Spatial and Temporal Variations in Antarctic Sea-Ice (1973-82)

CHESTER F. ROPELEWSKI

Climate Analysis Center, NMC, NWS, NOAA, Washington, DC 20233

(Manuscript received 10 September 1982, in final form 30 November 1982)

ABSTRACT

Monthly estimates of Antarctic sea-ice area for the past decade were extracted from operational charts. Empirical orthogonal function analyses of these satellite-derived data revealed the existence of six distinct ice area sub-regions. Comparison of ice area time series for these sub-regions highlights the substantial differences among them. For example, total sea-ice extent typically reached a maximum in either August or September, while the Ross Sea often exhibited two relative maxima (July and October). The data show considerable year-to-year variability during this short period of record with the minimum sea-ice area varying by more than a factor of two and maximum sea-ice area varying by almost 20%. The large year-to-year variability precludes a reliable identification of longer term trends during the relatively short era of satellite observations.

1. Introduction

There has been considerable recent interest in the temporal and spatial behavior of Antarctic sea-ice. This interest has been spurred in part by suggestions from numerical model studies (e.g., summarized by Goody, 1980) that climatic changes in temperature may be most pronounced and thus most easily detected in high latitudes. Presumably, variations in temperature would result in variations in the sea-ice extent. Previous to 1973, however, there were no regular analysis or observations of sea-ice for the entire Southern Hemisphere. Data were available for either relatively short periods of intensive observation such as during the International Geophysical Year in 1958 or from irregularly scheduled observations, such as ships logs and limited aircraft reconnaissance. Starting in January 1973 the first regularly scheduled satellite observations of the Antarctic sea-ice became available. In this paper, I examine monthly sea-ice extent obtained from an analysis of these observations using charts prepared by the Navy-NOAA Joint Ice Center (JIC). The purpose of the analysis is to provide some realistic estimates of Antarctic sea-ice variability over the past decade. Although these estimates are for a relatively short period of record from a climatological standpoint, they should provide at least a crude framework from which variations in Antarctic sea-ice may be judged. This study differs from that of Kukla and Gavin (1981) in that it is limited to satellite era data only and areas of open water (or polynyas) are not included as sea-ice. This analysis covers a longer time period than the studies by Cavalieri and Parkinson (1981) and in greater spatial detail than Lemke *et al.*, 1980.

2. Data

The source of the data are charts analyzed by the Navy-NOAA JIC. These charts are prepared weekly using data from satellites supplemented by conventional observations. They depict the extent of the sea-ice and contain estimates of the sea-ice concentration. Over the period of record, data from several different satellites and sensors were used to construct these charts. Differences in the horizontal resolution (1 to 25 km) of these various sensors were much smaller than the digitizing resolution used in this study. A complete description of these charts may be found in Godin and Barnett (1979).

To obtain quantitative estimates of sea-ice area a 1° latitude × 2.5° longitude grid was placed over the analyzed charts. Grid boxes containing ice were summed in 1° latitude × 10° longitude slices and the areas computed. A grid box was considered to contain sea-ice if it were more than half filled. The concentration of sea-ice was not considered except that concentrations of less than 1/8, designated "open water," were not counted. Permanent shelf ice and areas of the charts depicted as part of the Antarctic continent were also excluded. All other areas designated as sea-ice were included in the areal estimates. It was not practical to analyze each of the weekly charts. Thus, the weekly chart dated closest to the end of the month was selected to represent sea-ice for that month. The selection of a weekly chart to represent the monthly sea-ice area introduces error, or noise, into these estimates for year-to-year comparisons. This error is likely to be smallest during the periods of primary interest i.e., periods of maximum or minimum sea-ice since visual examination of the charts shows that

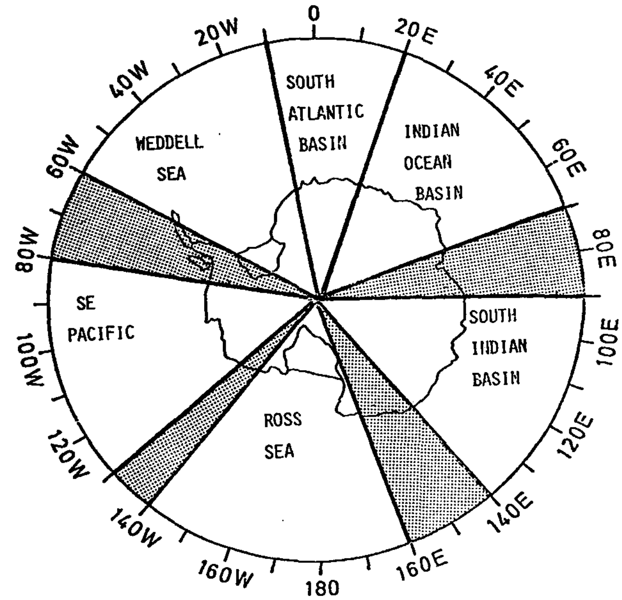

FIG. 1. Antarctic sea-ice sub-areas.

week-to-week changes are relatively small during these periods.

The areal estimates were consolidated into estimates for 10° longitude sectors. The monthly sea-ice areal estimates for each of the 36 longitudinal sectors from January 1973 to April 1982 from the data set analyzed below.

3. Analysis

The first step in the analysis was to identify areas of the Antarctic for which sea-ice behaves in a spatially coherent manner. The 36 sector by 112 month data array was analyzed using the asymptotic singular composition technique (Jalikee and Ropelewski, 1979) to form principal components or Empirical Orthogonal Functions (EOF). The first EOF, which includes the seasonal cycle, accounts for 81% of variance. The leading spatial component was used to define sub-areas which appear in Fig. 1. These areas are regions for which the magnitudes of the spatial EOF component were approximately the same. Areas indicated by shading in Fig. 1 did not easily fit into the sub-regions. They are excluded from the discussion of the behavior of sea-ice in individual regions but they are included in the analysis of the variations in total sea-ice area.

Time series plots of sea-ice for the individual sub-areas as well as the total area, Fig. 2, reveal many interesting similarities and differences among them.

The maximum in total annual sea-ice area shows a monotonic decrease from 205.0×10^5 km^2 in 1974 to its lowest value 168.6×10^5 km^2 in 1977. This amounted to a decrease of almost 20% in maximum sea-ice extent during a four year period. By 1979, however, the maximum had returned to near the 9 year mean (Table 2). The minima in total annual sea-ice area also shows large year-to-year variations. The year with the largest minimum (1973) had more than twice the amount of sea-ice as the year (1980) with the smallest minimum (Table 1). After reaching the lowest minimum of the 10-year record in February 1980 there was an increase in the minima of the following two years to values closer to the 10-year average.

The annual extremes in sea-ice extent tended to occur at the same time each year (Fig. 2), but there were some variations. The annual minima in total sea-ice occur in February, except for 1976 when the minimum occurred in January. The maximum total sea-ice extent occurred in August for 6 of the 9 years of record but in 1973, 1978 and 1981 the maximum occurred in September. Lemke *et al.* (1980) indicate that maximum total sea-ice extent occurs in October. They analyzed the JIC weekly charts for the period 1973 to 1979. The discrepancy between their findings and the data presented here may be due to their coarser spatial resolution and the fact that they excluded sea-ice areas with concentrations of less than 5/8. An examination of the means for each sub-area (Table 2) shows that the month of maximum concentration varies with sub-area. August is the month of mean maximum for the Weddell and Southeast Pacific sectors, September for the South Atlantic Basin and South Indian Basin, while October is the month of mean maximum for the Indian Ocean. The Ross Sea sector had the most interesting behavior, showing a primary maximum in July and secondary maximum in October for several individual years (Fig. 2). The time series for the Indian Ocean, South Indian Basins and the Southeast Pacific also showed evidence of two maxima for individual years. These three sectors plus the Ross Sea, account for almost 60% of the total sea-ice area. The Weddell Sea, which contains the most sea-ice and the South Atlantic Basin do not show bimodal maxima. The reasons for the bimodal maxima are not fully understood. One hypothesis is that after the winter (July–August) maximum extent the sea-ice begins to breakup and is transported northward in sufficient concentrations to produce a secondary maximum later in the year (Sep-

TABLE 1. Sea-ice area extremes (10^5 km^2).

Year	Maxima	Minima
1973	202.5 S*	56.4
1974	205.0	37.0
1975	195.1	34.1
1976	179.3	41.6 J*
1977	168.6	36.0
1978	173.0 S	40.3
1979	185.3	32.5
1980	181.6	26.7
1981	185.4 S	34.0
1982	—	31.4

* J, January minimum. S, September maximum.

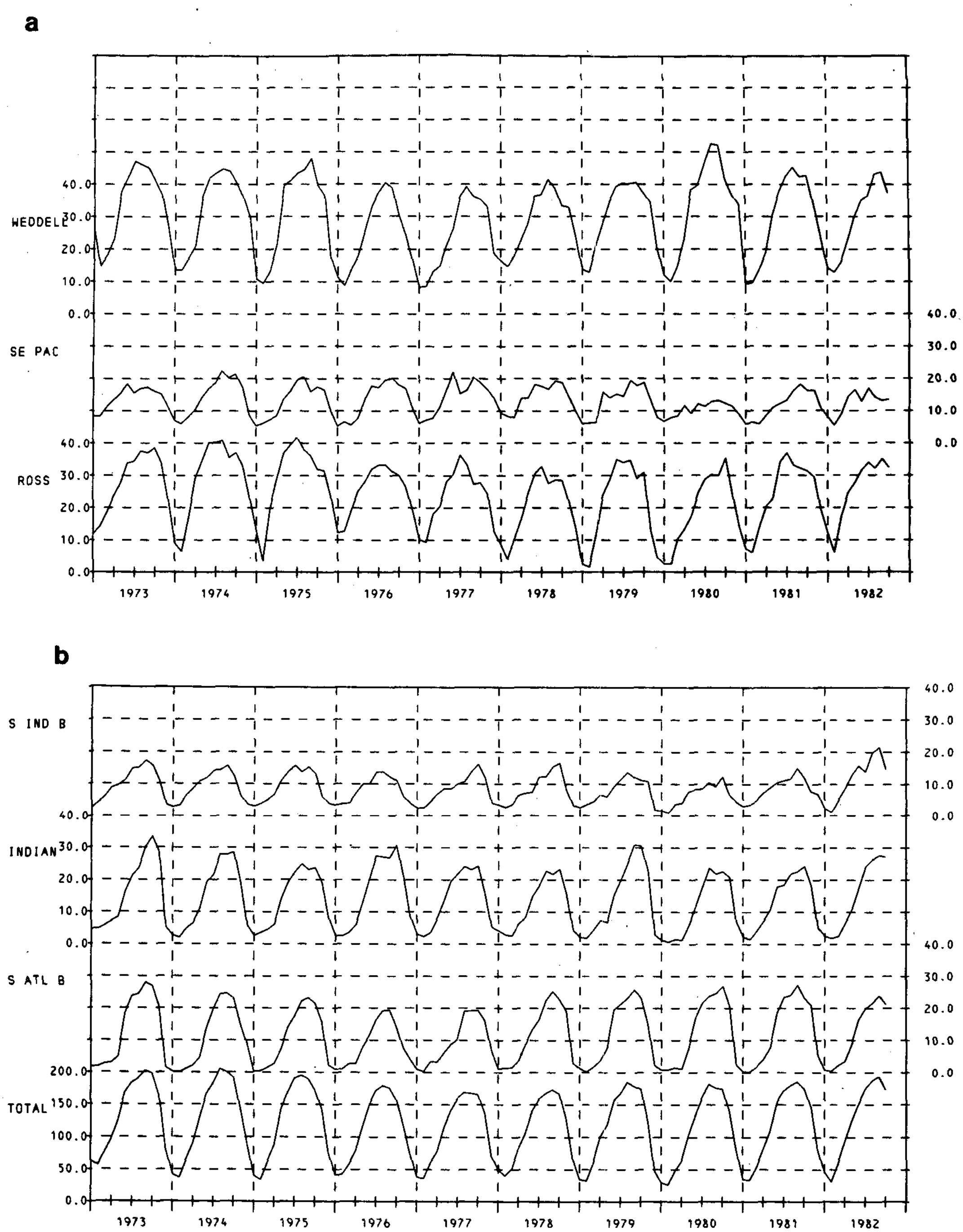

FIG. 2. Time series of monthly sea-ice extent (10^5 km^2) for (a) Ross, Southeast Pacific and Weddell sectors, and (b) South Indian Basin, Indian Ocean, South Atlantic Basin, and total sea-ice. Tick marks indicate the months April, July and October.

tember–October). This is consistent with Walsh and Sater (1981) using Arctic Data, and Lemke *et al.* (1980) in the Antarctic who found that sea-ice extent is correlated with the winds.

The time of occurrence of the minimum total sea-ice was less variable. The mean minimum sea-ice extent occurs in February (Table 2). The same is true for the individual sectors except for the South Indian Basin and Southeast Pacific, which show January minima. Individual years occasionally exhibit minima in January in the remaining sectors and the total sea-ice area in 1976, Fig. 2.

Following the annual minimum each year, the sea-ice area increased slowly during March and more rapidly in April, reaching a maximum mean growth rate of over 34.0×10^5 km^2 per month during May and

TABLE 2. Mean sea–ice extent (10^5 km^2) by month for the total and each of the six sub-areas. Values in italics indicate extrema.

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ratio*
Total	41.6	*37.7*	59.4	84.2	118.5	153.0	171.6	*184.0*	183.0	175.2	137.1	73.8	4.9
South Atlantic Basin	0.9	*0.7*	2.0	2.9	6.9	14.9	18.9	22.3	*23.8*	22.2	16.3	3.9	34.0
Indian Ocean Basin	2.8	*2.4*	3.8	6.2	10.1	17.1	20.9	24.9	25.7	*27.1*	20.3	5.9	11.3
South Indian Basin	*2.8*	3.2	4.9	7.0	8.9	10.1	12.4	13.0	*13.9*	13.6	8.4	3.6	5.0
Ross Sea	8.6	*6.7*	15.5	22.3	77.6	33.3	*35.4*	34.5	31.8	*32.5*	26.1	16.7	5.3
South East Pacific	*6.7*	7.0	7.6	11.2	13.9	16.5	15.9	*18.1*	18.0	17.7	15.2	10.2	2.7
Weddell Sea	13.5	*11.4*	15.9	21.2	32.3	37.5	41.5	*43.6*	42.9	37.4	33.9	23.5	3.8

* Maximum/minimum.

June. A maximum in sea–ice area is reached in August, followed by relatively small changes (i.e., ~7%) from July through October. Ice cover decreased substantially in November and exhibited a maximum decrease (64.0×10^5 km^2) in December. The maximum mean rate of decrease of sea–ice area is almost twice the maximum rate of increase. The asymmetry in rates of growth and decay of sea–ice is most apparent in the South Indian Basin time series (Fig. 2).

One of the most dramatic features of Antarctic ice cover is its large annual cycle. The ratio of mean maximum to mean minimum sea–ice extent is 4.9 in agreement with other studies (Goody 1980). This ratio is much larger, however, for the South Atlantic (34.0) and Indian Ocean Basins (11.3) where the ice boundary sometimes nearly retreats to the coast during the Southern Hemisphere summer. For example, the South Atlantic basin was virtually devoid of sea–ice in January 1975. Other sectors show a much smaller annual range, the smallest being the Southeast Pacific Sectors, which includes the Bellingshausen Sea. The Southeast Pacific Sector contains only a small percentage of the total sea–ice during periods of maximum sea–ice. During the Southern Hemisphere summer, however, this sector is second in sea–ice area only to the Weddell Sea sector. The Weddell sector, which generally contains the most sea–ice, shows a smaller ratio of maximum to minimum sea–ice (3.8) than the total. In summary, the ratios of mean maximum to mean minimum sea–ice varied roughly between 3 and 30 depending on sector. Estimates of total sea–ice extent derived from observations in one sector may be quite unrepresentative of other sectors.

4. Summary and discussion

Estimates on monthly Antarctic sea–ice area were extracted from operational charts. Empirical Orthogonal Functions were used to identify six homogeneous sub-areas within the Antarctic. Comparison of the temporal behavior of the six sub-area and total sea–ice area reveals substantial differences among them. While total sea–ice extent reached a maximum in either August or September for each year of record, the sub-areas adjoining the Western Antarctic often exhibited two relative maxima (July and October). The minimum sea–ice extent generally occurred at the end of February for the total area and all except two of the sub-areas. Minimum sea–ice extent varied by over a factor of 2 from a low of 26.7×10^5 km^2 in 1980 to a high of 56.4×10^5 km^2 in 1973. Maximum sea–ice extent also varied extensively from 205.0×10^5 km^2 to 168.6×10^5 km^2 over the period of record. No clearly established trends were evident. The large year to year variability in sea–ice extent underscores the hazards involved in trying to identify significant trends with only a few years of data.

Acknowledgments. I wish to thank Mr. R. Godin of the Navy/NOAA Joint Ice Center for providing the sea–ice charts. The tedious task of extracting the first 9 years of data was cheerfully performed by Ms. Ann Conjura. Mr. John Kopman has been ably updating these data as the current charts are received.

The helpful discussions with Mr. P. Clapp and Mr. F. Kniskern are appreciated. The manuscript was typed by Ms. T. Mothershead.

REFERENCES

Cavalieri, D. J., and C. L. Parkinson, 1981: Large-scale variations in observed Antarctic sea–ice extent and associated atmospheric circulation. *Mon. Wea. Rev.*, **108**, 2323–2336.

Godin, R. H., and D. G. Barnett, 1979: Global sea ice limits. *Inventory of Snow Cover and Sea Ice Data*, R. G. Crane, Ed. Rep. GD-7, Institute of Arctic and Alpine Research, University of Colorado, Boulder, 171 pp.

Goody, R., 1980: Polar process and world climate (A brief overview). *Mon. Wea. Rev.*, **108**, 1935–42.

Jalickee, J. B., and C. F. Ropelewski, 1979: An objective analysis of the boundary-layer thermodynamic structure during GATE. Part I: Method. *Mon. Wea. Rev.*, **107**, 68–76.

Kukla, G., and J. Gavin, 1981: Summer ice and carbon dioxide. *Science*, **214**, 497–503.

Lemke, P., E. W. Trinkl and K. Hasselmann, 1980: Stochastic dynamic analysis of polar sea ice variability. *J. Phys. Oceanogr.*, **10**, 2100–2120.

Walsh, J. E., and J. E. Sater, 1981: Monthly and seasonal variability in the ocean–ice atmospheric systems of the North Pacific and North Atlantic. *J. Geophys. Res.*, **86**, 7425–7445.