over-exploited (Brown & Brownell 2001). Most of these minke whales were taken in IWC areas V (130^{o}E – 170^{o}W) and VI (170^{o}W – 120^{o}W), or that part of the Southern Ocean that includes the Ross Sea (Fig 9). As Area VI is mostly covered by pack ice year round at the latitude of the Ross Sea, and whale boats do not enter the pack ice, the catch in Area V is the most important in terms of direct impact on the RSShelfE and RSSlopeE. In other words the Area VI catch must be mostly from the area along the large- scale ice edge north of the eastern Ross and Amundsen seas (cf Figs 2, 3).

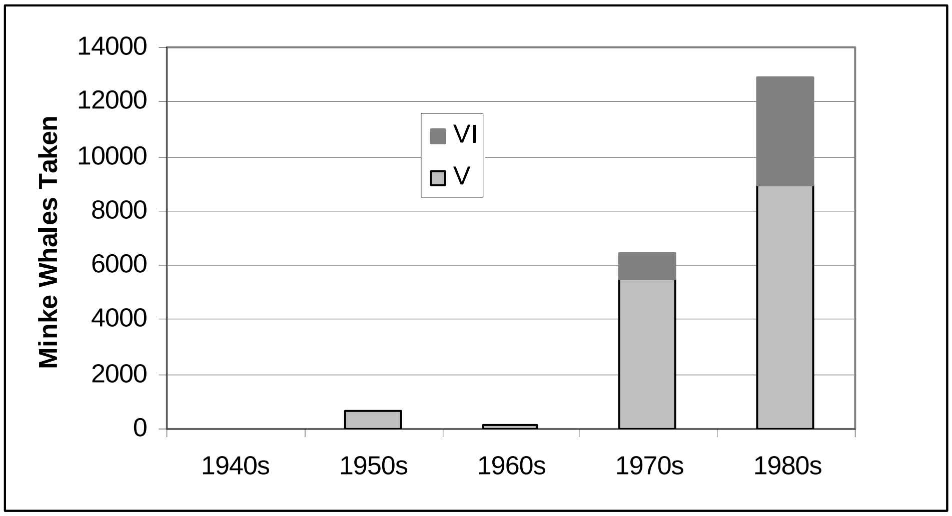

Figure 9. The commercial take of minke whales in IWC sectors V and VI, by decade. The moratorium on commercial whaling went into effect in 1986. Data from Brown & Brownell 2001.

Since the moratorium went into effect, Japan has been permitting the take of this species in the Southern Ocean for scientific purposes as provided for in the International Whaling Convention, although this action has been questioned by many members of the IWC and its Scientific Committee (IWC 1997, Brown & Brownell 2001; Fig 10). About 80 whales, with more than half being pregnant females, have been taken annually within the Ross Sea, principally along the continental slope (i.e., the RSSlopeE; Ichii et al. 1998; Fig 11). Therefore, several hundred minke whales have been taken from the relatively small area of the Ross Sea since the late 1980s and during a period of minke whale population decline (see below).

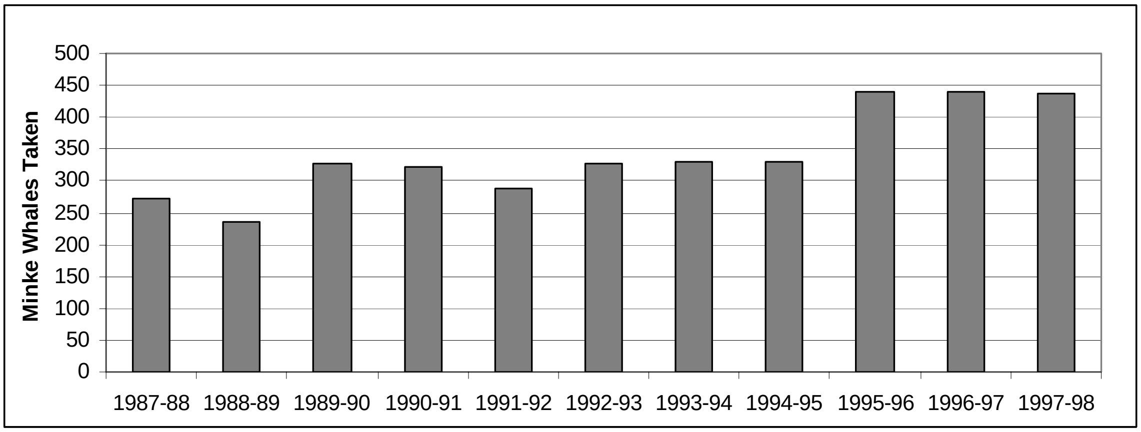

Figure 10. Minke whales taken under a permit for scientific research in IWC areas V and VI, 1987-1997 (data from Brown & Brownell 2001). In 1990-91, 1992-93 and 1994-95, respectively, 79, 68 and 87 were taken from within the RSShelfE and, especially, RSSlopeE; of these 67%, 62% and 52% were pregnant females (Ichii et al. 1998).

Like the toothfish, minke whales live for decades and have a low reproductive rate (sexual maturity at 4-5 years of age; no more than one calf per year per mature female).

The scientific take has been concentrated in IWC Areas V and VI (Ross Sea sector of Southern Ocean), rather than being spread widely. Therefore, the ‘local’ impact potentially is great. Little is known about the persistence of local populations of this species. Like all the top predators, minke whales prey on crystal krill and silverfish in the RSShelfE, and on Antarctic krill in the RSSlopeE (Ichii et al. 1998). It is preyed upon extensively by killer whales (Mikhalev et al. 1981).

A single MW feeding twice daily consumes an estimated 21.5-33.8 mt (male and female minke, respectively) of food over 3-4 mo in the Antarctic (Armstrong & Siegfried 1991). Some estimates are even higher. According to Ichii & Kato (1990), a single minke whale consumes 4% of body mass per day. That translates to 330 kg of food per day for females and 280 kg for males. A single Adélie penguin consumes about 0.9 kg per day during the chick provisioning and subsequent pre-molt periods (Ainley 2002). Therefore, the removal of several hundred minke whales can have potentially important impacts on penguin foraging success. Adélie (and emperor penguins) from southern Victoria Land molt in the eastern Ross Sea (RSSlopeE) during February (Kooyman et al. 2000, Ainley 2002), at the time when the whale exploitation is underway in the RSSlopeE. The penguins are particularly voracious at that time, as they do not feed at all once the molt begins. Therefore, gathering adequate forage could well affect the subsequent survival of these penguins. Whether the penguins’ population growth, and especially that since the mid-1980s (cf Figs 7, 9), is a consequence of more prey being available with reduction of minke whales is unknown, but this is certainly a possibility.

Within ice-free waters surveyed by the IWC, a significant circumpolar decline in minke whale abundance occurred between the mid-1980s and the late 1990s; in the Ross Sea, an order of magnitude decline is evident from 101,590 (C.V. = 0.32) during 1985/86 to 11,038 (C.V. = 0.45) during 1991/1992 (Branch & Butterworth 2001). Unknown is whether changes in climate, sea ice concentration, productivity, and/or prey availability have played a role, or whether commercial catches during the 1970s and 1980s (and more recent scientific ones) are showing a long-term, delayed response.

Rather enigmatic is the low body mass of minke whales, and especially pregnant females, taken from the Ross Sea (Ichii et al. 1998). Pregnant whales should be feeding voraciously. That being the case, Ichii et al. (1998) were at a loss to explain why these whales were so numerous in the Ross Sea (Fig 11, left panel), if foraging opportunities apparently were so poor. Because killer whales are also abundant, they reasoned that the minke whales would not be using the Ross Sea (and the sea ice so persistent there) in order to avoid predation (killer whales to a greater degree avoid pack ice). Ichii et al., however, did not entertain the idea that the whales could be avoiding whale catcher boats.

The fact that minke whales have low body mass in the Ross Sea is a further indication — besides the prey depletion exhibited by Adélie penguins and Weddell seals — that the RSShelfE food web is sensitive to top-down forcing (see above). This is a concept difficult to fathom for most ‘blue-water’ marine biologists but, then, few have ever worked in a system where all the top-trophic predator populations are still robust. In systems without any top-down forcing, other than human fishing pressure, it is easy to assume that bottom-up forcing is the key to understanding food-web structure and population variations. Ultimately, then, the food web of RSShelfE appears also to be very sensitive to perturbation. Loss of minke whales could well bring pressure for killer whales to seek alternate prey (even greater numbers of toothfish, seals, etc.), with consequent ecosystem repercussions.

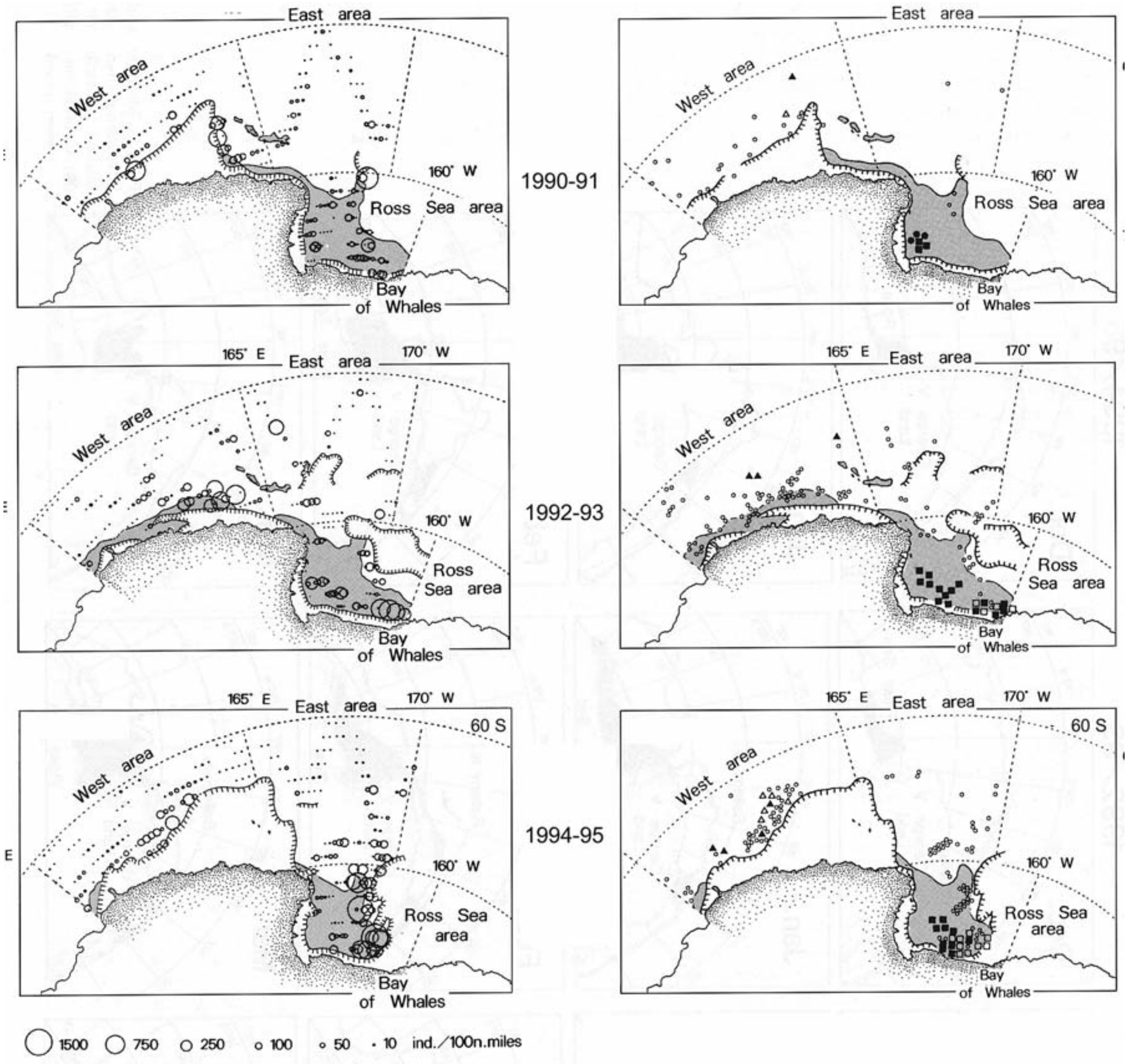

Figure 11. Left panel: The distribution of minke whales sighted on IWC surveys in 1990-91, 1992-93 and 1994-95; right panel: diet of minke whales taken by JARPA during the same year (figure redrawn from Ichii et al. 1998). Continental shelf and slope shaded; compare with Figure 2. In right panel, open circles indicate diet dominated by *E. superba*; squares *E. crystallorophias* (dark dominant, open subordinant to *E. superba*); dark circles *Pl. antarcticum.* Hatched lines indicate boundary of pack ice.

6.0 PLANNING FOR THE FUTURE

In marine ecosystems throughout the world, investigations and analyses are underway to determine how living resources can be managed sustainably in the context of increasing harvest pressure, rapidly changing climate, and other variables. A major problem is that most systems, other than the Ross and Weddell seas, have been altered in uncertain and undocumented ways by decades and, in some cases, centuries of human activities. Thus, it is difficult to differentiate the effects of natural variation from the effects of harvesting, climate change, point and non-point source pollution, etc. Effective fishery management, thus, is a difficult challenge.

Continuing to intensively investigate and monitor the few relatively unperturbed marine ecosystems, like the Ross Sea, which have been studied greatly and where we know that direct human influence has been minimal, can provide a body of information that can be used to help predict the short-, mid-, and long-term effects of climate change and to identify and model alternative management strategies. As noted earlier, for example, owing to interest in the history of the West Antarctic Ice Sheet, changes in the Holocene climate of few places on Earth are as well known as in the Ross Sea, as revealed in ice and sediment cores as well as the remains of marine creatures such as bivalves and penguins. While we have learned a great deal about recent ecosystem structure and climate change in the Ross Sea during the past few decades, we have a long way to go before we can relate magnitude and sources of present day natural variation to the Holocene record. To achieve that goal, we need to gather data through several more decadal cycles.

The ability to monitor the physical environment and primary and secondary productivity is better now than ever before thanks to development of satellite technology, which has been available only since the late 1970s (not much more than a single decadal climate cycle: Ainley, et al. ms), and automatic weather stations, which have been in use for about 15 years. What is missing, but attainable, are long-term data from ocean moorings to track the behavior of water masses, such as the infusion of Circumpolar Deep Water onto the Ross Sea Continental Shelf, and data on the natural history and natural variability in the distributions, abundance, and productivity of important middle trophic level species, such as Antarctic silverfish and crystal krill. Development of reliable data on these subjects, along with continuation of the kinds of studies described above, will allow better predictive modeling of natural variation and ecosystem response to climate change, the direct and indirect effects of living resource harvesting, and other variables of interest and concern. Such knowledge can be used by the Antarctic Treaty Parties, CCAMLR, SCAR, the IWC, and other management authorities and advisory bodies to help develop optimal research and management strategies for marine ecosystems in the Antarctic and throughout the world.

CCAMLR and the other authorities responsible for regulating and monitoring harvesting of living resources and other activities in the Ross Sea should consider what more might be done to assess and maximize the value of the Ross Sea as an "ecosystem" laboratory.

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