Exploring Sea Ice Indexes for Polar Ecosystem Studies

Sea ice indexes can give a common context to link variability in sea ice coverage to variability in marine ecosystems

Raymond C. Smith, Karen S. Baker, and Sharon E. Stammerjohn

Nothing more dramatically illustrates the extreme seasonality of the Southern Ocean physical environment than the annual waxing and waning of sea ice over 20 million km^2 of ocean. In winter, sea ice can almost double the surface area of the Antarctic continent, whereas in summer, sea ice covers approximately one-sixth of the area it covers in winter and is confined to just a few basins. These differences are as extreme as the perpetual night and day associated with those two seasons, except that seasonal changes in both the timing and magnitude of sea ice coverage are far more variable than seasonal changes in solar radiation. In this tempestuous environment, local atmospheric and oceanic forces shape the vast sea ice landscape of the Southern Ocean, creating not only high seasonal variability but also high spatial variability and, consequently, different regional sea ice environments (Zwally et al. 1983, Gloersen et al. 1992, Parkinson 1992, 1994).

The ecological impact of sea ice is a complex space–time matrix of biology and physical forcing

In the context of this high regional variability, marine ecologists seek to understand how interannual fluctuations and the extreme seasonality of sea ice coverage are linked to variability in the marine ecosystem. External physical forcing plays a more dominant role in causing variability in marine ecosystems than internal biological mechanisms, which may be more dominant in causing variability in terrestrial ecoystems (Steele 1991). To compare how sea ice coverage influences biological and ecological phenomena, a quantitative reference system is needed. However, no accepted standard exists to describe sea ice variability. Therefore, we propose a set of sea ice indexes that provide quantitative definitions of the timing and magnitude of sea ice coverage on temporal and spatial scales that are relevant to testing ice–ecosystem linkages. A sea ice index is a number (or, at most, a few numbers) that derives from a set of sea ice observations during a year and that may be used as a simplified ecological indicator of annual sea ice variability.

We first recognized a need for a systematic and quantitative approach to describe sea ice variability while working on the Palmer Long-Term Ecological Research project (Palmer LTER; Smith et al. 1995), which focuses on the marine ecosystem in the seasonal sea ice zone west of the Antarctic Peninsula (Figure 1; Ross et al. 1996). The central tenet of the Palmer LTER is that the annual advance and retreat of sea ice affects all levels of the Antarctic marine ecosystem, including, for example, the timing and magnitude of seasonal primary production; the dynamics of the microbial loop and particle sedimentation; the abundance, distribution, and recruitment of krill (*Euphausia superba*); and the breeding success and survival of apex predators.

Our work on sea ice variability (Stammerjohn and Smith 1996) has shown that various regions of the Southern Ocean have distinct seasonal and interannual characteristics. In particular, the LTER and Bellingshausen regions are the only regions of the Southern Ocean that show long-term persistence in monthly anomalous sea ice coverage—that is, several consecutive high sea ice years are followed by several consecutive low sea ice years. Because of this annual and interannual variability of sea ice in the western Antarctic Peninsula region, scientists have been able to monitor the ecosystem by measuring the abundance and distribution of key species before, during, and after seasons and years of different sea ice coverage.

Such a long-term sampling strategy is needed, for example, to understand how primary productivity is

---

Raymond C. Smith (e-mail: ray@icess.ucsb.edu) is the former director of the Institute for Computational Earth System Science (ICESS) and is currently a professor of geography at the University of California Marine Bio-Optics Group (UCMBO), Santa Barbara, CA 93106. Karen S. Baker (e-mail: karen@icess.ucsb.edu) is a data manager/analyst at UCMBO and at the Scripps Institution of Oceanography, La Jolla, CA 92093-0218. Sharon E. Stammerjohn (e-mail: sharon@icess.ucsb.edu) is a research analyst at ICESS, University of California, Santa Barbara, CA 93106.

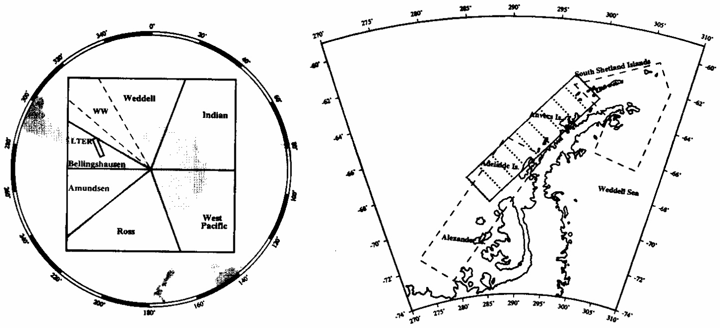


Figure 1. Southern Ocean (left) and LTER regional (right) maps. The map of the Southern Ocean is divided into sections to show the six main regions that have often been separated for study; the dotted lines within the Weddell region denote the boundaries of the western Weddell (WW) subregion. The large square outlines the area for which there is sea ice concentration data. In both maps, the rectangle to the west of the Antarctic Peninsula denotes the Palmer LTER region. The LTER regional map shows the Palmer LTER sampling transects (indicated by the dotted lines). Each of these sampling transects extending out from the coast are 200 km in length and are spaced 100 km apart; these transects are numbered from 000 (the most southern line) to 900 (the most northern line). The other two regions in the peninsula map (indicated by dashed lines) are the southwestern peninsula (SP) and northern peninsula (NP) regions.

influenced by interannual variability in seasonal sea ice cover. High rates of primary production in the spring have been associated with ice edge blooms during sea ice retreat, when meltwater and favorable meteorological conditions induce water column stability (Smith and Nelson 1986). However, in years when the extent of spring sea ice is low, either because the overall winter sea ice extent was low or because sea ice retreated earlier than normal, spring blooms can be low and/or early (Clarke et al. 1988, Murphy et al. 1995). Therefore, both the timing and magnitude of the spring sea ice retreat affect the associated spring phytoplankton blooms and subsequent food availability for krill and other grazers and, in turn, for top predators.

The life histories of various polar marine species are synchronized with the seasonality of sea ice (Smith et al. 1995). Sea ice is a major habitat for microorganisms, and the bacterial community goes through several stages of succession as the pack ice recedes (Christian and Karl 1994, Karl et al. 1996). Krill, a major herbivore for the transfer of energy within the Antarctic marine ecosystem, is closely coupled to sea ice during various periods of its annual life cycle (Robin Ross and Langdon Quetin, University of California–Santa Barbara, manuscript submitted). For example, high krill reproductive output has been associated with high winter sea ice concentrations (Siegel and Loeb 1995) and with abundant phytoplankton blooms along the receding ice edge in spring (Smetacek et al. 1990, Quetin et al. 1994). In addition, survival and recruitment of larval krill depend on food availability in summer, when they first arrive at the surface, approximately three weeks after being spawned, and on the presence and duration of winter sea ice, which provides both an under-ice refuge and a source of food by way of sea ice algae (Ross and Quetin 1991).

Many top predators, such as Adélie penguins (*Pygoscelis adeliae*), depend in turn on the availability of krill, particularly during the spring breeding and summer creche seasons, when their energetic requirements are high (Fraser et al. 1992, Trivelpiece and Fraser 1996). Winter pack ice conditions also influence the percentage of penguins that survive the winter in healthy condition to breed successfully the following spring (Trathan et al. 1996). Preliminary studies tracking winter migration of Adélie penguins show that the birds' overwinter feeding regions consist of 75% pack ice coverage (Davis et al. 1996). Thus, the magnitude and timing of sea ice has both direct and indirect effects at all trophic levels. Any temporal shifting of the annual cycle of regional sea ice coverage significantly changes the physical environment of any given season and, therefore, affects those ecosystem variables that are synchronized with the mean annual cycle of sea ice (Smith et al. 1995), such as the viability of Adélie chicks.

In addition to changes in the location of the sea ice edge (i.e., in the extent of sea ice), changes in sea ice concentrations within the boundary of the sea ice edge can influence both in situ biological communities and sea ice–related habitats. Sea ice concentrations typically increase from the ice edge toward the continent: The marginal ice zone is diffuse, the open pack ice zone is less diffuse, and, finally, the close pack ice zone is compact. However, the close pack ice zone can be interrupted by open water areas that are associated with fractures (any break in solid ice cover, which can be a few meters to several hundred meters wide and up to many kilometers long), leads (a large fracture that is navigable by surface vessel), or polynyas (any nonlinear opening enclosed in sea ice).

Year-to-year and seasonal changes in the distributions of these various sea ice zones can directly affect both low and high trophic levels. For example, changes in the relative contribution of marginal ice zone–associated primary production to total production modulates annual primary production (Smith et al. in press). For higher trophic levels, variability in sea ice concentrations can result in variability in habitat and foraging area. Three different sea ice–related habitats are associated with enhanced foraging opportunities for seabirds (Hunt 1991): open leads and polynyas within the pack ice, through which seabirds can gain access to the water column and the underside of sea ice; the ice edge (either compact or highly diffuse), which serves as a major ecological boundary; and the open ocean area just seaward of the ice edge, where meltwater helps to stabilize the water column and enhances primary production. Even for a single species (e.g., Adélie penguins), the physical and biological matrix of spatial and temporal variability is complex. To assess the degree to which sea ice variability influences various populations and trophic level couplings, it is important to quantify these sea ice–related habitats throughout the annual cycle and over the long term.

To define sea ice variability on spatiotemporal scales that are relevant to testing ecosystem responses, we turn to the data set that can best fulfill our needs—that from multifrequency passive microwave satellite sensors (i.e., Scanning Multi-Channel Microwave Radiometer [SMMR] and Special Sensor Microwave/Imager [SSM/I]). These satellite sensors provide the longest, most continuous, and most accessible data on polar sea ice coverage. Sea ice concentrations computed from the sensor data using the NASA Team algorithm (Cavalieri et al. 1984, 1995, Gloersen and Cavalieri 1986) are available from the National Snow and Ice Data Center's Distributed Active Archive Center at the University of Colorado (Web site: http://www-nsidc.colorado.edu).

Although the SMMR and SSM/I data have coarse spatial resolution (approximately 30–70 km), they are temporally continuous because the microwave signal is relatively unaffected by polar darkness or cloud cover. By contrast, higher spatial resolution satellite sea ice data from visible, infrared, and synthetic aperture radar (SAR) sensors have poor temporal resolution, either because clouds can obscure visible and infrared frequencies or because few SAR data are available. Thus, sea ice concentrations derived from SMMR and SSM/I provide the only adequate time series of sea ice variability needed to explore ice–ecosystem linkages. Therefore, a set of sea ice indexes derived from the SMMR and SMM/I data would bring much-needed consistency to studies searching for ice–ecosystem linkages. Too often, sea ice variability is described in terms of annual magnitude only (i.e., a high- or low-ice year), even though the ecosystem process under evaluation may be equally influenced by seasonal, monthly, or even daily variability. Thus, to appropriately summarize sea ice variability, both the magnitude and timing of variability must be specified.

The sea ice concentrations derived from the SMMR and SSM/I data cover the entire Southern Ocean and were originally in image format with pixel sizes of 25 km × 25 km. The SMMR data were recorded every other day, on average, from October 1978 to September 1995; the SSM/I data were recorded daily from June 1987 to the present. We calculated the monthly averaged images from October 1978 to September 1995, and for each region shown in Figure 1 we then derived three areal measurements: sea ice extent, sea ice area, and open water fraction. Sea ice extent is the ocean area enclosed by the 15% sea ice concentration contour and is determined by summing, for the region in question, the pixel areas that have 15% or greater sea ice concentration; consequently, it includes mixtures of open water and sea ice (from 15% to 100%) at subpixel resolution but does not include leads and polynyas that are greater than pixel resolution. Sea ice area is the ocean area covered only by sea ice with concentrations greater than 15% and is determined by multiplying the pixel area by the sea ice concentration, if the sea ice concentration is equal to or greater than 15%, and then summing those pixel areas for the region in question. Open water fraction is the fraction of open water at subpixel resolution within the 15% sea ice concentration boundary; it is determined by subtracting sea ice area from sea ice extent, and then dividing by sea ice extent.

To use the passive microwave data in a systematic manner (e.g., through the use of sea ice indexes), it is important to be aware of both the strengths and weaknesses of these data. Sources of error in estimating sea ice concentrations from passive microwave data using the NASA Team algorithm are discussed in detail elsewhere (Comiso et al. 1992, 1997, Gloersen et al. 1992, Emery et al. 1994). In general, the error associated with estimates of sea ice extent depends mostly on the accuracy of the algorithm in distinguishing large bodies of open ocean from large bodies of sea ice; this error has been estimated to be less than 2% for total Southern Ocean sea ice extent (Comiso et al. 1992). A much higher error is associated with estimates of sea ice area (and, therefore, with open water fraction); this error depends on the algorithm's accuracy in determining sea ice concentrations between 15% and 100%. Comparisons between sea ice concentrations derived from SMMR and SSM/I data using the NASA Team algorithm and sea ice concentrations derived from other higher resolution satellite data show that the NASA Team algorithm typically underestimates sea ice area (Comiso et al. 1997). Consequently, annual, seasonal, and monthly indexes of sea ice area (and open water fraction) should be used for interannual comparisons only and should not be treated absolutely or literally. The unknown error involved in the estimates of sea ice area and open water fraction will particularly influence the accuracy of estimates made for the smaller regions. Therefore, the observed variability in open water fraction in the LTER region, for example, should be considered only as an indication that the amount of open water–like surface characteristics has changed, but this variability should not be regarded as necessarily indicating absolute changes in the amount of open water.

In this article, we first analyze the kinds of information that can be obtained from sea ice indexes derived from temporal scales including annual, seasonal, and monthly and from spatial scales ranging from 20 million km^2 (total Southern Ocean) to 200,000 km^2 (the Palmer LTER study region). Sea ice indexes are defined here as indicators, or measures, of the spatial and temporal variability of sea ice coverage. We then give a few examples of how these indexes can be used to identify and quantify potential physical forcing of the ecosystem and the consequent ecosystem response.

An annual index of interannual variability

To quantitatively define the annual magnitude of sea ice coverage, we calculated annual means of sea ice extent, sea ice area, and open water fraction for the 16 complete years of

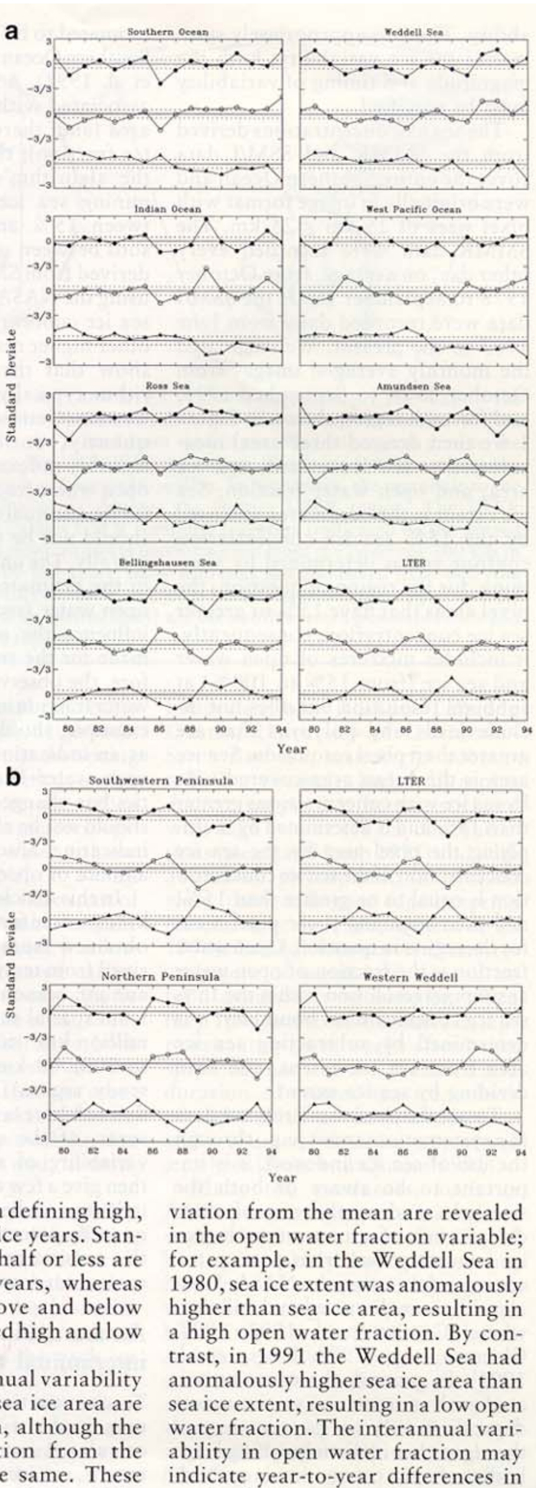


Figure 2. Standard deviates (the monthly anomaly divided by standard deviation) of annual sea ice extent, sea ice area, and open water fraction for various regions of the Southern Ocean (a) and the Antarctic Peninsula (b) from 1979 to 1994. Solid circles indicate sea ice extent; open circles indicate sea ice area; and solid triangles indicate open water fraction. Solid horizontal lines represent the 1979–1994 mean, whereas the dotted lines denote ± 0.5 standard deviations about the mean.

sea ice concentration data (1979–1994) for several regions of the Southern Ocean (Figure 1), including the Palmer LTER region. To show how each year departs from the long-term mean and to compare these departures among regions of different sizes, we calculated the standardized annual anomalies (i.e., standard deviates) for each variable by dividing the annual anomalies (i.e., the annual value minus the 1979–1994 mean) by the standard deviation (Figure 2a). The zero (i.e., mean) and half-standard deviation lines have been included to aid in defining high, average, and low sea ice years. Standard deviates of one-half or less are considered average years, whereas standard deviates above and below one-half are considered high and low years, respectively.

In general, interannual variability in sea ice extent and sea ice area are similar in each region, although the magnitude of deviation from the mean may not be the same. These differences in the magnitude of deviation from the mean are revealed in the open water fraction variable; for example, in the Weddell Sea in 1980, sea ice extent was anomalously higher than sea ice area, resulting in a high open water fraction. By contrast, in 1991 the Weddell Sea had anomalously higher sea ice area than sea ice extent, resulting in a low open water fraction. The interannual variability in open water fraction may indicate year-to-year differences in sea ice habitat types (i.e., marginal ice zone, open pack ice, and close pack ice). For example, in the Bellingshausen region, high open water years, such as 1984, 1989, and 1991, may indicate more diffuse sea ice conditions (i.e., more open pack ice), whereas low open water years, such as 1979 and 1987, may indicate more consolidated sea ice conditions (i.e., more close pack ice).

In general, as Figure 2 indicates, years of high sea ice extent and area appear to be characterized by low open water fractions, and years of low sea ice extent and area by high open water fractions, although there are a few exceptions, as in 1980 in the Weddell Sea. Also noticeable in Figure 2 is the downward trend in open water amount in the Southern Ocean as a whole and in several regions in particular (e.g., the Weddell Sea, the Indian Ocean, and the West Pacific Ocean), an observation that we will return to later in this article and that is explored in full in another study (Stammerjohn and Smith 1997). Figure 2a also shows that each region has a unique set of high, average, and low sea ice and open water years, although the Bellingshausen and LTER sets are most similar to one another because the LTER region is a longitudinal subset (i.e., incorporating both north and south environments) of the Bellingshausen region. These regional differences in high, average, and low sea ice and open water years should result in regional differences in interannual variation in marine ecosystem parameters.

The Palmer LTER study region spans six degrees of latitude, with strong north–south gradients in year-to-year variability of sea ice coverage; the southern end is more consistently ice covered than the northern end. To investigate how different sea ice conditions in the northern and southern regions might affect the marine ecosystem, we defined two additional regions in the vicinity of the western Antarctic Peninsula (Figure 1): the southwestern peninsula (SP) and the northern peninsula (NP) regions, both of which are comparable in surface area to the LTER region. The NP region is defined as extending southeast of the tip of the Antarctic Peninsula to include the region to which the breeding penguin populations on the South Shetland Islands most likely migrate in autumn and winter (Trivelpiece and Fraser 1996). In addition, a pie piece–shaped section of the western Weddell (WW), in the vicinity of the Antarctic Peninsula (Figure 1), was defined to encompass an area studied by other marine ecological programs.

A comparison of interannual variability in the SP, NP, and WW regions with interannual variability in the LTER region (Figure 2b) shows both similarities and differences. The SP and LTER regions have similar high, average, and low sea ice years, with the exceptions of 1983–1985 and 1990–1991. Although years 1983–1985 appear to have been average in the SP region, winter sea ice coverage was not extensive beyond the SP region, explaining the low sea ice years in the LTER region. By contrast, years 1990–1991, which followed a record low sea ice year in 1989 for all peninsula regions except WW, were still low sea ice years in the SP region but were near-average sea ice years in the LTER region. This difference is likely due to decreases in summer sea ice coverage in the SP region, where perennial sea ice concentrations were still recovering from the record low in 1989 (Jacobs and Comiso 1993, 1997).

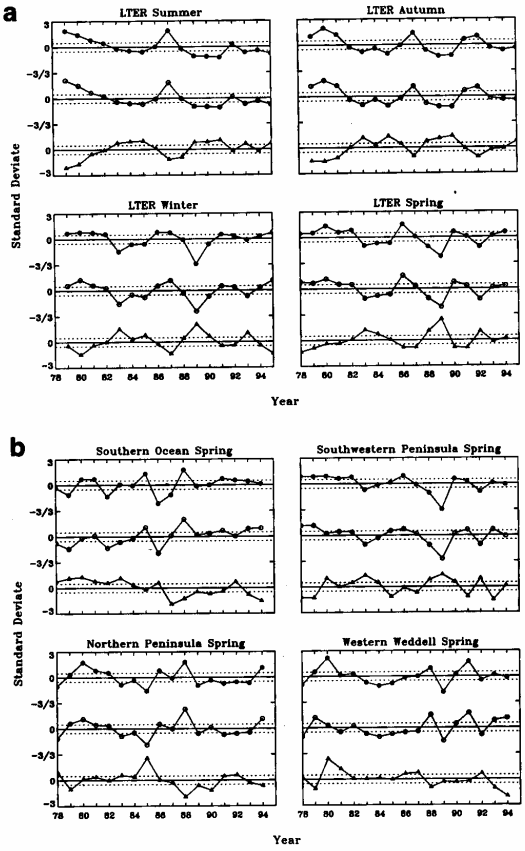


Figure 3. Standard deviates of seasonal sea ice extent, sea ice area, and open water fraction for the Palmer LTER region (**a**) and for various regions of the South Ocean in the spring only (**b**). Solid circles indicate sea ice extent, open circles indicate sea ice area, and solid triangles indicate open water fraction. Solid horizontal lines represent the October 1978 to September 1995 mean, whereas the dotted lines denote ± 0.5 standard deviations about the mean.

The interannual variability in the NP region, in contrast to the SP and LTER regions, shows possible influences from the WW region. For example, 1989 was not the extreme low sea ice year in the NP that it was in the SP and LTER. However, 1985 and 1993 were low sea ice years in the NP but not in the SP and LTER. In addition, 1988 was a high sea ice year in the NP, when the downward trend in sea ice coverage was already under way in the SP and LTER regions. The interannual variability in the WW region is different from the other three regions but is similar to the interannual variability in the greater Weddell region shown in Figure 2a. These distinct differences in sea ice variability, even among these relatively small subregions (i.e., SP, LTER, NP, and WW), underscore the need to give careful consideration to the geographic region of physical influence when investigating ice–ecosystem linkages.

A seasonal index of interannual variability

Although the annual index defines quantitatively high, average, and low sea ice and open water years and permits regional comparisons, it does not address the timing and magnitude of seasonal sea ice coverage. For example, it cannot be assumed that for an average sea ice year, ice coverage was average during all seasons or that sea ice arrived and departed at the average times. Seasonal differences are striking and could have important implications for the marine ecosystem.

For each region and each variable (i.e., sea ice extent, sea ice area, and open water fraction), seasonal standard deviates were determined for summer (January–March), autumn (April–June), winter (July–September), and spring (October–December). Figure 3a shows such seasonal indexes for the Palmer LTER region. As was observed in the annual index time series, seasonal sea ice extent and area show similar interannual variability, with high sea ice years associated with low open water fractions and low sea ice years with high open water fractions. However, only the two extreme high and low sea ice extent and sea ice area years have the same classifications (i.e., high, average, or low) across all four seasons: 1980 (high every season) and 1989 (low every season). All other years exhibit interseasonal variability with respect to high, average, and low sea ice extent and area. For example, in 1990, an average sea ice year for the LTER region (Figure 2), sea ice extent was low in summer and autumn, average to low in winter, and high in spring. By contrast, in 1992, also an average sea ice year for the LTER region, sea ice extent was average in summer and winter, high in autumn, and low in spring. Figure 3b shows that the spring sea ice index alone varied from region to region. In particular, the interannual variability of spring sea ice coverage for each peninsula region is distinct, defining different physical environments for the local marine populations.

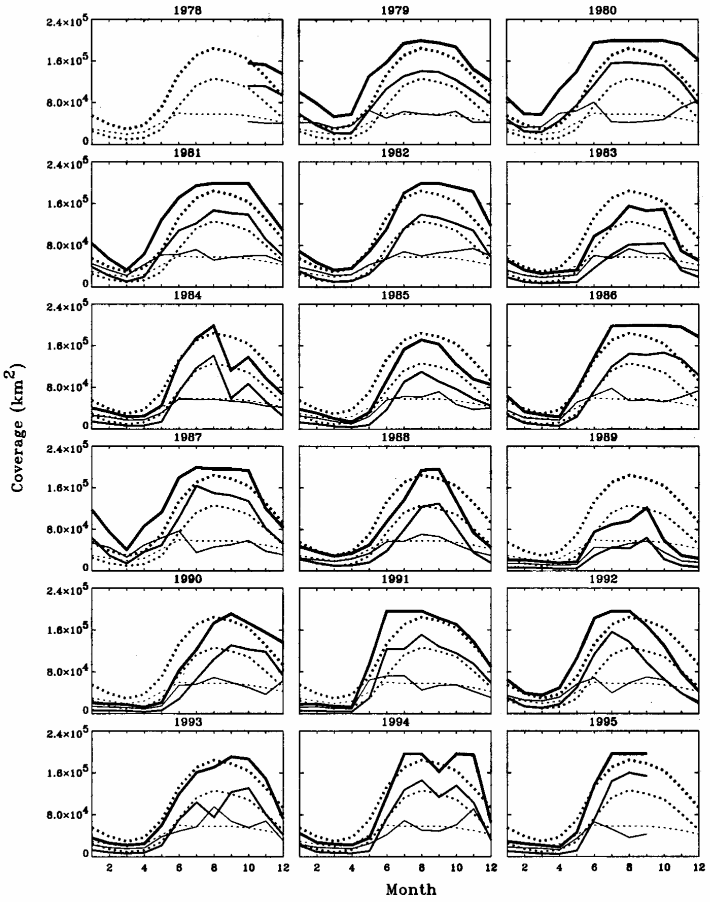


Figure 4. Annual curves of monthly sea ice extent, sea ice area, and open water area for the Palmer LTER region from October 1978 to September 1995. Solid lines indicate annual curves of monthly sea ice extent (thick line), sea ice area (medium line), and open water area (thin line). Dotted lines represent the October 1978 to September 1995 mean for each sea ice variable.

A monthly index of interannual variability

Monthly annual curves of sea ice extent, sea ice area, and open water area from October 1978 to September 1995 for the Palmer LTER region (Figure 4) provide a good illustration of year-to-year differences in the timing of the seasonal progression of sea ice coverage. This figure uses open water area instead of open water fraction to show the relative areal amounts of each variable over the sea ice advance and retreat cycles. Each of the three annual curves is superimposed on its mean to illustrate the seasonal departures with respect to magnitude and, in particular, timing.

For most years, sea ice extent and sea ice area have similar annual cycles. Those exceptional years (e.g., 1993) when the two annual cycles differ significantly indicate large changes in open water amount within the sea ice extent boundary, perhaps due to strong weather events. Other years of interest, in addition to overall extreme high (e.g., 1980, 1981) and low (e.g., 1983, 1985, 1989) sea ice years, are those that deviate significantly, if only for a few months, from the mean annual curve. For example, the annual curve in 1990 and 1992 was shifted to the right (later) and to the left (earlier), respectively, in both variables. In 1990, summer and autumn sea ice extent were below average, the winter maximum arrived one month later (September), and spring sea ice extent was high. By contrast, in 1992 both summer and autumn sea ice extent were above average, and the winter maximum arrived two months earlier (June) and lasted until August, when a dramatic decline in sea ice coverage took place, resulting in a below-average spring sea ice extent.

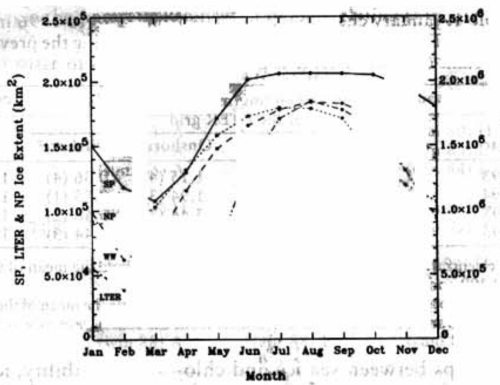
The seasonal progression of sea ice coverage also differs significantly among regions. Figure 5 shows the mean annual curves of sea ice extent for the four peninsula regions. Each region shows a distinctly different annual cycle, which illustrates two important features of the sea ice environment: the mean months of minimum and maximum ice coverage and the mean duration of ice advance and retreat. The two regions that include the most southern latitudes, SP and WW, have long and short periods of maximum and minimum ice extent, respectively. Both regions also have quick periods of ice advance and retreat, although the period of ice advance is longer in the WW region than in the SP region. By contrast, the two regions located in more northerly latitudes, LTER and NP, have short and long periods of maximum and minimum ice extent, respectively, and slow, gradual periods of ice advance and ice retreat. The LTER region also has the lowest summer ice extent, because there is little perennial sea ice in that region. The mean month of minimum ice extent is February for the NP and WW regions, and March for the LTER and SP regions. The mean month of maximum ice extent is less pronounced for all regions except the LTER region, which, on average, peaks in August. The broad maximum peaks for the SP and WW regions appear to occur in August, whereas for the NP region the maximum occurs in July. In general, the monthly annual curves show that the timing of the seasonal progression of sea ice coverage is variable from year to year and from region to region; this variability affects those local ecosystem variables that are synchronized with the mean annual cycle of sea ice coverage.

Sea ice forcing and ecosystem response

A contour plot of LTER monthly standard deviates of sea ice extent further illustrates seasonal differences in sea ice extent from year to year (Figure 6). This plot also provides an objective overview of long-term variability in sea ice extent and of the possible ecological consequences of this variability. Figure 6 emphasizes the Ackley and Sullivan (1994) conceptual model of the seasonal cycle of sea ice: Sea ice formation begins in fall (around April), with the possible entrainment of phytoplankton as a seed population; it reaches its maximum extent in winter; and it begins to melt or retreat in late spring and summer, with the potential for bloom inoculum and sedimentation of particulate organic matter.

Within this context, the monthly standard deviate contour plot of LTER sea ice extent (Figure 6) illustrates several significant points. First, the periods of anomalously high (1979–1981 and 1986–1987) and low (1983–1985 and 1988–1990) sea ice extents stand out clearly. Moreover, these consecutive two- to three-year high and low sea ice extent periods persisted from the late 1970s throughout the 1980s. Ecosystem responses to these anomalies, for example recruitment of krill (Siegel and Loeb 1995, Quetin et al. 1996) and sea birds (Trivelpiece and Fraser 1996), have been described. These studies capitalized on the distinct ecological differences between high and low sea ice years to test the interrelationships between organisms and sea ice. High sea ice extent years are associated with higher krill biomass and Adélie penguin survival; conversely, low sea ice extent years are associated with lower krill biomass and lower Adélie chick survival. This linkage to sea ice is thought to reflect enhanced primary productivity, which influences the entire food chain, or, in the case of Adélie chick survival, suitable foraging distances for the adult penguins during chick rearing. It is noteworthy that the significance of these strong linkages results largely from the observed persistence (several years of high sea ice extent followed by several years of low sea ice extent) from the late 1970s throughout the 1980s.

Figure 5. Mean annual sea ice extent cycles for the four Antarctic Peninsula regions in our study. Solid line indicates SP; dotted line indicates NP; dashed line indicates WW; and dash-dotted line indicates LTER. The y-axis at left refers to the SP, LTER, and NP annual curves; the y-axis at right refers to the WW annual curve.



The second point to emerge from the contour plot is that in the 1990s, anomalies have generally been lower, and their timing more erratic, than in previous years. Indeed, this shift in the broad anomaly pattern underscores the need to examine seasonal variability in greater detail and to develop the indexes presented here. The Ackley and Sullivan (1994) conceptual model of the annual cycle of sea ice formation, growth, and decay is a framework within which to test hypotheses associated with the colonization of sea ice by microalgae during autumn, their subsequent growth and accumulation within the sea ice during winter, and the potential for their deposition into the water column as a bloom inoculum during spring. According to this model, the seasonal timing of sea ice coverage is a critical factor in determining subsequent primary productivity within the system.

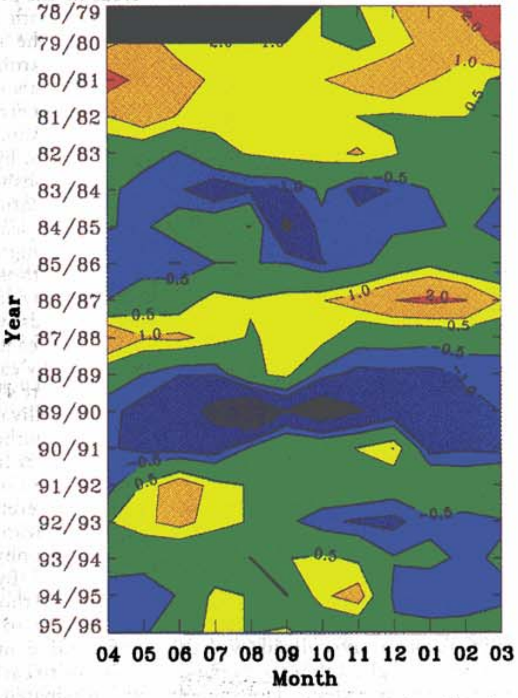


Figure 6. Monthly standard deviate contour plot of sea ice extent in the Palmer LTER region from October 1978 to March 1996 (the September 1995 to March 1996 data have not been fully verified but are shown here for illustration). Dark to light blue = anomalously low periods (less than –0.5 standard deviates); green = average periods (more than –0.5 but less than 0.5 standard deviates); and yellow to red = anomalously high periods (more than 0.5 standard deviates). Note that the x-axis begins at month 4; consequently, the seasonal progression begins during autumn and ends during summer (month 3).

Given the evidence for linkages between sea ice coverage and the marine ecosystem, we looked at rela-

Table 1. January chlorophyll biomass from 1993 to 1996 in various sectors of the Palmer LTER grid in relation to sea ice extent during the previous winter and spring. The rank of each variable is given in parentheses to assist in cross-comparisons.

Year	Chlorophyll (mg/m^3) in four sectors of the LTER grid				Sea ice extent (km^2) the previous	
	Central^a	Southern^a	Onshore^b	Offshore^b	Winter	Spring
1993	1.36 (3)	0.59 (4)	1.15 (4)	0.36 (4)	184,888 (2)	82,174 (4)
1994	1.23 (4)	1.39 (1)	1.94 (3)	0.85 (1)	172,297 (4)	134,373 (2)
1995	2.42 (2)	1.07 (2)	3.46 (2)	0.56 (2)	183,118 (3)	150,220 (1)
1996	2.65 (1)	0.87 (3)	5.00 (1)	0.44 (3)	194,320 (1)	113,664 (3)

[a] The central and southern areas of the LTER grid include the mean of transect lines 500 and 600, and 200 and 300, respectively (see Figure 1).

[b] The onshore and offshore areas of the LTER grid include the mean of the innermost station (nearest the coast) and outermost station (farthest from the coast), respectively, of all transect lines.

tionships between sea ice and chlorophyll biomass variability using the Palmer LTER data from 1993 to 1996. During four six-week cruises beginning each January, we took chlorophyll biomass measurements within our regular sampling grid (Figure 1), which includes stations spaced every 20 km along cardinal lines (200 km long, 100 km apart) that are perpendicular to the peninsula (Waters and Smith 1992). The spatial coverage and resolution of stations allow us to resolve north–south and onshore–offshore gradients along the western Antarctic Peninsula.

Comparing the variability of the chlorophyll biomass with the sea ice indexes (Table 1) suggests several possible relationships between sea ice forcing and ecosystem response. Because we are comparing only four years of data, these observations provide only an initial construct for illustrating the use of sea ice indexes. Table 1, for example, lists mean chlorophyll biomass concentrations for the central and onshore regions of the LTER grid, which show a stronger relationship with the previous winter sea ice extent than with the previous spring sea ice extent. For example, the lowest and highest years of chlorophyll biomass in the central LTER grid region (i.e., 1994 and 1996, respectively) coincide with the lowest and highest years of previous winter sea ice extent. The highest year of chlorophyll concentration in the onshore LTER grid region also coincides with the highest year of previous winter sea ice extent. These correlations are expected in the context of the hypothesis that an increase in the areal extent of the marginal ice zone increases the spatial and temporal extent of water column stability, ice algae inoculation, and phytoplankton blooms (Smith and Nelson 1986). A high winter sea ice extent year means an increase in the spatial and temporal extent of sea ice in the central and northern regions of the LTER grid, thus increasing the potential for greater influence (both spatially and temporally) of the retreat of sea ice on phytoplankton production.

Table 1 also lists the mean chlorophyll concentrations for the southern and offshore regions of the LTER grid, which, by contrast to the central and onshore regions, show a stronger relationship with the previous spring sea ice extent. The two highest spring sea ice extent years (in relation to those four years) are characterized by late sea ice retreat or melt periods, whereas the two lowest spring sea ice area years are characterized by early sea ice retreat periods (Figure 4). In the context of the Ackley–Sullivan conceptual model, the high southern and offshore biomass concentrations are hypothesized to be a result of the late sea ice retreat, whereby the recently inoculated meltwaters contribute to the high chlorophyll biomass observed in January. By contrast, the early retreats are thought to have contributed either to no blooms (due to unfavorable meteorological conditions) or to earlier blooms that were well dissipated by January, resulting in the lower chlorophyll biomass measurements. Although these possible relationships between seasonal sea ice and chlorophyll biomass are tentative, it is interesting to note that the four years (1993–1996) for which we have sea ice and chlorophyll biomass data have been average years with respect to the 1979–1994 annual means of sea ice extent. However, on a seasonal and monthly basis, these four years were extremely variable, with both high and low monthly anomalies occurring in each year.

The importance of the timing of the seasonal advance and retreat of sea ice coverage is also consistent with recent research showing a more complex response of krill to sea ice coverage than the earlier hypothesized high versus low sea ice year dichotomy. Langdon Quetin and Robin Ross (University of California–Santa Barbara, personal communication) suggest that a combination of timing (average or earlier) and duration (average or longer) of winter sea ice area is required to produce average to higher winter survival of larval krill. They also note that the positive effects of an early advance and longer than average winter sea ice coverage can be negated by an early sea ice retreat, leaving the larvae with less food and a lower potential for survival. The timing, duration, and magnitude of sea ice may mediate food resources and habitat availability for ovarian development of the female in the spring (Robin Ross and Langdon Quetin, University of California–Santa Barbara, unpublished data) and for larval and juvenile survival the following winter (Langdon Quetin and Robin Ross, University of California–Santa Barbara, personal communication). Thus, evidence is accumulating that for all trophic levels, both the timing and magnitude of the seasonal advance and retreat of sea ice coverage play a critical role when relating sea ice variability to ecosystem response.

Sea ice indexes

It is axiomatic that variability in sea ice has an effect on all levels of the Antarctic marine ecosystem. However, because the ecological impact of sea ice variability is a complex space–time matrix of biology and physical forcing, a single annual index that is fixed in space and time is unlikely to provide an optimum measure of the total variance observed in a population. Instead, a suite of indexes, at relevant spatial and temporal scales, is necessary to quantitatively investigate ice–ecosystem linkages. As we have shown, interannual variability of annual, seasonal, and monthly sea ice coverage is distinct, even among the relatively small subregions of the Antarctic Peninsula (i.e., SP, LTER, NP, WW), emphasizing the importance of identifying the geographic region of influence on the particular marine species under scrutiny. In addition, this area of influence may change seasonally, depending on events such as migration and foraging patterns.

The annual, seasonal, and monthly sea ice indexes presented here are equally applicable to other polar marine ecology studies. For example, Table 2 lists several marine ecology studies that took place in the Antarctic Peninsula region during different years and seasons. Table 2 emphasizes that the sea ice conditions before and during these field programs varied from year to year and from program to program, meaning that significantly different physical forcing took place on the observed ecosystem. A case in point are the three BIOMASS cruises, which all took place during average summer sea ice extent years. However, whereas summer 1981 followed high winter and spring sea ice extent seasons, summer 1984 followed low winter and spring sea ice extent seasons and summer 1985 followed low winter but average spring sea ice extent seasons. Consequently, the BIOMASS observations come from several cruises for which sea ice has preconditioned the environment with significantly different sea ice conditions, both in terms of the magnitude of the previous winter sea ice extent and the timing of the previous spring sea ice retreat. We would expect, therefore, that the effect that the sea ice forcing exerted on the ecosystem under study differed greatly among these three BIOMASS cruises.

By placing observations made from polar marine ecology studies into a broader temporal and spatial reference system of sea ice variability, polar marine ecologists can begin to consistently evaluate the forcing of sea ice variability on the structure and function of the polar marine ecosystem. The Antarctic marine ecosystem is globally significant, yet it has been infrequently studied and is poorly understood compared with more accessible marine ecosystems. In particular, systematic observations linking sea ice concentrations with ecosystem processes are limited and have not generally been placed into a broader temporal context of seasonal and interannual variability. Without an overview of the spatial and temporal variability of sea ice concentration, it has not been possible to quantitatively evaluate the impact of sea ice on the structure and function of the Antarctic marine ecosystem. Our sea ice index permits previous observational programs to be placed into a broader context.

Table 2. Past field studies in the Antarctic Peninsula region in relation to mediating sea ice extent.

Field program	Location	Sea ice extent[a]		
		Season 0[b]	Season 1	Season 2
BIOMASS 1[c]	NP	(sum 81) A	(spr 80) H	(win 80) H
BIOMASS 2	NP	(sum 84) A	(spr 83) L	(win 83) L
BIOMASS 3	NP	(sum 85) A	(spr 84) A	(win 84) L
RACER 1[d]	NP	(sum 87) H	(spr 86) H	(win 86) H
RACER 2	northern LTER	(sum 92) A	(spr 91) A	(win 91) A
BOFS[e]	near SP	(spr 92) L	(win 92) A	(aut 92) H
AMERIEZ 1[f]	northern WW	(spr 83) L	(win 83) L	(aut 83) H
AMERIEZ 2	southern WW	(sum 86) L	(spr 85) L	(win 85) L
AMERIEZ 3	northern WW	(win 88) A	(aut 88) L	(sum 88) L

[a] Seasonal sea ice extent is designated as average (A), high (H), or low (L), as in Figure 3.
[b] Seasons are abbreviated as follows: sum (summer), spr (spring), win (winter), aut (autumn).
[c] Biological Investigations of Marine Antarctic Systems and Stocks (El-Sayed 1994).
[d] Research on Antarctic Coastal Ecosystem Rates (Huntley et. al. 1991).
[e] British Ocean Flux Study (Turner and Owens 1995).
[f] Antarctic Marine Ecosystem Research on Ice Edge Zones (Smith and Garrison 1990).

To provide a common context for other Southern Ocean marine ecological programs, we determined annual curves and seasonal indexes of sea ice variability for all other regions depicted in Figure 2 (Stammerjohn et al. 1997). Ideally, seasonal and interannual variability should be analyzed in the context of long-term variability to distinguish signal from noise and to identify anthropogenic impacts from natural variability. The sea ice record analyzed here is only from October 1978 to September 1995; nevertheless, we identified apparent decadal trends in some of the regional annual index plots of Figure 2 and in the seasonal index plots of Figure 3. In another study analyzing the same sea ice record (Stammerjohn and Smith 1997), increasing trends in sea ice coverage during nonwinter seasons were observed everywhere in the Southern Ocean, except in the Amundsen and Bellingshausen (AB) regions. In the AB regions, by contrast, decreasing trends in sea ice coverage during nonwinter seasons were observed. A decrease in sea ice coverage in the AB regions was first observed by Jacobs and Comiso (1993), who noted a record decrease in sea ice extent, especially in summer sea ice extent, from mid-1988 through early 1991. The record decrease they observed now appears to have been part of a decadal or longer-term trend (Jacobs and Comiso 1997). The Palmer LTER region, a subregion of the Bellingshausen region, shows similar decreasing trends in sea ice extent, sea ice area, and open water amount.

The Palmer LTER is one of a network of LTER sites (Callahan 1984) that addresses both temporal (Magnuson 1990) and spatial (Swanson and Sparks 1990) aspects of long-term ecological research (Likens 1989). The Palmer LTER is ideally located for the investigation of mechanisms linking physical forcing and ecosystem response under significantly different year-to-year climatic conditions. Moreover, having begun in 1991, the Palmer LTER is poised not only to investigate year-to-year differences in sea ice forcing and ecosystem response, but also to place those observations in the context of long-term variability so that scientists can distinguish natural variability from possible anthropogenic impacts. Results from sea ice (Stammerjohn and Smith 1996) and surface air temperature (Smith et al. 1996) climatologies of the western Antarctic Peninsula region, including the Palmer LTER, show the following features: an annual sea ice cycle involving a relatively short period of ice advance (approximately five months) followed by a longer period of ice retreat (approximately seven months), which contrasts with other Southern Ocean regional annual cycles, where ice advance typically is longer than ice retreat; large regional variability, whereby seasonal and annual coefficients of variation are 2–15 times higher than total Southern Ocean variability; significant warming trends in surface air temperatures for summer (+ 1.5 °C) and autumn (+ 4 °C) over the past half-century (1941–1991), in agreement with Stark (1994) and King (1994); significant anti-correlation between surface air temperatures and sea ice extent; long-term persistence in monthly sea ice and surface air temperature anomalies, wherein consecutive high ice–low temperature years are followed by consecutive low ice–high temperature years; and long-term coherence between surface air temperatures and the Southern Oscillation Index (SOI, a measure of the seesaw in sea level pressure differences between the tropical Pacific and Indian Oceans, and an index of El Niño/Southern Oscillation [ENSO] activity).

The causes of sea ice variability and the temporal and spatial scales of influence on the marine ecosystem are topics of ongoing investigation by many polar marine ecologists. Recent observations of physical variability in the Southern Ocean show evidence of an Antarctic Circumpolar Wave (ACW), a disturbance in sea ice extent, sea surface temperature, wind stress, and sea-level pressure (White and Peterson 1996). This study shows that the atmosphere, ocean, and cryosphere are strongly coupled and that ACW moves eastward, taking 8–10 years for circumpolar propagation. Furthermore, evidence that ACW is associated with ENSO activity suggests low-to-high latitude linkages in large-scale atmospheric and oceanic circulation patterns. Other studies have also detected quasi-periodic SOI signals in Southern Ocean sea ice cover (Gloersen 1995, Murphy et al. 1995, Smith et al. 1996).

However, it should be noted that the data used to detect the sea ice trends and ACW began in the late 1970s, which longer-term meteorological records indicate was also the same time during which a regime shift in the southern hemisphere atmospheric circulation took place (van Loon et al. 1993). Thus, whether the ENSO signals are superimposed or coupled to the increasing and decreasing trends observed in the 1978–1995 sea ice record, and whether these trends are due to natural decadal fluctuations or to long-term change, are still unknown (Stammerjohn and Smith 1997). Furthermore, the extent to which oceanic and atmospheric forcing contribute to the opposition observed between the AB regions and the rest of the Southern Ocean is unknown. Finally, because sea ice extent and sea ice area provide different information on the properties of the sea ice environment, ecologists must carefully consider which sea ice variable to use when linking variability in sea ice to changes in the physical or biological environment.

Despite uncertainty in the causes of sea ice variability in the Southern Ocean, the regional trends in sea ice coverage clearly have varying impacts on local marine ecosystems. Because the seasonal progression of sea ice coverage shows considerable interannual variability, both annual timing and magnitude must be considered when evaluating how changes in sea ice coverage affects the Antarctic marine ecosystem. Thus, to summarize sea ice variability, such as through defining sea ice indexes, a variety of temporal scales, ranging from coarse (annual) to fine (monthly) must be considered. The appropriate spatial scale also must be defined based on the geographic region of physical influence, while keeping in mind seasonal changes in distribution patterns within the ecosystem. Once suitable sea ice indexes are identified, they provide a quantitative, consistent definition of the timing and magnitude of sea ice coverage on scales that are relevant to ice–ecosystem dynamics. Finally, sea ice indexes also provide a common context for intercomparison, both within as well as among polar marine ecological studies.

Acknowledgments

This work was funded by the National Science Foundation (grant no. DPP90-11927). The National Snow and Ice Data Center, of Boulder, Colorado, provided the SMMR and SSM/I sea ice concentration data. This article is Palmer LTER contribution no. 127.

References cited

Ackley SF, Sullivan CW. 1994. Physical controls on the development and characteristics of Antarctic sea ice biological communities—A review and synthesis. Deep-Sea Research 41: 1583–1604.

Callahan JT. 1984. Long-term ecological research. BioScience 34: 363–367.

Cavalieri DJ, Campbell WJ, Gloersen P. 1984. Determination of sea ice parameters with the NIMBUS 7 SMMR. Journal of Geophysical Research 89: 5355–5369.

Cavalieri DJ, St. Germain KM, Swift CT. 1995. Reduction of weather effects in the calculation of sea ice concentration with the DMSP SSM/I. Journal of Glaciology 41: 455–461.

Christian JR, Karl DM. 1994. Palmer LTER: Relative activities of several bacterial exoenzymes in the western Antarctic Peninsula during austral summer: Evidence of sea ice influence on pelagic bacterial communities. Antarctic Journal of the United States 29: 212–214.

Clarke A, Holmes LJ, White MG. 1988. The annual cycle of temperature, chlorophyll and major nutrients at Signy Island, South Orkney Islands, 1969–82. British Antarctica Survey Bulletin 80: 65–86.

Comiso JC, Grenfell TC, Lange M, Lohanick AW, Moore RK, Wadhams P. 1992. Microwave remote sensing of the Southern Ocean ice cover. Pages 243–259 in Carsey FD, ed. Microwave Remote Sensing of Sea Ice. Vol. 68. Washington (DC): American Geophysical Union.

Comiso JC, Cavalieri D, Parkinson C, Gloersen P. 1997. Passive microwave algorithms for sea ice concentration—A comparison of two techniques. Remote Sensing of Environment 60: 357–384.

Davis LS, Boersma PD, Court GS. 1996. Satellite telemetry of the winter migration of Adélie penguins (*Pygoscelis adeliae*). Polar Biology 16: 221–225.

El-Sayed SZ, ed. 1994. Southern Ocean Ecology: The BIOMASS Perspective. New York: Cambridge University Press.

Emery WJ, Fowler C, Maslanik J. 1994. Arctic sea ice concentrations from Special Sensor Microwave Imager and Advanced Very High Resolution Radiometer satellite data. Journal of Geophysical Research 99: 18329–18342.

Fraser WR, Trivelpiece WZ, Ainley DG, Trivelpiece SG. 1992. Increases in Antarctic penguin populations: Reduced competition with whales or a loss of sea ice due to environmental warming? Polar Biology 11: 525–531.

Gloersen P. 1995. Modulation of hemispheric sea-ice cover by ENSO events. Nature 373: 503–506.

Gloersen P, Cavalieri DJ. 1986. Reduction of weather effects in the calculation of sea ice concentrations from microwave radiances. Journal of Geophysical Research 91: 3913–3919.

Gloersen P, Campbell WJ, Cavalieri DJ, Comiso JC, Parkinson CL, Zwally HJ. 1992. Arctic and Antarctic sea ice, 1978–1987: Satellite passive microwave observations and analysis. Washington (DC): National Aeronautics and Space Administration. Publication no. NASA SP-511.

Hunt GL. 1991. Marine birds and ice-influenced environments of polar oceans. Journal of Marine Systems 2: 233–240.

Huntley ME, Karl DM, Niiler PP, Holm-Hansen O. 1991. Research on Antarctic Coastal Ecosystem Rates (RACER): An interdisciplinary field experiment. Deep-Sea Research 38: 911–941.

Jacobs SS, Comiso JC. 1993. A recent sea-ice retreat west of the Antarctic Peninsula. Geophysical Research Letters 20: 1171–1174.

______. 1997. Climate variability in the Amundsen and Bellingshausen Seas. Journal of Climate 10: 697–709.

Karl D, Christian JR, Dore JE, Letelier RM. 1996. Microbiological oceanography in the region west of the Antarctic Peninsula: Microbial dynamics, nitrogen cycle and carbon flux. Pages 303–332 in Ross RM, Hofmann EE, Quetin LB, eds. Foundations for Ecological Research West of the Antarctic Peninsula. Antarctic Research Series. Vol. 70. Washington (DC): American Geophysical Union.

King JC. 1994. Recent climate variability in the vicinity of the Antarctic Peninsula. International Journal of Climatology 14: 357–369.

Likens GE, ed. 1989. Long-Term Studies in Ecology: Approaches and Alternatives. New York: Springer-Verlag.

Magnuson JJ. 1990. Long-term ecological research and the invisible present. BioScience 40: 495–501.

Murphy EJ, Clarke A, Symon C, Priddle JJ. 1995. Temporal variation in Antarctic sea-ice: Analysis of a long term fast-ice record from the South Orkney islands. Deep-Sea Research 42: 1045–1062.

Parkinson CL. 1992. Interannual variability of monthly southern ocean sea ice distribution. Journal Geophysical Research 97: 5349–5363.

______. 1994. Spatial patterns in the length of the sea ice season in the Southern Ocean, 1979–1986. Journal of Geophysical Research 99: 16327–16339.

Quetin LB, Ross RM, Clarke A. 1994. Krill energetics: Seasonal and environmental aspects of the physiology of *Euphausia superba*. Pages 165–184 in El-Sayed SZ, ed. Southern Ocean Ecology: The BIOMASS Perspective. New York: Cambridge University Press.

Quetin LB, Ross RM, Frazer TK, Haberman KL. 1996. Factors affecting distribution and abundance of zooplankton, with an emphasis on Antarctic krill, *Euphausia superba*. Pages 357–371 in Ross RM, Hofmann EE, Quetin LB, eds. Foundations for Ecological Research West of the Antarctic Peninsula. Antarctic Research Series. Vol. 70. Washington (DC): American Geophysical Union.

Ross RM, Quetin LB. 1991. Ecological physiology of larval euphausiids, *Euphausia superba* (Euphausiacea). Memoirs of the Queensland Museum 31: 321–333.

Ross RM, Hofmann EE, Quetin LB, eds. 1996. Foundations for Ecological Research West of the Antarctic Peninsula. Antarctic Research Series. Vol. 70. Washington (DC): American Geophysical Union.

Siegel V, Loeb V. 1995. Recruitment of Antarctic krill *Euphausia superba* and possible causes for its variability. Marine Ecology Progress Series 123: 45–56.

Smetacek V, Scharek R, Nothig EM. 1990. Seasonal and regional variation in the pelagial and its relationship to the life history cycle of krill. Pages 103–114 in Kerry KR, Hempel G, eds. Antarctic Ecosystems: Ecological Change and Conservation. Berlin: Springer-Verlag.

Smith RC, et al. 1995. The Palmer LTER: A long-term ecological research program at Palmer Station, Antarctica. Oceanography 8: 77–86.

Smith RC, Stammerjohn S, Baker KS. 1996. Surface air temperature variations in the western Antarctic peninsula region. Pages 105–121 in Ross RM, Hofmann EE, Quetin LB, eds. Foundations for Ecological Research West of the Antarctic Peninsula. Antarctic Research Series, Vol. 70. Washington (DC): American Geophysical Union.

Smith RC, Baker KS, Byers ML, Stammerjohn SE. In press. Primary productivity of the Palmer Long Term Ecological research area and the Southern Ocean. Journal of Marine Systems.

Smith WO, Garrison DL. 1990. Marine ecosystem research at the Weddell Sea ice edge: The AMERIEZ Program. Oceanography 3: 22–29.

Smith WO, Nelson DM. 1986. Importance of ice edge phytoplankton production in the Southern Ocean. BioScience 36: 251–257.

Stammerjohn S, Smith RC. 1996. Spatial and temporal variability of western Antarctic peninsula sea ice coverage. Pages 81–104 in Ross RM, Hofmann EE, Quetin LB, eds. Foundations for Ecological Research West of the Antarctic Peninsula. Antarctic Research Series Vol. 70. Washington (DC): American Geophysical Union.

______. 1997. Opposing Southern Ocean climate patterns as revealed by trends in regional sea ice coverage. Climatic Change 37: 617–639.

Stammerjohn S, Baker KS, Smith RC. 1997. Sea ice indexes for Southern Ocean regional marine ecology studies. La Jolla (CA): University of California at San Diego, Scripps Institution of Oceanography. Report no. SIO Ref. 97-01.

Stark P. 1994. Climatic warming in the central Antarctic Peninsula area. Weather 49: 215–220.

Steele JH. 1991. Can ecological theory cross the land-sea boundary? Journal of Theoretical Biology 153: 425–436.

Swanson FJ, Sparks RE. 1990. Long-term ecological research and the invisible place. BioScience 40: 502–508.

Trathan PN, Croxall JP, Murphy EJ. 1996. Dynamics of Antarctic penguin populations in relation to interannual variability in sea ice distribution. Polar Biology 16: 321–330.

Trivelpiece W, Fraser W. 1996. The breeding biology and distribution of Adélie penguins: Adaptations to environmental variability. Pages 273–285 in Ross RM, Hofmann EE, Quetin LB, eds. Foundations for Ecological Research West of the Antarctic Peninsula. Antarctic Research Series. Vol. 70. Washington (DC): American Geophysical Union.

Turner DR, Owens NJP. 1995. A biogeochemical study in the Bellingshausen Sea: Overview of the STERNA 1992 expedition. Deep-Sea Research 42: 907–932.

van Loon H, Kidson JW, Mullan AB. 1993. Decadal variation of the annual cycle in the Australian dataset. Journal of Climate 6: 1227–1231.

Waters KJ, Smith RC. 1992. Palmer LTER: A sampling grid for the Palmer LTER program. Antarctic Journal of the United States 27: 236–239.

White WB, Peterson RG. 1996. An Antarctic circumpolar wave in surface pressure, wind, temperature and sea-ice extent. Nature 380: 699–702.

Zwally HJ, Comiso JC, Parkinson CL, Campbell WJ, Carsey FD, Gloersen P. 1983. Antarctic Sea Ice, 1973–1976: Satellite Passive-Microwave Observations. Washington (DC): National Aeronautics and Space Administration. Publication no. NASA SP-459.