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AREAL AND SEASONAL EXTENT OF SEA-ICE COVER OFF THE NORTHWESTERN SIDE OF THE ANTARCTIC PENINSULA: 1979 TO 1996

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Abstract

Analysis of seasonal sea-ice cover of an area measuring 1.25 x 10^6 km^2 off the northwestern side of the Antarctic Peninsula indicates that there were four periods of extensive ice cover during the last 18 years. Variability in seasonal timing, areal extent, seasonal duration and persistence of sea-ice over multiple years is apparent and is consistent with features described by Stammerjohn and Smith (1996) for ice cover in the Bellingshausen Sea. Periods of extensive winter ice cover peaked in 1980, 1986, 1991 and 1995 and were foreshadowed by the late retreat of ice during the springs of 1985, 1990 and 1994. Ice cover during the summer months and winter ice cover during years between periods of extensive ice cover decreased during the second half of the time series. Maximum ice cover during the periods of extensive ice cover did not change. Annual curves of sea-ice cover were integrated over time to produce an annual index of sea-ice cover in units of 10^6 km^2/month. This index may be used in conjunction with studies of variability in biological production, particularly the reproductive success of Antarctic krill, in the Antarctic Peninsula area.

Résumé

L'analyse de la couverture saisonnière de glace de mer d'un secteur de 1.25 x 10^6 km^2 au large de la partie nord-ouest de la péninsule Antarctique met en évidence pour ces 18 dernières années quatre périodes de glaces marines d'une très grande superficie. La variabilité des glaces de mer sur plusieurs années est évidente en ce qui concerne leur apparition au cours de la saison, leur étendue, leur durée pendant cette saison et leur persistance, et concorde avec les caractéristiques de la couverture de glace dans la mer Bellingshausen décrites par Stammerjohn et Smith (1996). Les périodes de couverture de glace d'hiver les plus prononcées correspondaient à 1980, 1986, 1991 and 1995 et étaient prévisibles vu le retrait tardif des glaces durant les printemps 1985, 1990 et 1994. La couverture de glace, qu'il s'agisse de celle des mois d'été, ou bien de celle d'hiver les années séparant les périodes de couverture extrême, a diminué au cours de la deuxième partie de la série chronologique. La couverture de glace maximale durant les périodes de couverture extrême n'a pas changé. Les courbes annuelles de la couverture de glace de mer ont été intégrées au cours du temps en vue de produire un indice annuel en unités de 10^6 km^2/mois. Cet indice peut être utilisé parallèlement aux études de la variabilité de la production biologique, notamment la réussite de la reproduction du krill antarctique, dans le secteur de la péninsule Antarctique.

Резюме

Результаты анализа сезонного распространения морксого льда в районе площадью 1,25 x 10^6 км^2 к северо-западу от Антарктического полуострова указывают на то, что за последние 18 лет имели место четыре периода обширного ледяного покрова. Отмечена изменчивость сроков и площади ледяного покрова, а также продолжительность и постоянство присутствия морского льда в разные годы, что согласуется с выводами Стаммерджон и Смита (1996), касающимися особенностей ледяного покрова в море Беллинсгаузена. Периоды обширного зимнего ледяного покрова достигали максимумов в 1980, 1986, 1991 и 1995 гг., о чем можно было судить по позднему отступлению льда весной 1985, 1990 и 1994 гг. Летний и зимний ледяной покров в период между периодами обширного ледяного покрова снижался во второй половине временного ряда. Максимальная протяженность ледяного покрова в течение периодов обширного ледяного покрова не изменялась. Годовые кривые распространения морского льда были интегрированы по времени с целью получения годового индекса протяженности ледового покрова, выражаемого в единицах 10^6 км²/месяц. Этот индекс можно использовать в исследованиях изменчивости биологической продуктивности (в особенности репродуктивного успеха антарктического криля) в районе Антарктического полуострова.

Resumen

El análisis de la cubierta de hielo de un área de 1.25 x 10^6 km² frente a la costa noroeste de la Península Antártica en distintas estaciones indica que en los últimos 18 años hubo cuatro períodos cuando la cubierta de hielo fue extensa. Se ha podido comprobar una gran variabilidad en el inicio, duración, extensión y persistencia de la cubierta de hielo en varios años, lo que concuerda con la descripción de Stammerjohn y Smith (1996) de la cubierta de hielo del Mar de Bellingshausen. En las primaveras de 1985, 1990 y 1994 se dieron períodos tardíos de retroceso del hielo, que presagiaron los períodos de cubierta máxima de hielo invernal de 1980, 1986, 1991 y 1995. La cubierta de hielo durante los meses de verano e invierno disminuyó en la segunda mitad de la serie cronológica en los años transcurridos entre los períodos de cubierta máxima de hielo. No hubo variación en la cubierta máxima de hielo durante los períodos cuando la cubierta de hielo fue extensa. Se efectuaron integraciones de las curvas anuales de la cubierta del hielo marino en función del tiempo para producir un índice anual de la cubierta del hielo marino en unidades de 10^6 km²/mes. Este índice puede ser utilizado en estudios de la variabilidad de la producción biológica, en particular el éxito reproductor del kril antártico, en el área de la Península Antártica.

Keywords: Antarctic Peninsula, sea-ice, time series, CCAMLR

INTRODUCTION

Several authors have suggested relationships between seasonal sea-ice cover in the Antarctic Peninsula area and primary, secondary and tertiary production (Fraser et al., 1992; Siegel and Loeb, 1995; Fraser and Trivelpiece, 1996; Loeb et al., in press). These suggestions followed comments by many other authors on the importance of sea-ice habitats and dynamics to biological processes, based on studies conducted in both hemispheres (e.g. Smith and Nelson, 1985; Ainley et al., 1986; Smith and Vidal, 1986; Walsh and McRoy, 1986; Kottmeier and Sullivan 1987; Smith et al., 1988; Hunt, 1991).

Fraser et al. (1992) used a correlation between the ice edge, as defined in charts of sea-ice cover produced by the US Navy-NOAA Joint Ice Center (JIC), and surface air temperatures to infer sea-ice cover back to 1944. Ice concentration data published by the US National Snow and Ice Data Center (NSIDC) were used by Siegel and Loeb (1995) to index weekly ice concentrations at two locales near the South Shetland archipelago as part of a study of the causes of variability in the recruitment of Antarctic krill (*Euphausia superba*).

Although Siegel and Loeb (1995) demonstrated significant correlations between krill reproduction, survival at early-life stages and sea-ice cover, the indices of ice cover were based on a set of locations and may not have represented events occurring throughout the Antarctic Peninsula area. Siegel (1988) and Siegel and Loeb (1995) describe a model of ontogenetic movement of krill along the western side of the Antarctic Peninsula: in the spring juvenile krill move with the prevailing current in a northeasterly direction along the western side of the peninsula from nearshore protected waters into the vicinity of the South Shetland Islands which form a barrier along the northwestern side of the peninsula; they are joined by maturing adult krill moving in a northeasterly direction along the seaward side of the South Shetland Islands from the Bellingshausen Sea. In order to complement summertime studies of krill demographics in the vicinity of the South Shetland Islands, an improved ice index would thus need to reflect seasonal ice cover upstream in the Bellingshausen Sea. These studies are expected to continue in the future under the sponsorship of the US Antarctic Marine Living Resources (AMLR) program. To be useful, the index should be easily calculated from readily available data, thus allowing updates to the index time series as new data become available.

The index described here follows the work of Stammerjohn (1993), who used microwave imagery to describe the spatial and temporal variability of sea-ice in the Southern Ocean. Stammerjohn and Smith (1996) described the variability in sea-ice cover for several regions in the western Antarctic from October 1978 to August 1994, including the Long Term Ecological Research (LTER) survey grid off the western side of the Antarctic Peninsula. This paper makes use of the same data sources to derive an index of ice cover for a larger area, encompassing the LTER study area, off the northwestern side of the Antarctic Peninsula and extends the time series through 1996.

It is hypothesised that the seasonal and spatial extent of sea-ice cover influence the structure of the zooplankton community as well as the reproductive success of krill (Loeb et al., 1997). A single index is proposed to describe the temporal and spatial variability of sea-ice cover between years. It is anticipated that the annual index may be easily updated with new data, facilitate correlations with biological processes, and contribute to predictive models.

MATERIALS AND METHODS

Satellite images of sea-ice concentrations derived from passive microwave radiometer data were used as data sources. The images, published electronically by the NSIDC*, were derived from data on daily average temperature brightness using the so-called NASA Team algorithm (Cavalieri et al., 1984). Images were derived by Gloersen et al. (1992) from data collected by the Scanning Multichannel Microwave Radiometer (SMMR) from October 1978 to August 1987. Images were derived by NSIDC from data collected by the Special Sensor Microwave/Imager (SSM/I) from July 1987 to December 1996. Comparison of ice concentrations estimated from SMMR and SSM/I data during two months of sensor overlap in 1987 indicated differences of less than 1% (Gloersen et al., 1992). Images were projected in polar stereographic format. Grid size was constant for the entire period with nominal pixel size set to 25 km x 25 km.

Images were subsampled for an area of 40 x 50 pixels (1.25×10^6 km^2) centred on the northwestern side of the Antarctic Peninsula (Figure 1). Most of this area is within the Bellingshausen sector of the Southern Ocean as defined by Stammerjohn (1993). The Bellingshausen sector was shown to have a high degree of homogeneity with respect to interannual variability in ice coverage (Stammerjohn and Smith, 1996). Pixel statistics were derived for each subsampled image, and ice cover was estimated as the total number of pixels minus those coded for land, open water and missing data. Open water was defined as less than 15% ice concentration, and includes areas inside and outside the contour defining the most seaward extent of sea-ice.

Using the SMMR data series, images were selected as close as possible to the middle day of each month. Images were rejected when areas of missing data impinged on the ice cover and thus would bias calculations. Using the SSM/I data series, monthly averaged images were used and missing data were therefore not a problem. Slightly different land-contour masks were used between the data series, but the discrepancy was less than 1.5% of the total area.

Annual curves of sea-ice cover were drawn from monthly estimates for each year (Figure 2). The area under the curve was estimated by numerical integration in units of 10^6 km^2-months in order to produce an annual index of the areal and seasonal extent of sea-ice cover (I_i):

$$I_i = 0.25\left(A_{i-1,12} + A_{i+1,1}\right) + 0.75\left(A_{i,1} + A_{i,12}\right) + \sum_{j=2}^{11} A_{i,j}$$

where $A_{i,j}$ is ice cover within the subsampled area in km^2 during the ith year and jth month.

RESULTS AND DISCUSSION

The Bellingshausen Sea is unique among the various sectors of the Southern Ocean in that variability in sea-ice cover shows long-term persistence of several months to years (Stammerjohn and Smith, 1996). This is evident in Figure 3, which describes the seasonal variability in sea-ice cover over the subsampled area in a time series from 1979 to 1996. When ice cover is contoured over a matrix of months versus years, four periods of extensive ice cover are evident. The first period peaked in August 1980 and was more extensive seasonally and temporally between years relative to the other four periods. The second peaked in August–September 1986; the ice did not fully retreat during the following summer and in 1987 ice cover peaked in July–August, a month earlier than the preceding year. The third period peaked in June–July 1991

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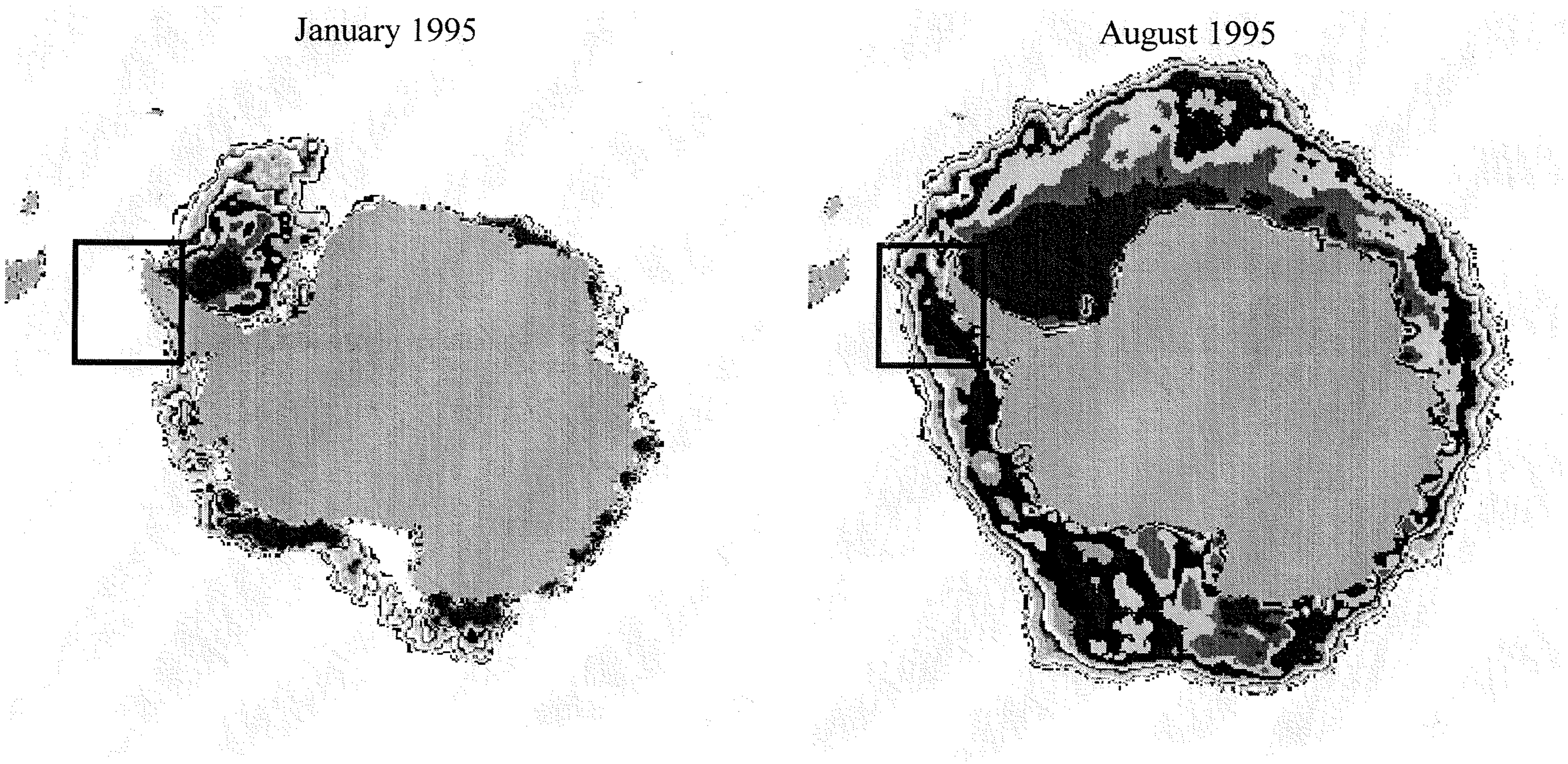

Figure 1: Sea-ice cover in January and August 1995 derived from SSM/I passive microwave radiometer data. Box delineates area of 40 x 50 pixels subsampled from images of sea-ice cover.

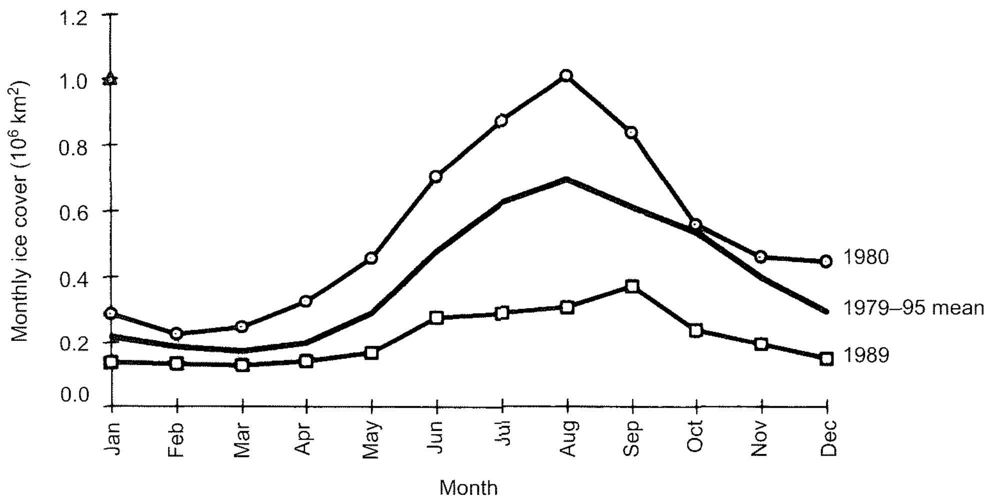

Figure 2: Annual curves of sea-ice cover for 1980, 1989 and 1979–96 mean.

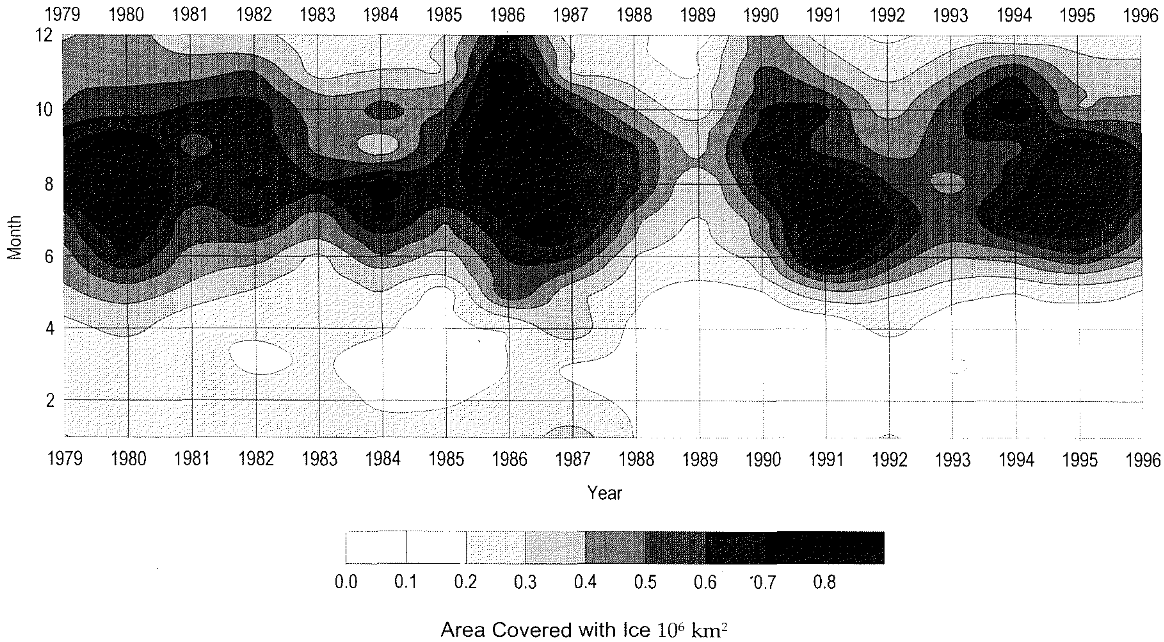

Figure 3: Areal and seasonal extent of sea-ice cover off the northwestern side of the Antarctic Peninsula, 1979 to 1996.

and was preceded by a late retreat of the ice following the winter of 1990. The fourth peaked in August 1995 and was also characterised by a late retreat of ice following the preceding winter in 1994.

During each of these periods more than 65% (0.8×10^6 km^2) of the subsampled area was covered with sea-ice for at least one month. Although there does not appear to be a trend in the total area cover by sea-ice during its maximum extent between the four periods, at least two differences between the first and second halves of the time series are apparent. First, ice cover during the summer months was lower during the latter part of the time series: over the period 1988 to 1996 ice cover during the late summer was consistently less than 8% (0.1×10^6 km^2), whereas ice cover was less than 8% during only two summers (in 1984 and 1985) within the time period 1979 to 1987. Second, the maximum ice cover during the winters between extensive ice periods was lower during the latter part of the time series: maximum ice cover during winters between the last three periods of extensive ice cover never exceeded 50% (0.6×10^6 km^2), whereas maximum ice cover was greater than 50% during all of the winters between the first two periods.

Annual estimates of the seasonal and areal extent of sea-ice cover in units of 10^6 km^2-months reflect the four periods of extensive ice described above (Table 1, Figure 4). It is suggested that these values be used as a single index of ice cover for the area off the northwestern side of the Antarctic Peninsula. The peak value of the index during the last three extensive ice periods (1987, 1991 and 1995) has declined. This reflects that although the maximum extent of the ice during winter has varied little between these years, the seasonal duration of extensive ice cover has declined and the area with little or no ice during the summer has increased.

Table 1: Annual estimates of the areal and seasonal extent of sea-ice cover determined by numerical integration of annual curves similar to Figure 2.

Year	Annual Ice Cover Index (10^6 km^2-months)
1979	5.29
1980	6.43
1981	4.90
1982	5.12
1983	3.90
1984	4.48
1985	4.15
1986	6.77
1987	5.78
1988	3.76
1989	2.56
1990	4.35
1991	5.33
1992	4.27
1993	3.91
1994	4.86
1995	5.08
1996	4.02

These findings confirm much more extensive analyses conducted by Stammerjohn (1993) and reported by Stammerjohn and Smith (1996). They describe long-term persistence in monthly ice-cover anomalies in the Bellingshausen Sea such that a cyclical trend is apparent between consecutive high-ice years followed by several consecutive low-ice years. They suggest a periodicity of five to eight years in ice cover and note a five-year periodicity apparent in the air temperature record over the last 50 years at Faraday Station located on the Antarctic Peninsula, which is significantly anticorrelated with the ice-cover time series (Smith et al., 1996). Smith et al. (1996) also report a significant anticorrelation of ice cover in the LTER area with the Southern Oscillation Index.

Stammerjohn and Smith (1996) note an asymmetry in the annual ice cycle, also unique in the Bellingshausen Sea among sectors in the Southern Ocean, where the ice advance in autumn is more rapid than ice retreat in spring. This is apparent in the mean monthly ice cover for the subsampled area used in this study (Figure 2). Stammerjohn and Smith (1996) discuss various factors that may cause the asymmetry and suggest that advection of ice into the area during autumn may accelerate the expansion of sea-ice and that melting of ice in place rather than advection of ice out of the area may slow the retreat of ice during spring. This may be complemented by northerly meridional transport northwest of the Antarctic Peninsula during autumn and southward meridional transport during spring as described by Harangozo (1994). Stammerjohn and Smith (1996) also note that the southern portion of the LTER study area experiences the most consistent

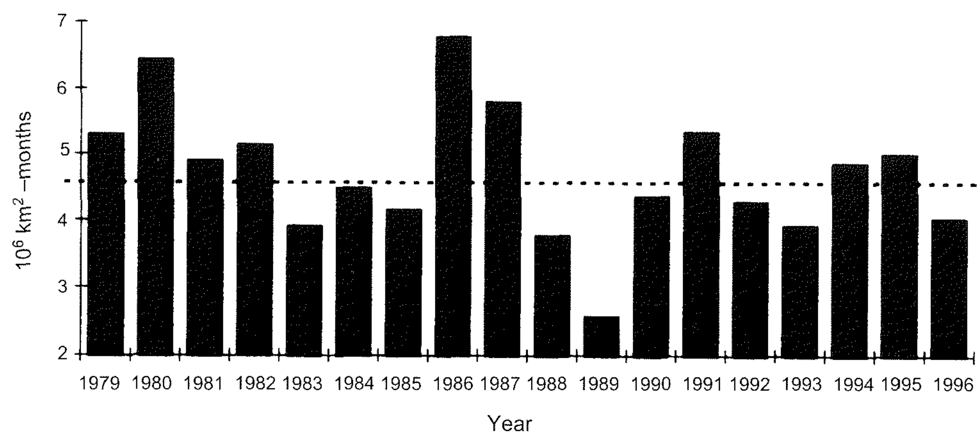

Figure 4: Annual estimates of the areal and seasonal extent of sea-ice cover determined by numerical integration of annual curves similar to Figure 2. Dotted line indicates mean value.

ice cover, whereas interannual variability is much greater in the area to the northeast where coastal polynyas were often detected. They suggest that the intrusion of relatively warm, saline Circumpolar Deep Water (CDW) onto the shelf (as described by Hoffman et al., 1996) may contribute to the formation of nearshore polynyas and moderating both sea-ice production and climate. The last three periods of extensive ice cover were preceded by higher-than-average ice cover during the previous spring. Thus it would appear that the factors postulated to affect the springtime retreat of ice may also affect the expansion of sea-ice during the following winter. This effect seems to be mostly on the extent of the area covered by ice rather than its seasonal timing.

While the annual index of sea-ice cover proposed here combines both area and seasonal extent, it may not capture some aspects of sea-ice dynamics that could be important to biological production. Small leads and polynyas are not detected with the coarse-resolution (25 km) images produced with passive microwave sensors. Stammerjohn and Smith (1996) compared high-resolution visible images with microwave images obtained for similar time periods and showed that the microwave data tended to overestimate ice cover for low-to-moderate ice concentrations. The visible images that they published showed numerous leads, polynyas and diffuse marginal ice zones that may profoundly affect net primary and secondary production; these were not described by the microwave imagery. These features may be particularly important during the spring retreat of ice which appears to be slower and more sporadic than the expansion of ice in autumn: judging from the monthly images, ice cover appeared to retreat then advance and retreat again during 1981, 1984, 1991, 1993 and 1994. Even more complex dynamics are apparent in the daily images. Unfortunately, cloud cover limits the use of most of the visible imagery and sea-ice concentrations derived from passive microwave radiometry are currently the only viable option for assembling a time series of ice cover in the Antarctic Peninsula area.

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CONCLUSION

Four cycles of extensive and weak winter sea-ice development off the northwestern side of the Antarctic Peninsula are apparent in a time series of average monthly sea-ice cover from 1979 to 1996. Maximum ice cover during the periods of extensive ice cover did not change, however ice cover during the summer months and winter ice cover during years between periods of extensive ice cover decreased during the second half of the time series. An annual index is proposed that combines measures of both the areal and the seasonal extent of sea-ice in the region. The estimates of ice cover are derived from relatively coarse resolution imagery and do not reflect small-scale features in the ice cover that, in the aggregate, may affect net primary and secondary production. This may be important relative to processes occurring during the spring retreat of the ice, which appears to be a precursor to the extent of sea-ice development during the following winter.

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