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Variability of Antarctic Sea Ice and Changes in Carbon Dioxide

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The possible consequences of a CO_2-induced warming of the atmosphere have been examined extensively (*1–6*), leading to considerable interest in detecting early climatic changes that may be caused by increases in CO_2 or other anthropogenic trace gases (*7, 8*) in the atmo-

Summary. A definitive long-term decrease in the extent of antarctic sea ice is not detectable from 9 years (1973 to 1981) of year-round satellite observations and limited prior data. Regional interannual variability is large, with sea ice decreasing in some regions while increasing in others. A significant decrease in overall ice extent during the mid-1970's, previously suggested to reflect warming induced by carbon dioxide, has not been maintained. In particular, the extent of ice in the Weddell Sea region has rebounded after a large decrease concurrent with a major oceanographic anomaly, the Weddell polynya. Over the 9 years, the trends are nearly the same in all seasons, but for periods of 3 to 5 years, greater winter ice maxima are associated with lesser summer ice minima. The decrease of the mid-1970's was preceded by an increase in ice extent from 1966 to 1972, further indicating the presence of cyclical components of variation that obscure any long-term trends that might be caused by a warming induced by carbon dioxide.

sphere. Modeling studies suggest that a CO_2-induced climatic change would include a polar warming several times the global average warming (*9*), which has been variously estimated to be from 1 to 4 K for a doubling in CO_2 (*5, 9–12*). Hence, the predicted change in polar atmospheric temperature is large and a response to increased CO_2 may be noticeable in the polar regions earlier than in the tropics or mid-latitudes (*1, 11*). However, there are suggestions that the natural variability is larger in the polar regions and the signal-to-noise ratio lower than in the mid-latitudes (*13*). In any event, the predicted amplification of the atmospheric temperature response in polar regions is largely dependent on the change in albedo resulting from the reduction in sea ice cover, and the extent of sea ice is an important variable to observe and analyze.

Although the sensitivity of antarctic sea ice to a change in atmospheric temperature is not well known, an empirical analysis at one location suggests a sensitivity of the meridional ice extent as large as 2.5 degrees of latitude per Kelvin (*14*). This sensitivity implies that a 1 K change in surface air temperature at high latitudes would produce a change in sea ice area of approximately 5×10^6 km^2 (a 40 percent change in mean area, or a change in the average meridional extent of 275 km). Although other studies suggest that the sensitivity is generally not this great (*15, 16*), a very large change in the extent of sea ice should accompany an atmospheric temperature change of the magnitude predicted for CO_2 increases.

Recently, Kukla and Gavin (*17*) reported a decrease in the extent of antarctic sea ice in summer of about 2.5×10^6 km^2 and suggested that the decrease might reflect a CO_2-induced warming of the atmosphere. They did not, however, find similar changes in sea ice or snow cover in the Northern Hemisphere. Thompson and Schneider (*18*) concluded that the significance of these and other results is too small to proclaim detection of a CO_2-induced warming.

Since our present knowledge of the natural variability of sea ice cover is limited and since there are significant regional differences in ice variations, further analysis of possible trends in the data is needed. In particular, the suggestion by Kukla and Gavin (*17*) of a long-term decrease in the extent of summer ice was strongly influenced by the mid-1970's decrease of sea ice in the vicinity of the Weddell polynya (around 0°E). Their suggestion was largely based on a comparison with ship reports from the 1930's in the South Atlantic between 60°W and 90°E. While 85 percent of the ship-based observations of the ice edge between 60°W and 90°E during 1929 to 1938 were north of the 1973–1980 mean ice edge, only 58 percent of the other ice-edge observations around the continent were north of the recent mean. Furthermore, the 1973–1980 mean is not necessarily representative of recent ice extent, because recent data show that the mid-1970's decrease in the Weddell region was temporary. On a longer time scale, 5 of the 11 observations of ice extent from the 18th and 19th centuries reported by Kukla and Gavin were less than the mean ice extent for the 1970's and six were greater, suggesting comparable ice extents during the two periods. Other evidence from limited satellite observations (*19–21*) in the 7 years before 1973 indicate that the total extent of antarctic sea ice actually increased during those years before decreasing in the mid-1970's.

Our primary concern centers on the variability of antarctic sea ice and on whether the available data show a definite long-term trend. Clearly, the natural variability of the ice cover must be considered in attempts to detect any long-term trend attributable to a CO_2-induced

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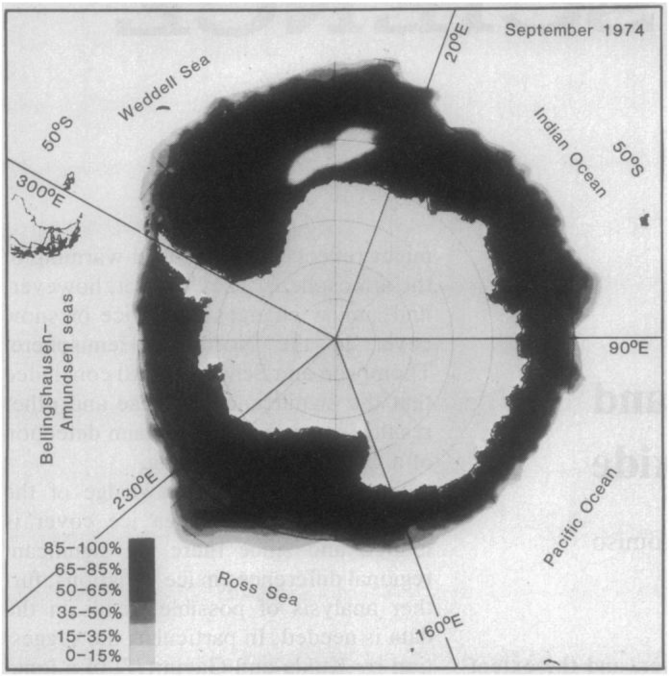


Fig. 1. Average ice concentrations for September 1974, as derived from Nimbus 5 passive microwave data. The Weddell polynya is visible at 0°E, 67°S.

climatic warming. Observed ice fluctuations could be within the natural variability of sea ice and unrelated to changes in CO_2 or other anthropogenic trace gases. In this article we compare two sources of sea ice data from satellite observations for 1973 to 1976, describe the regional and interannual variability of the antarctic sea ice from 1973 through 1981 on a seasonal basis, and examine the data for possible trends in ice extent.

We found that a definitive decrease in antarctic sea ice is not detectable from 9 years of year-round satellite data (1973 to 1981) and limited prior data. Regional variability in ice extent is large, with ice decreasing in some regions while increasing in others. In general, the extent of ice in the southern ocean did decrease substantially from 1973 through 1977, but this decrease was partly a relaxation from the increases in the preceding years, and from 1977 through 1981 the ice cover rebounded. Regionally, the strong decrease in sea ice from 1973 to 1977 in the Weddell Sea was concurrent with the formation of the Weddell polynya (Fig. 1), and since 1977 the ice extent there has recovered to the 1973 level. Changes in total ice extent occurred in all seasons, but the similarity among seasons depends on the time scale of the comparison.

Sea Ice Extent and Concentration

Sea ice extent, which is defined as the area of ocean at least 10 to 15 percent of which is covered by ice, is widely used in describing sea ice coverage. The percentage of a given area of ocean covered by ice is called the sea ice concentration. Although various values of minimum sea ice concentration (such as 10, 12, or 15 percent) are used to define ice extent, the differences are not significant because the concentration usually increases from 10 percent to more than 15 percent less than 10 km from the ice edge. Furthermore, most methods of determining sea ice concentration are less accurate than these differences in definition.

A more meaningful parameter than ice extent is the actual ice area, which is obtained by excluding the area of open water due to leads and polynyas. However, reliable data on ice concentration, which is needed to calculate ice area, are not as extensive as the data on ice extent. Although there are short-term differences between variations in actual ice area and variations in ice extent, the trends of these two parameters over 4 years of detailed analysis are very similar (*22*). Therefore, the longer record of sea ice extent is adequate for analysis of long-term variations in sea ice coverage.

As with other climatic parameters, such as atmospheric temperature, sea ice extent exhibits substantial interannual variations that differ from one region to another. Furthermore, increases in ice coverage in one region are sometimes compensated by decreases elsewhere (*22–25*), and decreases during winter are not necessarily followed by similar decreases during summer (*25*). Although changes in atmospheric temperature and circulation are related to changes in sea ice cover (*24, 26–28*), the interactive physical processes are complex and the total response of sea ice to a specific change in atmospheric temperature is not well determined. Also, the sea ice response may differ substantially from one region to another because of regional differences in the relative importance of changes in atmospheric temperature, circulation, oceanic parameters, and radiation balance. Because some models (*5, 11*) indicate that a warming induced by CO_2 should have seasonal characteristics, corresponding seasonal differences in sea ice changes may be expected (*4, 17*). Another potentially important seasonal factor, for example, is that a spring decay of the ice that is early by only several weeks would significantly increase the heat absorbed by the ocean during the period when solar insolation is approaching its annual maximum (*29*). Increased heat in the upper layers of the ocean could affect the ice cover in subsequent seasons. Consequently, it is important to examine the total variability of the antarctic sea ice on a regional and seasonal basis in an attempt to identify consistent overall behavior or specific behavior that can be related to changes in the climatic system.

Data Sources

Microwave observations. Sea ice concentrations have been derived from the Nimbus 5 electrically scanning microwave radiometer (ESMR) with an estimated accuracy of 15 percent (*22, 30*). The ability to derive ice concentration from passive microwave imagery stems from the sharp contrast between microwave emissivities for sea ice (0.80 to 0.95) and seawater (0.40) (*31*). ESMR data on microwave emissions at a 1.55-cm wavelength have been acquired for much of the time since the satellite was launched in December 1972, but the data obtained after 1976 are complicated by instrument degradation, and several months of data for both 1973 and 1975 are not available. In October 1978 a scanning multifrequency microwave radiometer (SMMR) was placed in orbit on the Nimbus 7 satellite, and some SMMR sea ice data have been mapped since that time. Hence, since 1973 there has been nearly continuous global coverage by satellite instruments, but the data are not of uniform quality. An atlas of antarctic sea ice conditions from 1973 through 1976 has been constructed on the basis of the Nimbus 5 ESMR observations (*22*).

Figure 1 shows an example of ice concentrations derived from the Nimbus 5 ESMR for a typical winter month (September 1974) during a year when the Weddell polynya existed. The mapping procedure and the algorithm used to derive ice concentration from the ESMR brightness temperature and NCAR (National Center for Atmospheric Research) climatological air temperature data are described elsewhere (*30*). The ice extents were obtained by summing the areas of all map elements (each roughly 30 by 30 km) containing calculated ice concentrations of at least 15 percent.

The Navy-NOAA maps. Since 1973 the Navy and the National Oceanic and Atmospheric Administration (NOAA) have jointly been producing weekly maps of ice coverage (*32*). The maps are less definitive than the ice concentration images derived from calibrated ESMR data (*33*), but have the advantage of being a complete sequence from the start of 1973. These maps incorporate information from various sources, including

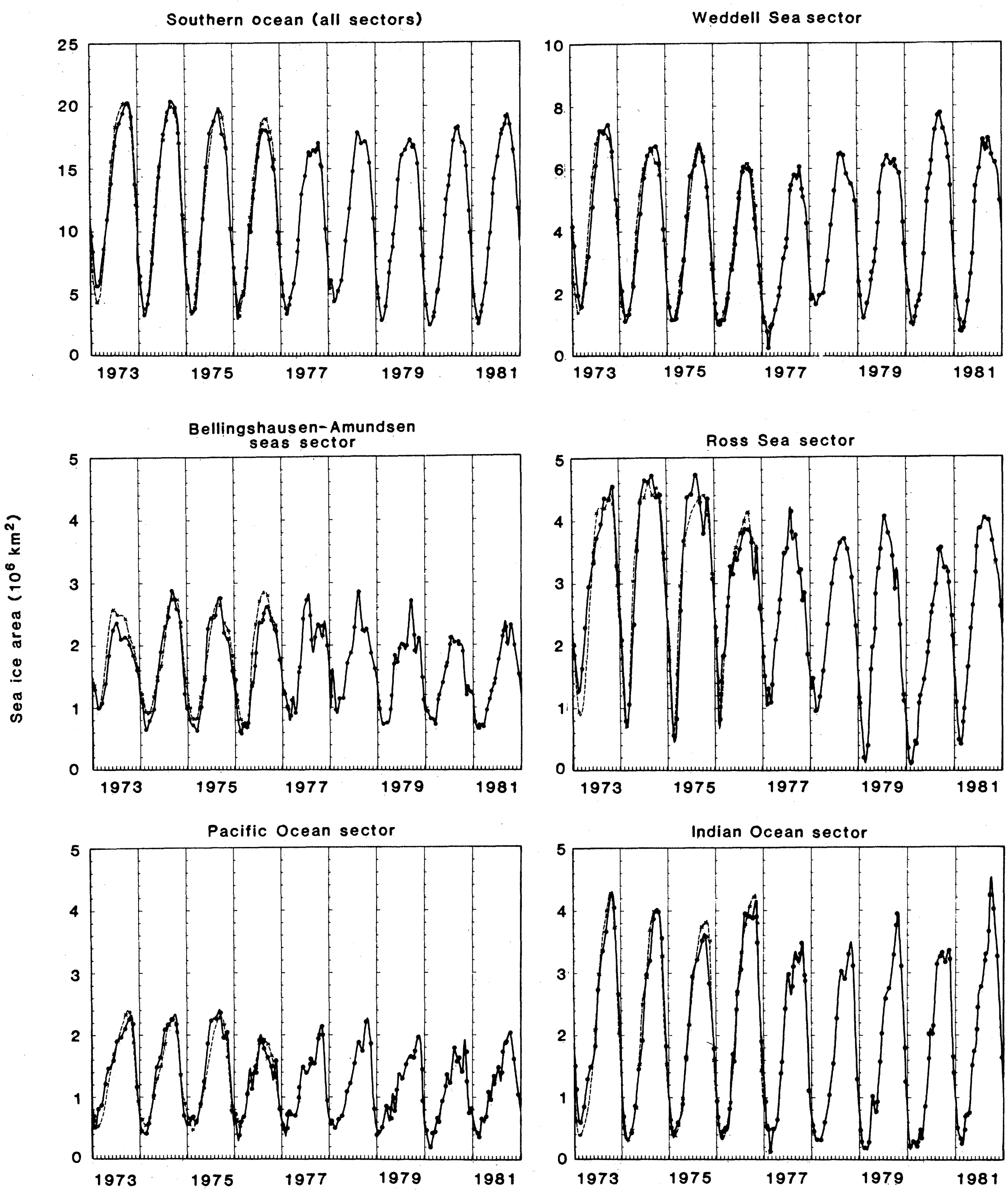


Fig. 2. Sea ice extents in each of the five sectors and over the total southern ocean, as derived from satellite observations for 1973 to 1981. Continuous lines show areas determined from Navy-NOAA ice maps in the middle of each month; dashed lines show monthly averages derived from the Nimbus 5 passive microwave data for 1973 to 1976.

uncalibrated ESMR and SMMR data that have been available on a near-real-time basis. Other sources for the Navy-NOAA maps, especially during spring and summer, include ship reports and satellite infrared data from the NOAA 5 very high resolution radiometer and visible light data from Landsat (*16*). At times when current information was unavailable, data from previous weeks were used, reducing the quality of the data during those periods. Also, the data tended to be of lesser quality in early 1973 because of greater reliance on interpolation over cloud-covered regions and lesser reliance on the microwave data, which are unaffected by cloud cover. The Navy-NOAA maps were the major data source for the study of Kukla and Gavin (*17*).

An ice concentration cutoff of 12 percent was initially used in the Navy-NOAA maps to define the ice edge; recently the cutoff has been 10 percent. This is a slightly lower cutoff than the 15 percent used for the analysis of ESMR data. However, the ice classification scheme used for the Navy-NOAA maps is normally subjective, and, especially with satellite infrared and visible light imagery, the difference between a 10 percent cutoff and a 15 percent cutoff is probably insignificant. The ice edge contours in the Navy-NOAA maps were digitized for this study with an HP 9874A digitizer monitored by an HP 9845C computer. The coordinates of points (6 mm apart) along the contour lines of the ice edge and areas of open water and polynyas were measured. Polynyas larger than about 60 by 60 km were not included in the ice areas. The contours were then reconstructed with the same computer and the areas were determined by using numerical integration. Map areas were normalized at 60° latitude and corrected for elliptical distortion.

The sea ice areas calculated from the Navy-NOAA maps are not identical to those calculated from ESMR data (Figs. 2 and 3). The procedure used by Kukla and Gavin (*17*) to digitize the Navy-NOAA maps was somewhat different from that described above, also resulting in slightly different sea ice areas (Fig. 3). In January and February 1973, when antarctic mapping by the Navy was begun routinely, the Navy-NOAA ice areas (mid-month) exceeded the ESMR-derived areas (monthly averages) by about 10^6 km^2. In general, the two sets of values now agree much better, and both sets show essentially the same trends. Over the 4 years, the ESMR and Navy-NOAA ice extents for the total southern ocean differ by 2 percent in the mean of the monthly values, and the standard deviation of the differences is 10 percent. The average of the five standard deviations for the individual sectors is 15 percent. Because the precision (standard deviation of the error) of the ESMR monthly values is about 2 percent (*30*), the precision of the Navy-NOAA values is approximately the standard deviation of the difference from the ESMR values. These estimates of the precision of the Navy-NOAA values from the monthly standard deviations are then divided by $\sqrt{12}$ or $\sqrt{3}$ to obtain the respective estimates of precision for the yearly and seasonal ice areas shown in Table 1, under the reasonable assumption that the measurement errors are independent from month to month.

Table 1. Nine-year mean extent of sea ice, parameters of linear fits, and estimated precision of the data. The standard deviation of the slope is δ_b and the standard deviation of the points about the linear fit is δ_y.

Season	Mean ice area (10^6 km^2)	Slope: 10^6 km^2 per year	Slope: Percent of mean area per year	δ_b: 10^6 km^2 per year	δ_b: Percent	δ_y: 10^6 km^2	δ_y: Percent	Estimated precision of data (percent)
Total southern ocean								
Annual	11.8	−.27	−2.3	0.08	28	0.60	5.1	2.9
Winter	17.4	−.27	−1.5	0.12	46	0.95	5.4	5.8
Spring	15.0	−.25	−1.7	0.14	56	1.07	7.2	5.8
Fall	10.1	−.31	−3.1	0.09	28	0.68	6.7	5.8
Summer	4.6	−.27	−5.9	0.09	34	0.71	15.4	5.8
Weddell Sea sector								
Annual	4.10	.004	0.1	0.065	1520	0.50	12.3	4.3
Winter	6.23	.026	0.4	0.084	319	0.65	10.5	8.7
Spring	5.43	.038	0.7	0.086	228	0.67	12.3	8.7
Fall	3.21	.003	0.1	0.060	1840	0.46	14.5	8.7
Summer	1.53	−.050	−3.3	0.059	117	0.46	29.9	8.7
Bellingshausen-Amundsen sector								
Annual	1.67	−.035	−2.1	0.013	38	0.10	6.2	4.3
Winter	2.33	−.049	−2.1	0.023	47	0.18	7.7	8.7
Spring	1.91	−.029	−1.5	0.027	94	0.21	11.1	8.7
Fall	1.52	−.043	−2.8	0.022	52	0.17	11.4	8.7
Summer	0.91	−.018	−2.0	0.024	132	0.19	20.4	8.7
Ross Sea sector								
Annual	2.75	−.14	−5.2	0.03	24	0.27	9.7	4.3
Winter	3.91	−.11	−2.8	0.05	46	0.39	10.1	8.7
Spring	3.21	−.17	−5.2	0.06	36	0.46	14.4	8.7
Fall	2.75	−.16	−5.9	0.06	35	0.44	15.9	8.7
Summer	1.12	−.13	−11.6	0.04	30	0.30	26.7	8.7
Pacific Ocean sector								
Annual	1.26	−.049	−3.8	0.010	22	0.08	6.4	4.3
Winter	1.80	−.084	−4.7	0.026	31	0.20	11.3	8.7
Spring	1.53	−.018	−1.2	0.026	142	0.20	13.2	8.7
Fall	1.16	−.070	−6.0	0.009	12	0.07	5.7	8.7
Summer	0.57	−.022	−3.8	0.012	55	0.09	16.0	8.7
Indian Ocean sector								
Annual	1.99	−.052	−2.6	0.025	48	0.19	9.8	4.3
Winter	3.17	−.048	−1.5	0.037	77	0.29	9.0	8.7
Spring	2.89	−.069	−2.4	0.069	58	0.31	10.8	8.7
Fall	1.42	−.040	−2.8	0.040	75	0.23	16.5	8.7
Summer	0.48	−.050	−10.5	0.017	34	0.13	27.7	8.7

Analysis of Sea Ice Area, 1973 to 1981

The interannual variability of sea ice extent includes year-to-year variations, short-term variations (over several years), and possible long-term trends (extending over a decade and longer). The interannual variability is examined here for each season in five regions. Summer (January, February, and March) is defined to be centered around the February sea ice minimum, winter (July, August, and September) is near the sea ice maximum, fall (April, May, and June) is the time of the most rapid growth, and spring (October, November, and December) is the time of most rapid decay. Because the season of ice growth is longer than the season of ice decay, winter is centered about 1 month before the ice maximum, which typically is in September.

To examine regional behavior, we divided the southern ocean into five sectors (Fig. 1), each characterized by certain regional oceanographic and meteorological features. For example, the Weddell sector (60°W to 20°E) is strongly influenced by the topographic barrier of the Antarctic Peninsula and the ocean gyre in the Weddell Sea. The large area of compact sea ice remaining east of the peninsula each summer is related to these features, as is perhaps the occasional occurrence of the Weddell polynya in winter. In the Indian Ocean sector (20°E to 90°E) and the Pacific Ocean sector (90°E to 160°E), the continent extends farther from the pole and the sea ice retreats to the coast in many locations during summer. In the Ross Sea sector (160°E to 130°W), the ocean extends closest to the pole and the ocean circulation away from the ice shelf significantly influences the amount of open water within the ice pack in front of the shelf. The sector of the Bellingshausen and Amundsen seas (130°W to 60°W) is influenced by the continental configuration of West Antarctica and the Antarctic Peninsula, and in this sector a relatively large ice cover is retained in summer.

Figure 2 shows the annual cycle of antarctic sea ice area in each sector and over all sectors for each year from 1973 through 1981. Differences in seasonal ice extent at times other than the winter maxima and summer minima are difficult to discern, but regional differences are evident. For the southern ocean, minimum ice areas are indeed lower for the last 3 years than for earlier years, but maximum areas have increased considerably in recent years from the 17×10^6 km^2 value in 1977. Relatively large amounts of ice in a given season do not imply anomalously high values in succeeding seasons as well (*25*).

The primary annual cycle of growth and decay has some interesting amplitude and phase modulations. The individual sectors also have distinct characteristics, which may be interrelated. In the two principal sectors, the Weddell and Ross, and in the sector of the Bellingshausen and Amundsen seas, the amplitudes of the annual cycle are strongly modulated, changing by about 30 percent. The modulation is such that 3- to 5-year periods of greater maximum ice extents in winter have associated with them lesser minimum ice extents in summer. This short-term tendency of greater maxima near lesser minima is only partially compensatory in the annual mean ice areas. In these three sectors the modulation of amplitudes appears with a relative phase shift of about 2 to 3 years successively from the Weddell to the Ross to the Bellingshausen and Amundsen seas. The modulation of the entire southern ocean ice area is principally a summation of the Weddell and Ross sector modulations. The Indian Ocean sector has some long-term similarities to the adjacent Weddell sector, and only the Pacific Ocean sector appears to have a continued downward trend in both the maximum and minimum ice extents over the 9 years.

Nine annual cycles is obviously too few to confirm that the amplitude modulation of the sea ice area is a persistent low-frequency cycle, but the data are consistent with a modulation frequency on the order of 10 years. It is clear, however, even from this limited set of data, that cyclical components of variability in the extent of antarctic sea ice are at least as strong and as definitive as any monotonic or linear changes over the 9 years.

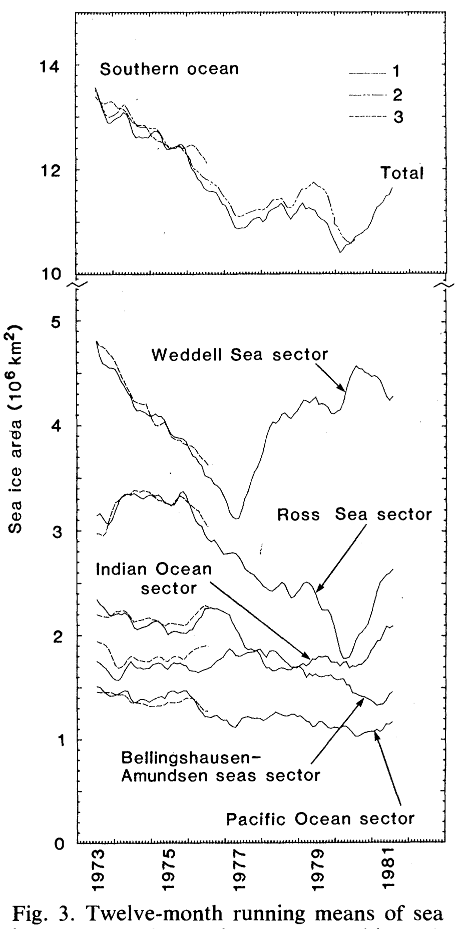


Fig. 3. Twelve-month running means of sea ice extent on the southern ocean and in each of the five sectors. Type 1 traces show areas calculated from the Navy-NOAA maps; type 2 traces, areas for the southern ocean for 1973 to 1980, obtained from Kukla and Gavin (*17*); and type 3 traces, areas for 1973 to 1976, derived from Nimbus 5 passive microwave data.

Considering the year-to-year variations of the maximum and minimum ice extents (Fig. 2), the random-like year-to-year variations are generally smaller than longer term changes, even in the individual sectors. Some marked exceptions can be seen for which the year-to-year changes are large compared to the trends over several years. Examples are the 1980 maximum in the Weddell Sea sector, the 1976, 1979, and 1981 maxima in the Indian Ocean sector, and the 1979 and 1980 minima in the Ross Sea sector.

The annual mean ice extent (Fig. 3) is a highly averaged parameter analogous to global mean temperature. The 12-month running means for the southern ocean include, for comparison, our reading of the Navy-NOAA maps, data replotted from Kukla and Gavin (*17*), and the 1973–1976 ESMR data. The total area of sea ice generally decreased from 1973 to 1977, increased slightly over the next 2 years, decreased from 1979 to its lowest value in 1980, and then increased from 1980 to 1981. The range of the annual mean ice area is about 3×10^6 km^2, which is comparable to the change in summer ice of 2.5×10^6 km^2 emphasized by Kukla and Gavin. Therefore it is possible to deduce from only their annual mean data that the decrease in sea ice extent between 1973 and 1980 was not primarily in the summer or spring.

Figure 3 shows that the initial overall decrease of the annual mean to a temporary minimum in 1977 was almost entirely due to the decrease in the Weddell Sea sector. As the ice extent recovered in the Weddell sector, the overall extent was sustained at a lower level through 1980, mainly by the 1×10^6 km^2 decrease in the Ross Sea sector to a sharp minimum in 1980. The ice extent in the Indian Ocean and Bellingshausen-Amundsen sectors underwent little change from 1973 to 1977, but from 1977 to 1980 the ice extent in the Indian Ocean sector was depressed during the 3-year interval between the Weddell and Ross minima. Only the ice extent in the Pacific Ocean sector appears to have a persistent downward trend in the annual mean over the 9 years.

A foremost consideration in evaluating the significance of the observed variations is the short length of the data set. Another essential consideration is the difference between evaluating whether a significant change occurred during a given period and whether such a change is an indication of a long-term trend. With these considerations in mind, variations of ice extent on a seasonal and regional basis are shown in Fig. 4. The areas derived from the Navy-NOAA maps for the entire period are used, although the 1973 summer values from the Navy-NOAA maps are probably too high, as previously noted. For each season, linear least-squares fits are determined through the nine data points.

The predominance of negative slopes, except in the Weddell sector, might be viewed as confirmation of a long-term overall decrease. However, in our view no definitive conclusion can be made regarding long-term trends. Generally, the variability around the linear fits is large and includes errors in the data as well as possible year-to-year fluctuations and longer term cyclical components of sea ice variation. Various parameters of the linear fits to the annual means and seasonal averages are shown in Table 1, along with the estimate of data precision obtained from comparison with the ESMR data. The standard deviation of the points about the line, δ_y, is equal to the statistical chi, which, if normalized by the data error, goes to unity for a perfect linear fit. The standard deviation of the slope, δ_b, and σ_y have been calculated under the a priori assumption that the data are randomly distributed about a linear trend. These deviations can only be used to assess the statistical significance of the inferred linear component if the cyclical components appear to be small, which, as discussed later, is not the case.

Two principal features of the sea ice variability can be seen from a qualitative examination of the plots in Figs. 3 and 4 and from the quantitative parameters in Table 1. First, the slope is essentially zero in the Weddell sector, where the mid-1970's decrease was earliest and largest, but the slope is downward in the other sectors. One-half of the overall decrease of the southern ocean ice from 1973 to 1981 occurred in the Ross Sea sector, where the mid-1970's decrease followed the Weddell decrease by about 3 years. Second, each season has essentially the same slope for the southern ocean. In each sector the seasonal slopes are nearly the same, except in the Pacific Ocean sector, where the slopes for spring and summer differ from the other two by more than 1 standard deviation. A similar analysis for individual months shows that in most cases in each sector the changes for each month over 9 years are similar to the changes for the seasons.

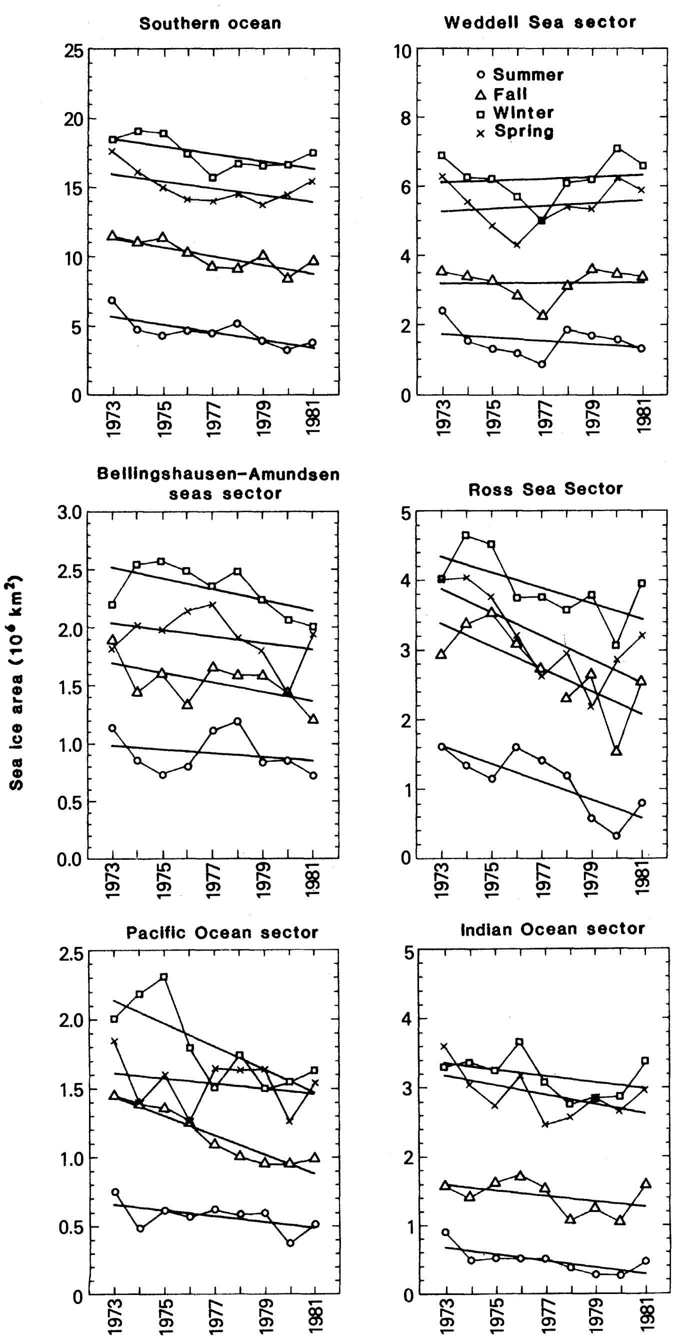


Fig. 4. Seasonally averaged sea ice extents with least-squares linear fits for each sector and for the southern ocean.

Overall, the linear fit indicates that the total sea ice extent decreased during the 9 years by $(0.27 \pm 0.08) \times 10^6$ km^2 per year, or 2.3 percent per year. Obviously, a decrease of this magnitude could not be maintained very long, because only about 20 years would be required to reduce the summer ice area to zero and the winter ice to 70 percent of its present mean extent. Although the sea ice extent did decrease significantly during this period, the significance of this result as an indicator of a long-term trend is not shown by these parameters. The linear component of change indicated by the linear fit must be considered in relation to other components of variability indicated by the data.

In the Weddell sector the linear fit shows no persistent change in ice area over the 9-year period, which is in marked contrast to the other sectors, where the percentage linear decreases are comparable to the decrease for the southern ocean. Because various regions may show quite different long-term trends or responses to a CO_2-induced warming, it is possible that the Weddell region is not typical of the overall or long-term behavior of the sea ice cover. However, the large regional variability and the cyclical nature of the sea ice variations in several regions cause a large uncertainty in any inferences that might be made regarding long-term trends.

In all sectors there is significant variation of the ice area around the linear slope that is greater than the relative data errors. The variation is indicated by the standard deviation of the nine points about the line, which, expressed as a percentage of the mean area, is generally larger than the estimated data error, except that the winter values are comparable in magnitude to the estimated precisions.

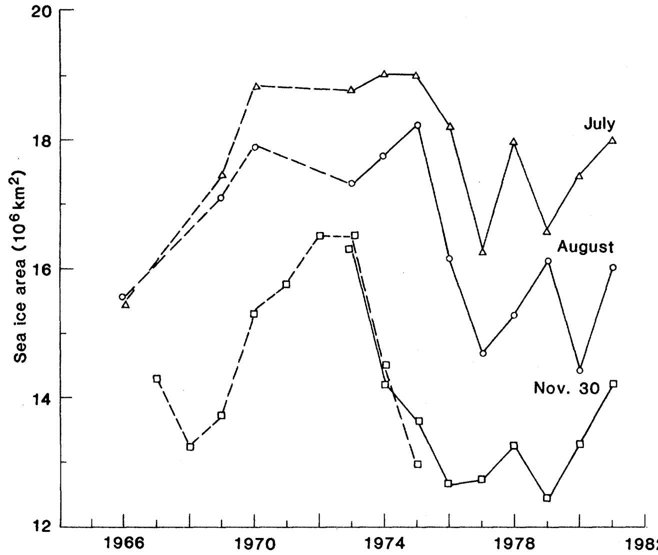
The variation around the linear slope does not appear to be primarily random, as might be caused by a large year-to-year variability or by nonsystematic errors in the data. There is an apparent year-to-year persistence in the deviations from the linear fit. The persistence for a given season from year to year appears to be greater than the persistence in successive seasons, for which the deviations are often of opposite signs. These characteristics of the persistence of the deviations may provide information on their possible causes and on related atmospheric and oceanic interactions.

Visual examination of the data also suggests that there are strong cyclical components of variation. These cyclical components may have a period of about 10 years, with a phase that appears to differ from region to region. Other suggestions of a 10-year cycle in southern ocean ice cover include that of Kusunoki (*16*), who analyzed 20 years of ship navigability near 40°E. However, no definitive conclusion regarding persistent long-term cyclical variations can be drawn. Nevertheless, the data from 1973 to 1981 clearly exhibit substantial deviations from a linear downward trend, including a recent increase suggesting that the overall decrease from 1973 to 1980 was temporary.

The slope of the linear component inferred from any other 9-year data set may be very different from the one obtained for 1973 to 1981. The changes in the Ross Sea sector appear to be lagging behind the changes in the Weddell Sea sector by about 3 years, so that a linear fit to the 1976–1984 data for the Ross Sea sector may imply no persistent change in the extent of sea ice in that region. Because the deviations from the linear fit appear to include cyclical components, the standard deviations in Table 1 should not be used as an indication of the statistical significance of any inferred linear change in ice extent.

Certain sectors or seasons might be more suitable for detecting climatic change due to the influence of oceanic and atmospheric parameters, but there is little evidence for this. The parameter σ_y is used here as an indicator of the nonlinear deviations with respect to possible linear trends. (It is recognized that σ_y includes both cyclical components and random variations.) The annual mean in the Pacific sector has the least variation around the linear fit, but additional data are needed to determine whether this is a

Fig. 5. Areal extent of antarctic sea ice from 1966 to 1982. Dashed lines show data compiled by Kukla (*21*), Streten (*20*), and Sissala *et al.* (*19*), which were based mainly on satellite visible light and infrared data. Continuous lines show data derived from the Navy-NOAA weekly ice maps. The data points are normalized such that the area of the antarctic continent is consistently 13.97×10^6 km^2.



long-term characteristic. In most sectors and overall, the deviation σ_y (square kilometers) is comparable for all seasons, but, expressed as a percentage of the mean area, this standard deviation indicates that winter shows the least variation about the linear component, except in the Pacific Ocean sector, where the variation is least in the fall.

As previously mentioned, some visible light and infrared data obtained by satellite before 1973 was analyzed for ice extent (*19–21*) and is included in Fig. 5 along with the more recent data. The increase in ice extent from 1967 to 1973 is approximately the same as the decrease between 1973 and 1980, further indicating strong cyclical components of variation, or at least the absence of a definitive downward trend worthy of extrapolation. Comparisons with earlier records of ice extent for limited periods, such as the 1929–1938 ship reports, must take into account variations of the type shown in Fig. 5. It should also be noted that, while sea ice extent probably would respond to any CO_2-induced climatic change, it can also be expected to respond in a similar manner to natural changes in atmospheric temperature. Therefore, comparisons with the 1930's, for example, should be made in light of the temporarily cooler temperatures in south polar regions reported for the late 1920's and early 1930's and of the anomalously greater winter ice duration during that period at Scotia Bay (60.7°S, 44.7°W) (*34*).

Conclusions

The large variability in the extent of antarctic sea ice is evident from the detailed satellite record for 1973 to 1981. Interannual variations within regions and contrasts between regions are large. In each region similar long-term interannual changes are observed in all seasons. For periods of 3 to 5 years greater winter maximum ice extents are associated with lesser summer minimum extents. Over longer periods there are substantial cyclical components of variation in the observed ice extent. For any given season there is a year-to-year persistence in the deviations from a linear fit to the 9-year data set. For successive seasons in a year the deviations are less persistent and often of the opposite sign.

Overall, the record of sea ice extent from 1966 to 1981 does not support a conclusion of a long-term downward trend. A significant decrease in ice extent during the 1970's has not been maintained, and may simply have been a natural fluctuation caused by complex oceanic and atmospheric interactions. The strong regional contrasts suggest that the observed changes are attributable to changes in atmospheric or oceanic circulation patterns rather than to a global warming induced by increasing levels of atmospheric CO_2.

Cyclical components of the interannual variability are large, as shown by a modulation of the amplitude of the annual cycle by about 30 percent and by the variation around linear fits to the 9-year data set. In the Weddell region, where the decrease of the mid-1970's was strongest, the ice extent had recovered from a 1977 minimum to the 1973 level by 1981. The decrease in the Ross Sea region followed the Weddell decrease by 3 years to a sharp minimum in 1980, which was reversed in 1981.

The major observed changes in ice extent are consistent with approximately a 10-year period of variation, but no conclusion can be made about the persistence of such a variation. Some of the regional variations appear to have relative phase shifts of 2 to 3 years from one region to another. Because the cyclical components of variation are at least as large as any long-term trend in the data, additional information on their relative magnitude is needed to determine the existence of any long-term trends. Additional information is also needed on the sensitivity of sea ice extent to atmospheric temperature and on the response to natural as well as CO_2-induced changes in temperature. Otherwise, it will not be possible to evaluate the significance of any observed changes.

The duration of the observed variations in sea ice extent, their regional and seasonal characteristics (such as the phase shift of the modulations of the annual cycle), and the possible cyclical components provide insights into physical relations that exist with other changes in the atmosphere and the ocean. The nature of the cyclical components and long-term trends should be investigated as satellites extend the sea ice data set in time.

References and Notes

1. J. H. Mercer, *Nature (London)* **271**, 321 (1978).
2. H. Flohn, in *Workshop on Environmental and Societal Consequences of a Possible CO_2-Induced Climate Change* (Conference 7904143, Department of Energy, Washington, D.C., 1980), pp. 183–187.
3. T. M. L. Wigley, in *ibid.*, pp. 141–147.
4. C. L. Parkinson and W. W. Kellogg, *Clim. Change* **2**, 149 (1979).
5. S. Manabe and R. J. Stouffer, *Nature (London)* **282**, 491 (1979).
6. J. S. Olson, in *Workshop on Environmental and Societal Consequences of a Possible CO_2-Induced Climatic Change* (Conference 7904143, Department of Energy, Washington, D.C., 1980), pp. 202–236.
7. W. C. Wang, Y. L. Yung, A. A. Lacis, T. Mo, J. E. Hansen, *Science* **194**, 685 (1976).
8. A. Lacis, J. Hansen, P. Lee, T. Mitchell, S. Lebedeff, *Geophys. Res. Lett.* **8**, 1035 (1981).
9. S. Manabe and R. T. Wetherald, *J. Atmos. Sci.* **32**, 3 (1975).
10. T. Augustsson and V. Ramanathan, *ibid.* **34**, 448 (1977); V. Ramanathan, in *Preprints of the Second Conference on Atmospheric Radiation* (American Meteorological Society, Boston, 1975); S. Manabe, in *Man's Impact on Climate*, W. H. Matthews, W. W. Kellogg, G. D. Robinson, Eds. (MIT Press, Cambridge, Mass., 1971), p. 256; G. B. Hunt and N. C. Wells, *J. Geophys. Res.* **84**, 787 (1979); S. Manabe and R. T. Wetherald, *J. Atmos. Sci.* **24**, 241 (1967); *ibid.* **37**, 99 (1980).
11. V. Ramanathan, M. S. Lian, R. D. Cess, *J. Geophys. Res.* **84**, 4949 (1979).
12. J. Hansen, D. Johnson, A. Lacis, S. Lebedeff, P. Lee, D. Rind, G. Russell, *Science* **213**, 957 (1981).
13. T. M. L. Wigley and P. D. Jones, *Nature (London)* **292**, 205 (1981).
14. W. F. Budd, *J. Glaciol.* **15**, 417 (1975).
15. Analysis of data presented by Kusunoki (*16*) on the variation of the summer ice edge off Syowa Station (69°S, 40°E) by R. Bindschadler (unpublished manuscript) suggests a sensitivity of 0.4 degree of latitude per Kelvin, but the winter ice edge along 40°E appears to be uncorrelated with the mean annual temperature at Syowa (*16*). Preliminary sea ice modeling by C. Parkinson (unpublished manuscript) suggests a sensitivity of the winter ice edge on the order of 1 degree of latitude per degree Kelvin.
16. K. Kusunoki, in *Sea Level, Ice and Climatic Change*, I. Allison, Ed. (International Association of Hydrological Sciences, Guildford, England, 1981), pp. 171–176.
17. G. Kukla and J. Gavin, *Science* **214**, 497 (1981).
18. S. L. Thompson and S. H. Schneider, *Nature (London)* **295**, 645 (1982).
19. J. F. Sissala, R. R. Sabatini, H. J. Ackerman, *Polar Rec.* **16**, 367 (1972).
20. N. A. Streten, *Arch. Meteorol. Geophys. Bioklimatol. Ser. A* **22**, 119 (1973).
21. G. J. Kukla, in *Climatic Change*, J. Gribbin, Ed. (Cambridge Univ. Press, London, 1978), pp. 114–129; G. J. Kukla, J. K. Angell, J. Korshover, H. Dronia, M. Hoshiai, J. Namias, M. Rodewall, R. Yamamoto, T. Iwashima, *Nature (London)* **270**, 573 (1977).
22. H. J. Zwally *et al.*, *NASA Spec. Publ. 459*, in press.
23. W. J. Campbell, R. O. Ramseier, H. J. Zwally, and P. Gloersen [in *Energy Resources of the Pacific* (American Association of Petroleum Geologists, Tulsa, Okla., 1981), pp. 343–354] reported compensating increases and decreases in ice extent in the Bering and Okhotsk seas. J. E. Walsh and C. M. Johnson (*24*) reported such changes for various arctic sectors and Zwally *et al.* (*22*) reported them for various antarctic sectors.
24. J. E. Walsh and C. M. Johnson, *J. Geophys. Res.* **84**, 6915 (1979).
25. H. J. Zwally, C. L. Parkinson, F. D. Carsey, P. Gloersen, W. J. Campbell, R. O. Ramseier, in *Fourth National Aeronautics and Space Administration Weather and Climate Program Science Review*, E. R. Kreins, Ed. (Goddard Space Flight Center, Greenbelt, Md., 1979), pp. 335–340.
26. S. F. Ackley, in *Sea Level, Ice and Climatic Change*, J. Allison, Ed. (International Association for Hydrological Sciences, Guildford, England, 1981), pp. 127–159.
27. G. F. Herman and W. T. Johnson, *Mon. Weather Rev.* **106**, 1649 (1978).
28. C. L. Parkinson and D. J. Cavalieri, *Ann. Glaciol.* **3**, 249 (1982).
29. J. O. Fletcher, in *Beneficial Modifications of the Marine Environment* (National Academy of Sciences, Washington, D.C., 1972), pp. 4–49.
30. J. C. Comiso and H. J. Zwally, *J. Geophys. Res.* **87**, 5836 (1982).
31. H. J. Zwally and P. Gloersen, *Polar Rec.* **18**, 431 (1977).
32. R. H. Godin and D. G. Barnett, in *Inventory of Snow Cover and Sea Ice Data*, R. G. Crane, Ed. (Glaciological Data Report GD-7, World Data Center A for Glaciology, Boulder, Colo., 1979), pp. 25–36.
33. H. J. Zwally, J. C. Comiso, C. L. Parkinson, *NASA Tech. Memo. 83812* (1981).
34. W. Schwerdtfeger, in *Climates of the Polar Regions*, S. Orvig, Ed. (Elsevier/North-Holland, Amsterdam, 1970), pp. 253–355.

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