ANTARCTIC SEA ICE: PHYSICAL PROCESSES, INTERACTIONS AND VARIABILITY
ANTARCTIC RESEARCH SERIES, VOLUME 74, PAGES 293-315

INTERANNUAL VARIABILITY IN SUMMER SEA ICE MINIMUM, COASTAL POLYNYAS AND BOTTOM WATER FORMATION IN THE WEDDELL SEA

Josefino C. Comiso

Laboratory for Hydrospheric Processes, NASA Goddard Space Flight Center

Arnold L. Gordon

Lamont-Doherty Earth Observatory of Columbia University

As sea ice formation plays a key role in driving Antarctic Bottom Water (AABW) production through brine rejection and the associated production of High Salinity freezing point Shelf Water (HSSW), a possible link between interannual variability of the ice cover and changes in AABW production is expected. Analysis of satellite data indicates that the summer minimum extents (and area) in the Weddell Sea were highly variable from 1979 through 1995, but the correlations of summer ice characteristics to those of subsequent winter are generally weak. We observed, instead, that unusually low summer minimum extents which occurred in 1981, 1985, 1988, and 1993 were preceded by high winter maximum extents (with effects in 1985 not as large as other years). During years of high winter maximum extents, the meridional winds were observed to be relatively strong and coastal polynya areas were greater than average. Wind effects appear to be an important factor in causing the large variability observed in the ice cover while the effects of air temperature variations are not apparent. Temporal variability of AABW in the western Weddell Sea from 1963 through 1993 also is observed, with the bottom water salinity being significantly lower in 1992 and 1993 than those in earlier decades. A strong direct connection of the ice data with AABW is not apparent from available data but our results suggest the intriguing possibility that AABW formation is affected by the passage of the Antarctic Circumpolar Wave.

1. INTRODUCTION

Around the periphery of Antarctica, the Weddell Sea has the most extensive sea ice cover both in summer and in winter. The sector that extends from 60°W to 20°E [after *Zwally et al.*, 1983*b*] has a sea ice areal extent that usually ranges from a summer minimum of about 0.9 x 10^6 km^2 to a winter maximum of about 7.9 x 10^6 km^2. The Weddell Sea has been cited as one of the major sources of bottom water for the world oceans [*Gordon*, 1991]. Recent studies [*Gordon et al.*, 1993; *Muench and Gordon*, 1995; *Fahrbach et al.*, 1995] indicate that in the western rim of the Weddell Sea, a 300 to 500 m thick bottom layer of very cold water (the average potential temperature of the lower 400 m of the water column is -0.8°C) is transported north-ward at a rate of 5 to 6 x 10^6 m^3 s^{-1}. Salinity stratification within this cold benthic layer suggests that a variety of processes may feed this large outflow of the concentrated Antarctic Bottom Water [AABW; *Gordon et al.*, 1993], which is referred to as the Weddell Sea Bottom Water (WSBW).

Passive microwave remote sensing from satellites, uninterrupted by the presence of clouds, provides an extraordinary time series of the Southern Ocean sea ice cover from 1973 to the present. As the sea ice is so closely linked with ocean-atmosphere coupling due to brine release during ice production, and is a causal factor in ocean overturning related to AABW formation, its long-term behavior is an important indicator of climate change. While the existing Weddell Sea oceanographic data is too sparse to construct a meaningful time series, sea ice variability may provide a proxy indicator of changes in ocean stratification, including the production of AABW.

In this paper, we first characterize the spatial extent and interannual variability of the Weddell Sea summer ice cover that reflects initial conditioning at the onset of the growth season. Relationships of the summer extent with subsequent and previous winter extents are then studied. Coastal polynyas are investigated in the context of ice production and the variability of winter extents. We assess the ice production contribution in both the western section of the Weddell Sea where the shelf is wide, and the eastern section where the shelf is narrow. Wind, surface air temperature, and hydrographic data are analyzed and relationships to the sea ice cover are explored.

2. THE WEDDELL SEA SUMMER ICE COVER

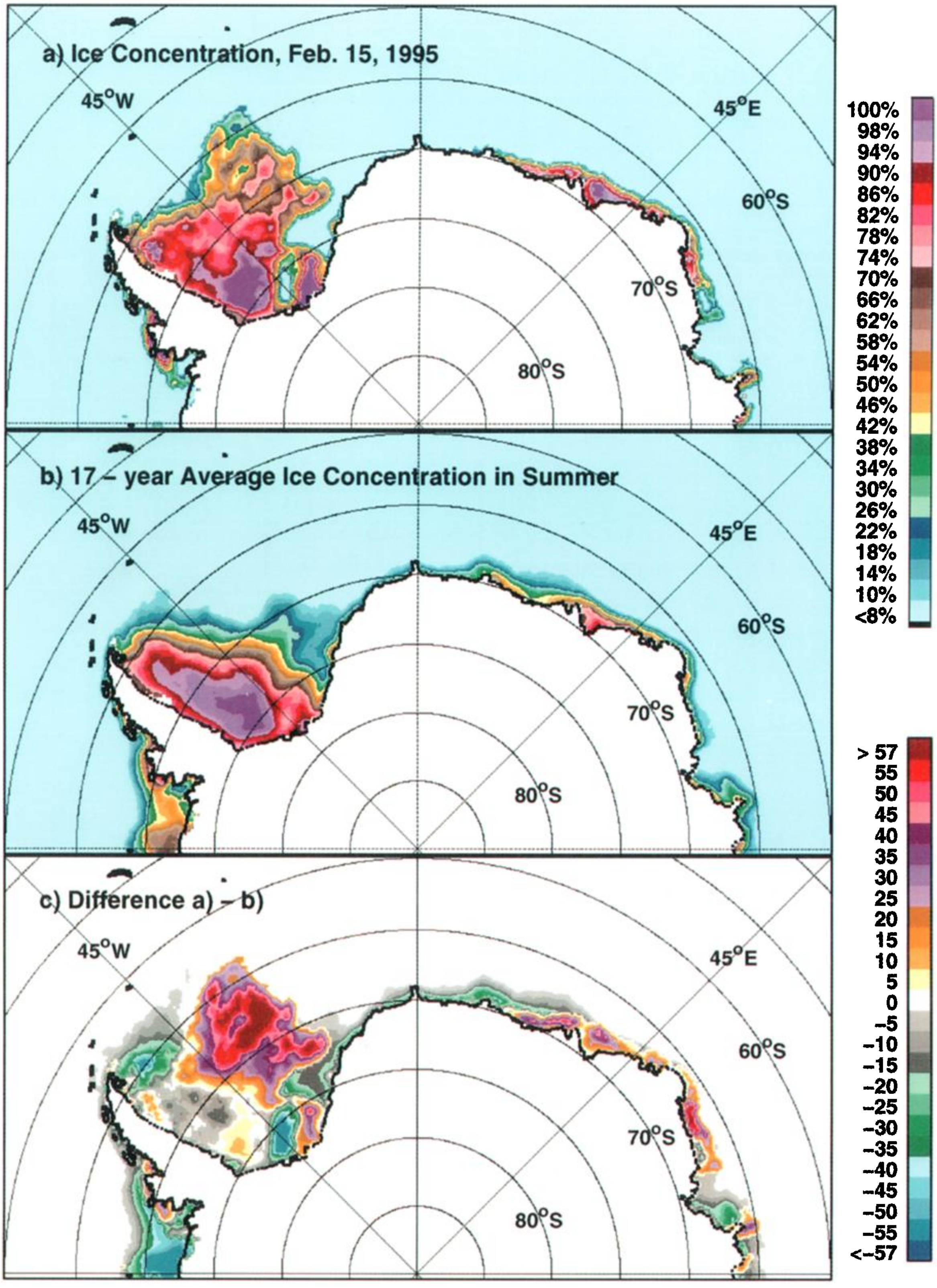
The summer sea ice cover in the Weddell Sea is generally located in the western region adjacent to the Antarctic Peninsula [*Zwally et al.*, 1983*b*; *Gloersen et al.*, 1992]. The presence of near-year-round ice cover keeps the surface of the ocean in summer colder than in other regions as the high albedo of ice keeps the ocean from absorbing solar energy. Additionally, summer meltwater from sea ice and the neighboring ice shelves contributes to a cold surface layer. The advection characteristics of the ice cover in autumn through winter, as inferred from buoy data [*Ackley and Holt,* 1984; *Massom*, 1992; *Kottmeier and Sellmann*, 1996], indicate that the region is a major source of sea ice and high salinity shelf water (HSSW), the key component of ice shelf water (ISW) and AABW.

The ice concentration maps used in our analysis were derived from Special Sensor Microwave Imager (SSM/I) data using the Bootstrap technique as described in *Comiso* [1995]. Changes in surface emissivity during the summer cause errors in the retrieval but the latter is minimized by using a set of reference brightness temperatures based on results of comparative analysis of SAR and SSM/I data [*Comiso and Ackley*, 1994]. Although an ocean masking has been applied on the daily images, some residuals in the open ocean remained and had to be removed manually using an interactive computer technique.

The summer minimum in 1995 (Plate 1*a*), which occurred on February 15, extended as far east as 20°W with a large fraction to the west of the 45°W. While a large part of the immediate coastal region in the eastern Weddell Sea was free of ice (east of 30°W), the normal situation, the 1995 summer ice cover appears different when compared with previous years [e.g. *Zwally et al.*, 1983*b*; *Gloersen et al.*, 1992] due to the presence of an extensive ice-covered area between 30°W and 45°W over the deep ocean. The average of the summer ice concentration maps in the Weddell Sea during summer minima from 1979 through 1995 (Plate 1*b*) depicts an ice cover significantly different from the single year coverage in 1995 (Plate 1*c*). The yellows, oranges, and reds represent positive changes (more ice in 1995 relative to the mean) in the ice cover, while the grays, greens, and blues represent negative changes (less ice). The difference image shows more quantitatively the large positive change in extent that occurred in the eastern region in 1995. Some negative changes are notable in the southern region where the coastal polynya occurred in 1995 and in the northern region adjacent to the tip of the Antarctic Peninsula, demonstrating the extent of variability in the summer ice cover that may be expected.

The interannual variability is indeed large for the years 1979 through 1994 (Plate 2). The summer ice cover is always concentrated in the western region adjacent to the Antarctic Peninsula, but the size, shape, and general location change considerably from one year to the next. During some years (e.g., 1980), a narrow tongue of ice extends from the tip of the Antarctic Peninsula towards the east. In other years (e.g., 1988, 1989), the coastal regions are basically free of ice from the east to as far west as the Filchner Ice Shelf (35°W), while in other years (e.g., 1991), the coastline is covered up to the Riiser-Larsenisen Ice Shelf (15°W). There are also years (e.g., 1993) when the ice cover is extremely

Plate 1. (*a*) Color-coded ice concentration map of the Weddell Sea ice cover during summer ice minimum in 1995; (*b*) Average ice concentration map of summer minima from 1979 through 1995; and (*c*) Difference between the average map and the 1995 summer ice minimum map.


a) Ice Concentration, Feb. 15, 1995
45°W
45°E
60°S
70°S
80°S
b) 17 – year Average Ice Concentration in Summer
45°W
45°E
60°S
70°S
80°S
c) Difference a) – b)
45°W
45°E
60°S
70°S
80°S
100%
98%
94%
90%
86%
82%
78%
74%
70%
66%
62%
58%
54%
50%
46%
42%
38%
34%
30%
26%
22%
18%
14%
10%
<8%
> 57
55
50
45
40
35
30
25
20
15
10
5
0
–5
–10
–15
–20
–25
–30
–35
–40
–45
–50
–55
<–57

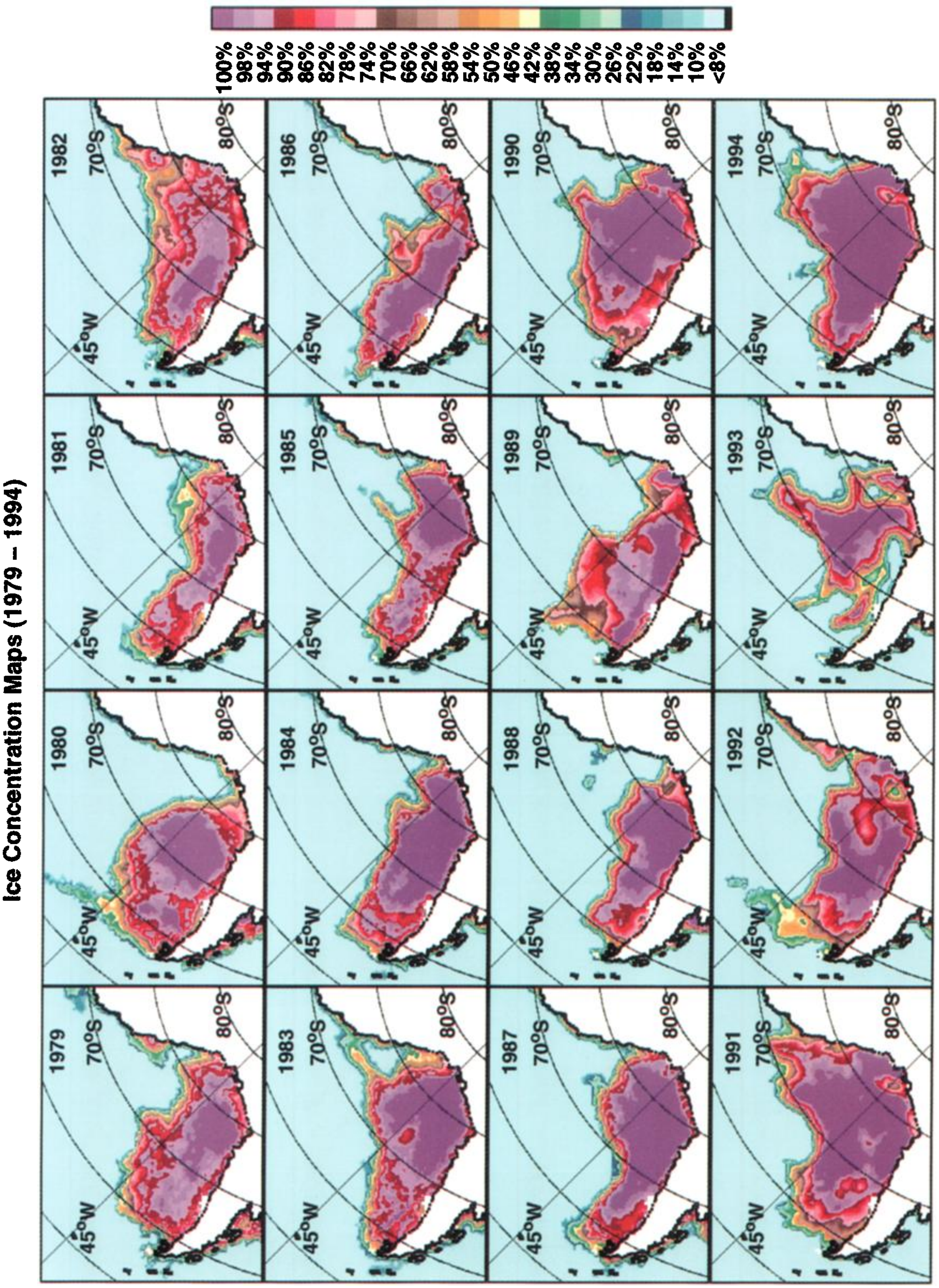


Plate 2. Color-coded ice concentration maps of the Weddell Sea ice cover during summer minimum for each year from 1979 through 1994. The Julian date of the occurrence of the minimum for each year is given in Table 1.

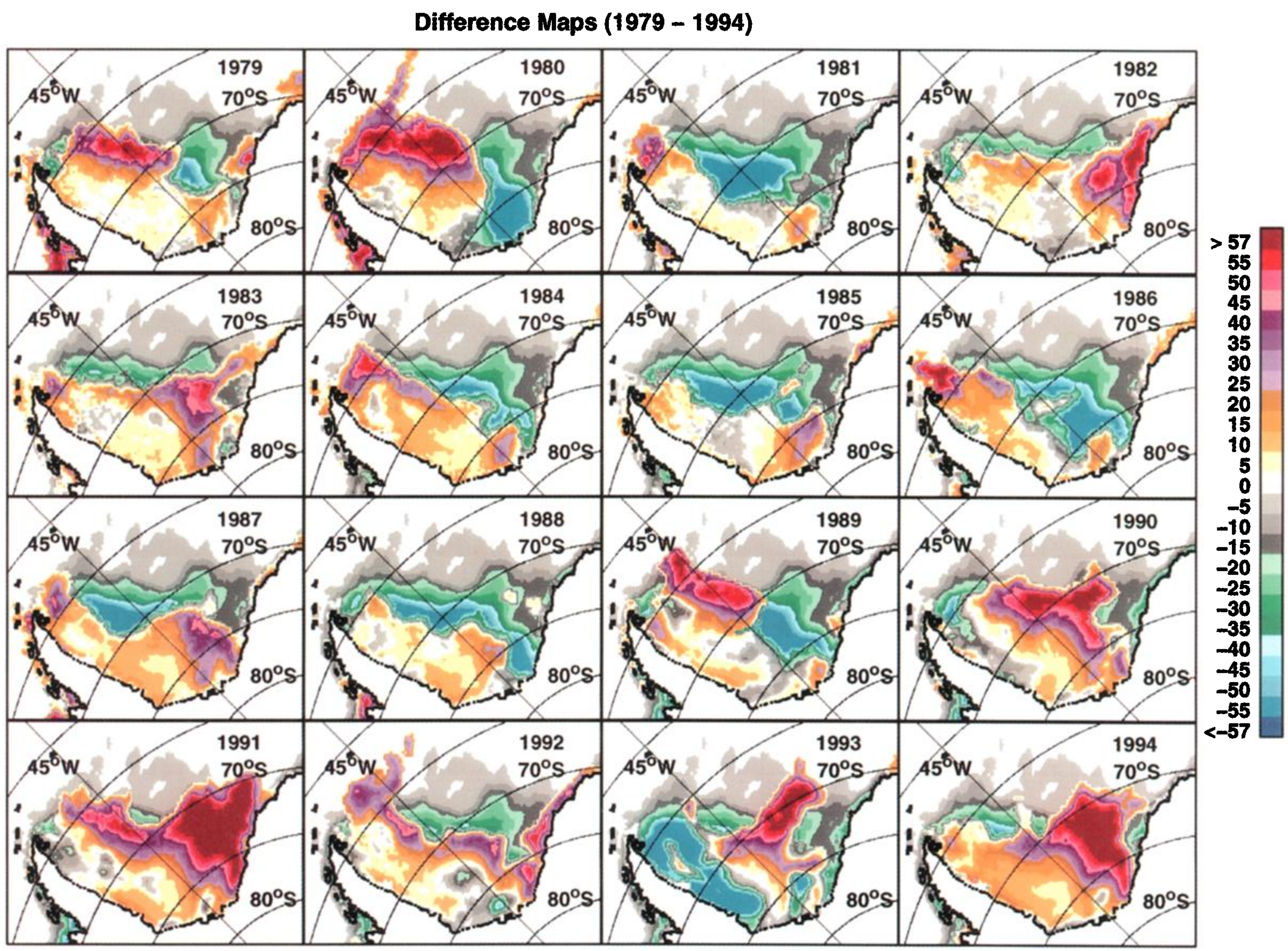


Plate 3. Color-coded summer sea ice minimum anomaly maps in the Weddell Sea from 1979 through 1994. Each map represents the difference between the ice concentration map of each year and the average ice concentration map shown in Plate 1*b*.

Table 1. Ice extents during summer minima and winter maxima, lengths of summer and winter, lengths of growth and decay, and expansion rate in winter. The numbers in parenthesis are the Julian dates (JD). Low values in summer and high values in winter are in bold type.

Year	Minima Summer 10^6km^2 (JD)	Maxima Winter 10^6km^2 (JD)	Lengtn Summer(days) <2M km^2 (JD)	Length Winter(days) >6M km^2 (JD)	Length Growth (days)	Length Decay (days)	Ave.. Exp. Rate
1979	1.33(48)	6.86(276)	59(23-83)	125(189-313)	228	147	0.0242
1980	1.37(57)	**7.89(267)**	77(22-98)	157(180-336)	210	166	0.0310
1981	**0.94(67)**	7.39(263)	104(4-107)	129(190-318)	196	169	0.0329
1982	1.33(66)	6.63(272)	87(9-95)	83(217-299)	206	143	0.0257
1983	1.25(49)	6.75(261)	71(18-88)	83(234-316)	212	153	0.0259
1984	1.14(48)	**6.90(258)**	79(15-93)	131(187-317)	210	158	0.0274
1985	**0.93(50)**	6.48(234)	87(12-99)	113(209-321)	184	189	0.0302
1986	1.08(57)	6.15(235)	91(16-106)	79(230-308)	178	183	0.0284
1987	1.20(52)	**7.37(243)**	89(15-103)	124(207-330)	191	181	0.0323
1988	**0.93(58)**	7.21(252)	99(10-108)	139(196-334)	194	179	0.0324
1989	1.11(65)	6.82(246)	91(11-101)	92(213-304)	181	169	0.0315
1990	1.38(49)	6.19(264)	73(13-95)	58(217-274)	215	159	0.0224
1991	1.58(57)	7.26(271)	54(26-79)	133(198-330)	214	152	0.0265
1992	1.37(57)	**7.55(220)**	58(24-81)	138(181-318)	163	191	0.0379
1993	**1.17(45)**	6.82(263)	80(13-92)	110(203-312)	218	151	0.0259
1994	1.48(48)	6.97(241)	59(19-77)	131(186-316)	193	171	0.0284
1995	1.67(46)	6.97(231)	53(30-82)		185		0.0286

different, with eastward projections in the north and the formation of large polynyas in the south.

The deviations from the average (Plate 3) provide a quantitative measure of how typical the ice cover has been for each year up to 1994. Summer ice minimum extent was close to average in 1983, and 1987. Relatively low values of ice area occurred in 1981, 1985, 1986, 1988, 1989 and 1993, while relatively high values occurred in 1979, 1980, 1982, 1990, 1991, 1992, and 1994. The historical record from 1979 through 1995 indicates that the highest value among the minimum extents occurred in 1995. Overall, the summer ice extent has been very variable, with those in the 1990s being more variable than in other years.

3. INTERANNUAL CHANGES IN ICE EXTENT AND ACTUAL ICE AREA

Ice extent is defined as the ocean surface area that is partly or completely covered by sea ice and is quantified by taking the sum of the areas of each pixel with ice concentrations greater than 15%. Actual ice area, on the other hand, is defined as the surface area occupied by sea ice and is derived from the sum of the product of the ice concentration and the area of each pixel with concentrations greater than 15%. The precision of our estimates of ice extent and actual ice area is of the order of 2% based on statistical and sensitivity analyses [*Zwally et al.*, 1983*b*; *Gloersen et al.*, 1992]. However, based on available validation data sets, the absolute error is larger and estimated to be about 3% or greater. The use of different sensors (i.e., SMMR from 1979 to 1987 and SSM/I from 1987 to 1995) introduces some uncertainties in the time series because of different antenna patterns and effects of sidelobes. However, the difference in extent during the sensor overlap period from mid-July through mid-August 1987 was very small.

Minimum ice extents and actual ice areas in the Weddell Sea sector from 1979 through 1995 during summer are presented in the first columns of Tables 1 and 2, respectively. Maximum ice extents and actual ice areas for the subsequent winter of each year are given in the second columns of the two tables. In this study, the western limit of the Weddell sector has been modified from 60°W to 62°W to include all sea ice to the east of the Antarctic Peninsula.

It is apparent that there are large seasonal and inter-

Table 2. Actual ice areas during summer minima and winter maxima, lengths of summer and winter, lengths of growth and decay, and ice expansion rate in winter. The numbers in parenthesis are the Julian dates (JD). Low values in summer and high values in winter are in bold type.

Year	Minima Summer 10^6km^2 (JD)	Maxima Winter 10^6km^2 (JD)	Length Summer(days) <1.5M km^2 (JD)	Length Winter(days) >5M km^2 (JD)	Length Growth (days)	Length Decay (days)	Ave. Exp. Rate
1979	1.01(48)	6.24(272)	58(20- 77)	163(172-334)	224	141	0.0233
1980	0.99(47)	**6.91(269)**	75(22- 96)	161(171-331)	222	160	0.0267
1981	**0.67(63)**	6.69(263)	105(2-106)	150(177-326)	200	141	0.0287
1982	0.93(38)	5.81(272)	83(5- 87)	118(190-307)	234	161	0.0218
1983	1.01(67)	6.12(259)	67(18- 84)	123(193-315)	192	165	0.0266
1984	0.90(58)	**6.18(260)**	77(11- 87)	139(184-322)	202	156	0.0261
1985	**0.72(50)**	5.96(263)	91(7- 97)	149(178-328)	188	160	0.0278
1986	0.80(57)	5.72(263)	93(2-104)	109(203-311)	206	155	0.0239
1987	0.96(52)	**6.52(252)**	89(13-101)	136(186-321)	200	171	0.0278
1988	**0.71(57)**	6.51(255)	103(1-104)	156(183-338)	198	162	0.0293
1989	0.86(51)	6.29(247)	91(10-100)	128(191-318)	196	167	0.0277
1990	1.12(48)	5.68(249)	78(14- 91)	110(198-307)	200	172	0.0228
1991	1.35(55)	6.58(274)	33(31- 69)	139(190-328)	219	147	0.0239
1992	1.01(55)	**6.45(220)**	53(22- 74)	147(173-319)	165	194	0.0330
1993	**0.75(48)**	6.15(263)	87(4-90)	138(187-324)	215	151	0.0251
1994	1.25(48)	6.29(242)	41(25- 65)	154(175-328)	194	171	0.0260
1995	1.11(47)	6.31(232)	55(27-82)		185		0.0281

annual variabilities in both extent and actual area. The ice extent is shown to have summer minimum values ranging from 0.9 x 10^6 km^2 to 1.9 x 10^6 km^2, while the winter maximum ranges from 6.1 x 10^6 km^2 to 7.9 x 10^6 km^2 (Table 1). High peak values during winter occurred in 1980, 1984, 1987, and 1992. These high values are shown to be followed by low summer values in 1981, 1985, 1988, and 1993, respectively. Also, low peak winter values in 1982, 1990 and 1993 are followed by relatively high summer minima in 1983, 1991 and 1994. This phenomenon was observed as a general pattern by *Zwally et al.* [1983*a*] and will be addressed in more detail in later sections. The yearly and seasonal characteristics of the actual ice areas (Table 2) appear to be similar to those in the ice extent plots. There are small differences in the relative location of peaks in the actual area data when compared with those of the ice extent (e.g., slightly higher winter maximum in 1988 than in 1987), but generally the features are similar.

To evaluate the possible direct influence of the summer ice cover, a regression analysis was done between the minimum extents and other parameters associated with ice growth. Among these parameters are lengths of summer and winter, defined (for the purpose of making comparisons) as the number of days in which the areal extents are <2 x 10^6 km^2 (summer) and >6 x 10^6 km^2, (winter), respectively. The respective values for summer and winter lengths are given in columns 3 and 4 of Table 1. Finally, the number of days from summer minimum to winter maximum and from winter maximum to summer minimum for each year are given in columns 5 and 6, respectively, while the areal expansion rates (defined as the change in ice extent/area from summer minimum to winter maximum divided by the number of days between minimum and maximum) are given in column 7.

The correlations of the summer ice minimum extent to the various variables are generally weak. The ice minimum is best correlated with the length of summer, the correlation coefficient being -0.88. This is expected since an early (or long) summer would allow for more solar radiation and warming of the ocean (due to lower albedo) leading to further melting of sea ice. The other parameters that correlate somewhat with minimum extent are the net change in extent and the areal expansion rate of the subsequent winter, with correlation coefficients of -0.42 and -0.30, respectively. These coefficients imply that 18% and 9% of the variations in the net change in extent and expansion rate, respectively, are accounted for by differences in summer minimum extents. However, the negative sign is opposite to that expected from the conditioning effect: that an expansive summer ice causes the enhancement of ice growth and ice production in the subsequent winter. Similar regression analysis was done using the ice area and the results are very similar to those of ice extent. The lack of a strong linear correlation between summer minima and the variables in subsequent winter is an indication that there are other factors that affect the relationships, as discussed in the following sections.

4. ATMOSPHERIC AND OCEANOGRAPHIC CONNECTIONS

One of the interesting results of the ice extent analysis is that high maximum extents (or ice area) in winter are followed by low minimum extents (or ice area) during the subsequent summer (in bold, Tables 1 and 2). This phenomenon occurred four times (1980, 1984, 1987, and 1992) during the 17-year study period, with the effect in 1984 not as big as those in the other three years. These high winter maximum values coincide approximately with the extended sea ice edge reported by *White and Peterson* [1996] for the Weddell region, which they connected to the eastward propagating Antarctic Circumpolar Wave (ACW) observed in a variety of ocean and atmospheric parameters. *White and Peterson* [1996] reported a more northerly sea ice edge passing by 60°W to 30°W in 1979-1980, 1983 (weak), 1987-1988 (strong), and 1991. Their study period ended in 1991 but two years are usually affected and the last occurrence likely extended through 1992. Also, the anomalously low summer minima immediately follow the winter maxima and are also likely influenced by the passage of the ACW.

4.1. Air Temperature and Ice Extent

Surface air temperature has been shown to be well correlated with sea ice extent [*Weatherly et al.*, 1991; *Jacka and Budd*, 1991; *Jacobs and Comiso*, 1993; *Smith et al.*, 1996]. A similar relationship is not apparent in the Weddell Sea region from averages of surface temperature data between 65°S and 78°S and from 1979 to 1995 (Figure 1*a*). The data used are from three different sources: (a) Temperature-Humidity Infrared Radiometer (THIR) satellite data (1979-1985) as described in *Comiso* [1994]; (b) European Center for Medium Range Weather Forecasts (ECMWF) data (1985-1995); and (c) the Australian Bureau of Meteorology (ABM) data set. The ECMWF temperature record is further subdivided into ECMWF-1 data (1985-1992), derived from climatological data, and ECMWF-2 data (1992-1995) derived using a prognostic equation for modeling surface air temperature. A summary of ECMWF analysis updates is given by *Trenberth et al.* [1989]. The change in technique on August 17, 1992 caused an apparent discontinuity or bias in the temperature record. The apparent difference is minimized by subtracting 5K (based on the difference of the averages between the two data sets) from each of the ECMWF-2 data points. We shall assume that the precision of data from each set, which appears consistent and coherent, is good enough to provide useful information

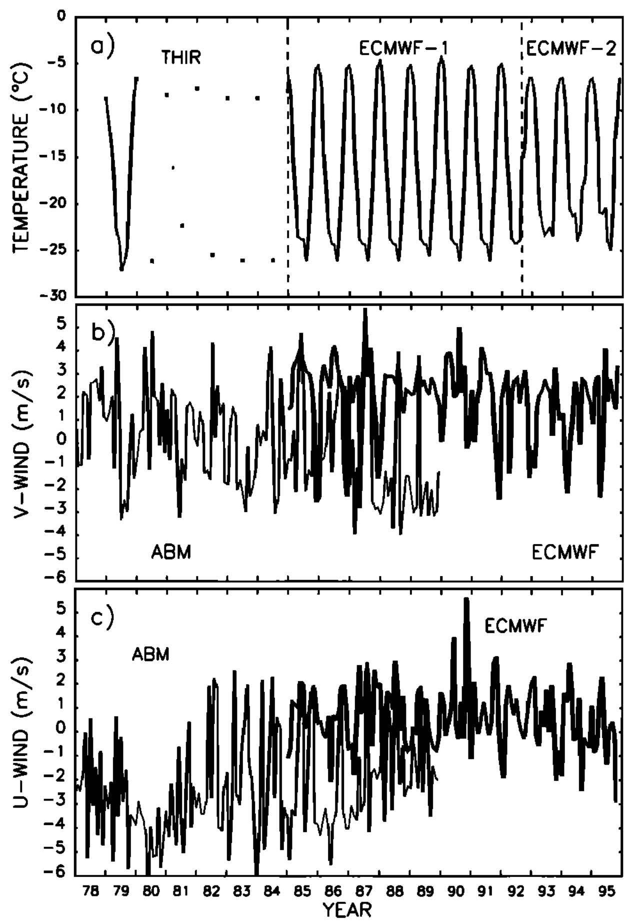


Fig. 1. (*a*) Monthly average surface temperatures in the Weddell Sea Sector for >65°S from 1979 through 1985 using satellite Nimbus-7 THIR data and ECMWF data; (*b*) Monthly meridional (V) winds in the Weddell Sea Sector from 1985 through 1995 using ABM and ECMWF data; and (*c*) Monthly zonal (U) wind in the Weddell Sea Sector from 1985 through 1995 using ABM and ECMWF data. The averages were over the area 62°W to 20°E and 65°S to the continent. Each tic mark along the abscissa represents one year of data starting with January.

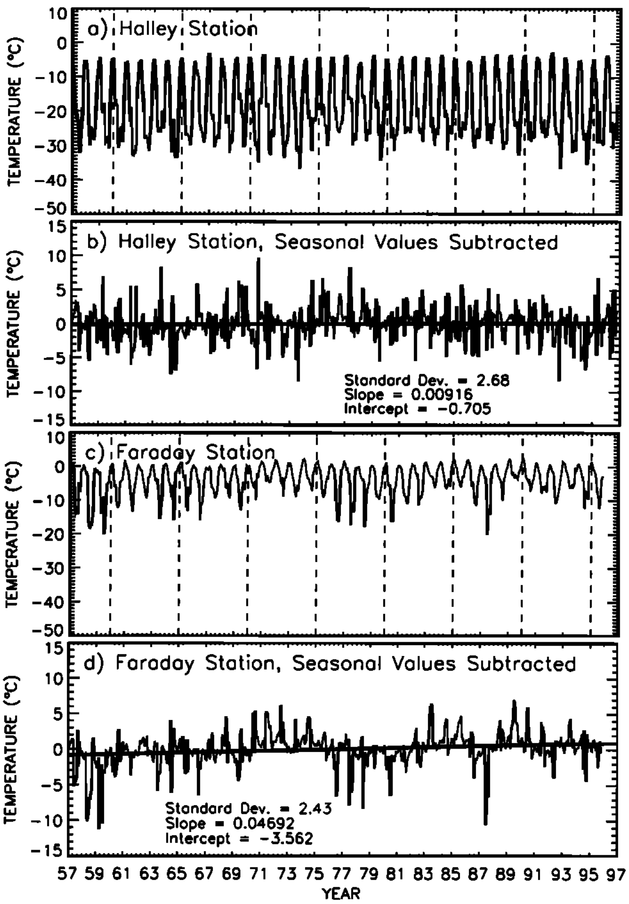


Fig. 2. Surface temperature air measurements (3 m from ground) from the meteorological stations in (*a*) Halley Station; (*b*) Halley Station with seasonal averages subtracted; (*c*) Faraday Station; and (*d*) Faraday Station with seasonal averages subtracted.

about the temporal variability of the surface air temperature.

The plot in Figure 1*a* shows that cold temperatures cannot explain the relatively high ice extent in 1980, since the THIR surface temperature record indicates warmer winter temperatures in 1980 than 1979 when the ice extent was considerably lower. Also, the ice extent peak values in 1987 and 1992 do not correspond to unusually cold winters in the ECMWF-1, and ECMWF-2 data. Similarly, the low extents in the summer of 1981, 1988, and 1993 do not appear to correspond to exceptionally warm periods.

The effect of temperature was further examined using meteorological station data at the Halley station (75.88°S, 26.07°W; Figures 2*a* and 2*b*) for the period 1957 through 1996. We analyze the entire data set, including those before 1978 to examine possible long term cyclical patterns that may be present in the temperature data. The Halley air temperature record reveals colder winter temperatures during some years (e.g., 1961, 1964, 1968, 1970, 1973, 1979, 1984, 1989, 1992, and 1994) than other years. Except for 1992, however, these years (from 1979) do not match those of the peaks in ice extent during winter. Some peaks in temperature (e.g., 1959, 1967, 1971, 1977, 1979, 1984, 1987, and 1992) also do not exactly match the dips in ice extent (Table 1). Meteorological station data at Cape Adams (75.01°S, 62.53°W), Butler Island (72.20°S, 60.34°W) and Larsen Ice Shelf (66.97°S, 60.55°W) from 1986 through 1995 were also examined and, again, the peaks (or troughs) in the temperature data do not show direct relationships with the peaks (or troughs) in the ice extent and ice area data.

To gain insight into the relationship of monthly temperature (as observed at the Halley Station) with ice extent, the same set of data is plotted twice in Plate 4 to show: (a) seasonal effects, indicated by different colors for each month (Plate 4*a*), and (b) interannual variability, indicated by different symbols and colors for each year (Plate 4*b*). A hysteresis loop is evident, showing a relatively strong but non-linear relationship of the two variables during the growth season but a much weaker one during the decay season. Ice extent is shown to have the highest values during the months of July, August, September, and October. During these months, the temperature ranges from -10°C through -37°C, which is about the same temperature range for the ice cover during the growth period. Also, during the decay period (i.e., December), the ice extent varied substantially from one year to another, although the temperatures were nearly the same (at close to melting temperatures). These phenomena may partly explain why the ice extent in this region is not well correlated with temperature. The scatter plots also show, from a different perspective, the relative location of the previously mentioned low summer extents in 1981, 1985, 1988, and 1993 and high winter extents in 1980, 1984, 1987, and 1992. The data for 1980 and 1990 are in closed symbols to illustrate the modulation (when matched with summers of 1981 and 1991) of the ice extent distribution as indicated earlier. Note that in 1992 when the surface temperature was coldest, the ice extent was not as high as in 1980 when the extent was highest.

The surface temperature data at the Faraday station (Figure 2*c*) were also analyzed because, although the station is located on the western side of the Antarctic Peninsula (65.25°S, 64.27°W), it is near the northern

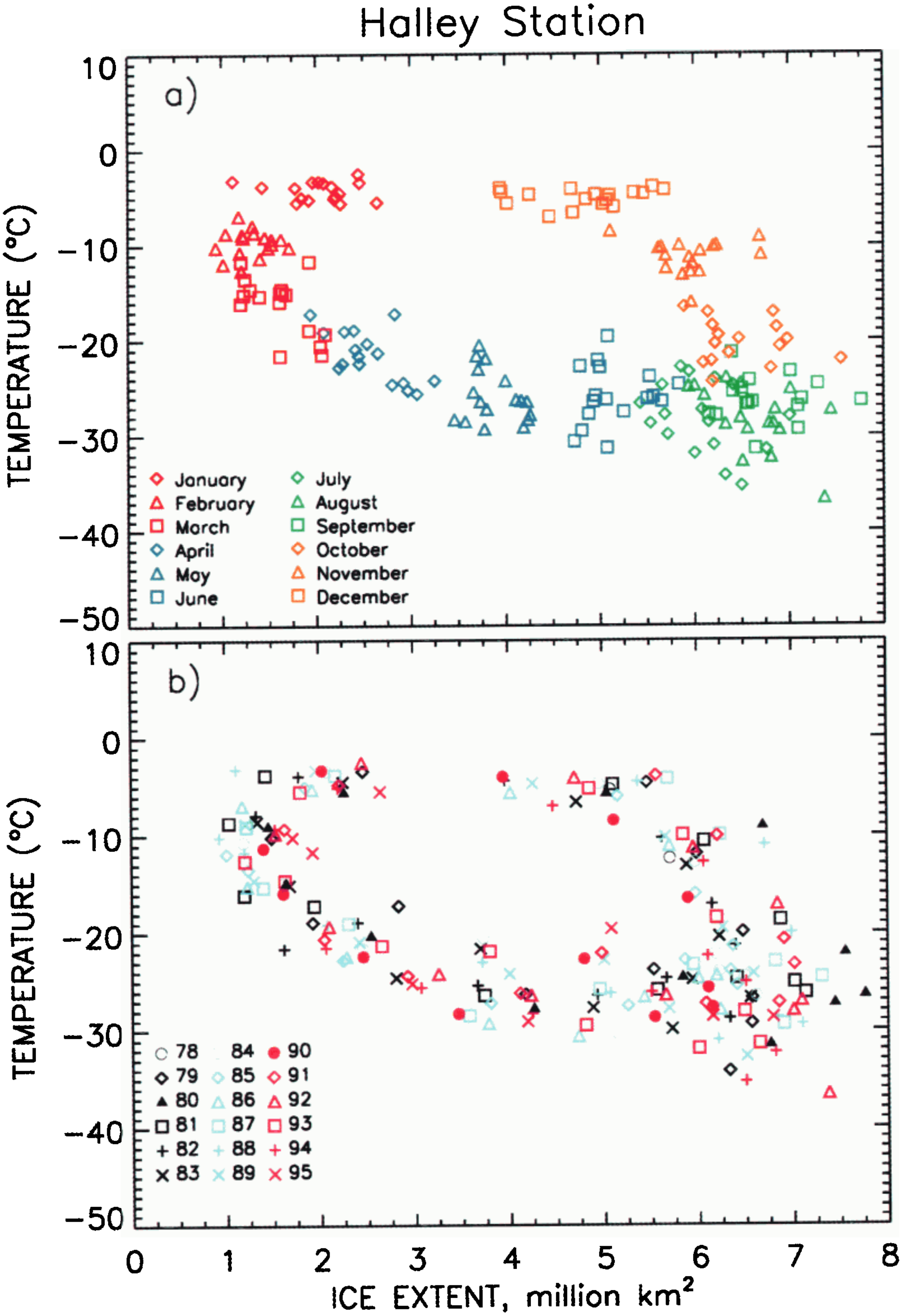


Plate 4. Surface temperature at Halley Station versus ice extent for each month from November 1978 through December 1995 with (*a*) different color symbols representing different months and (*b*) different symbol and color for each year (1978-1995).

Table 3. Average concentrations (weighted) during summer minima and winter maxima and polynya areas in Zones-, Zone-2, and Zone-3 in the Weddell Sea. Values in parentheses were derived using ice concentrations (IC-2) from the alternate (Arctic) algorithm.

Year	<C>		Winter Polynya Area(10^3km^2)			Salinization (°/₀₀)			
	Summer	Winter	Zone-1	Zone-2	Zone-3	Zone-1	Zone-2	Zone-3	Weighted
1979	0.759	0.910	20.8(13.4)	11.4(7.8)	39.5(31.4)	0.210	0.304	0.245	0.241
1980	0.723	0.876	24.4(11.4)	12.3(9.7)	39.9(36.6)	0.246	0.328	0.238	0.253
1981	0.713	0.905	17.5(11.6)	11.2(8.5)	35.3(29.4)	0.177	0.300	0.213	0.212
1982	0.699	0.876	19.6(15.6)	11.3(9.2)	32.7(27.3)	0.198	0.301	0.208	0.217
1983	0.808	0.907	18.4(12.4)	10.7(7.9)	39.3(33.8)	0.186	0.287	0.235	0.224
1984	0.789	0.896	18.2(13.9)	10.2(8.2)	33.2(27.6)	0.184	0.274	0.216	0.212
1985	0.774	0.920	25.5(17.7)	10.8(8.8)	33.6(28.9)	0.257	0.290	0.211	0.238
1986	0.741	0.930	18.9(13.1)	11.2(8.7)	33.3(27.3)	0.191	0.299	0.213	0.217
1987	0.800	0.885	17.4(9.4)	13.0(9.9)	36.2(28.8)	0.176	0.346	0.220	0.221
1988	0.763	0.903	19.5(7.9)	12.1(8.8)	40.2(32.7)	0.197	0.323	0.257	0.244
1989	0.775	0.922	19.4(12.7)	11.0(9.1)	37.4(28.9)	0.196	0.295	0.217	0.220
1990	0.811	0.917	20.7(7.8)	10.4(8.1)	33.6(26.1)	0.218	0.278	0.215	0.221
1991	0.854	0.906	24.8(11.2)	12.6(10.1)	30.8(25.1)	0.250	0.336	0.197	0.235
1992	0.737	0.854	21.5(9.8)	15.2(11.5)	40.5(25.2)	0.217	0.406	0.253	0.261
1993	0.641	0.902	21.5(10.3)	15.3(12.5)	34.0(23.7)	0.217	0.409	0.217	0.243
1994	0.844	0.902	20.9(10.1)	14.3(11.7)	32.1(24.1)	0.211	0.382	0.207	0.232
1995	0.665	0.905	32.0(7.6)	14.4(12.0)	35.6(26.3)	0.323	0.385	0.230	0.232

end of the peninsula. The surface air temperatures from this station may thus reflect those at the eastern side of the peninsula, especially near the ice edges. The correlation of these temperatures with the ice extents in the Weddell Sea is, however, poor. This may be partly because the average air temperatures in the Weddell Sea region are generally colder than those in the Bellingshausen Sea, with mean values in the former well below the threshold temperature for melting. Mean values of -18.4° are observed at Halley Bay and -5.5°C at the Faraday Station [*King*, 1991]. Also, after subtracting seasonal averages, the temperature plots shown in Figures 2*b* and 2*d* also indicate slopes of 0.009 and 0.047 for Halley and Faraday Stations, respectively. A significant warming trend observed at Faraday is not reflected in the Halley station data. Increasing air temperatures eventually affect the ice extent and the differences in magnitude and slope may explain why the decreasing ice extent observed in the Bellingshausen Sea region from 1979 through 1994 by *Jacobs and Comiso* [1997] is not observed in the Weddell Sea.

4.2. *Wind Effects and Ice Extent*

To investigate the effect of wind, we first examine interannual changes in the interior of the ice cover. The weighted averages of ice concentration in the Weddell Sea sector during summer minima and winter maxima for each year are given in columns 1 and 2 of Table 3. The weighted values, <C>, are calculated from

$$\langle C \rangle = \Sigma_i C_i A_i / \Sigma_i A_i \qquad (1)$$

where C_i is the ice concentration in the data grid element, i, with area A_i, and the summation, Σ_i, is taken for all data elements with ice concentration greater than 15% in the study area. The average concentration ranges from about 90% during the winter to about 70% during the summer. Note that in the winter of 1980, 1984 1987, and 1992, the weighted average concentrations were relatively lower than in other years except 1982 when the average values are similarly low. This suggests more divergence and hence larger extents during these years than other years. The data also show relatively low average concentrations in early summer (i.e., January) of 1981 and 1993, when the summer minima were unusually low, suggesting the possible influence of wind on the ice cover in summer.

The short term effect of wind on ice concentration was studied using concurrent daily wind and ice concentration data, from the Halley station and SSM/I, respectively, in a study area adjacent to the station. The results show good negative correlations between wind and ice concentrations during the time periods when the fluctuation in size of the coastal polynya areas was significant. The correlation coefficients for total and meridional winds versus ice concentrations are -0.63 and -0.46, respectively.

Monthly meridional (V) and zonal (U) winds from 1979 through 1995 (Figures 2*b* and 2*c*, respectively) are used to investigate long connections between wind and ice extent. We present data from 1979 through 1989, compiled by the Australian Bureau of Meteorology, and those from 1985 through 1995, from ECMWF. Again, we treat these two data sets separately because of possible biases which are apparent during overlap periods (1985-1989). However, many of the data points show similar temporal variabilities during the time of overlap. In 1980 when winter ice extent was relatively high, the meridional wind was also high and northerly while the zonal wind was high and easterly. The strong wind caused divergence that likely led to more extensive ice cover than other years.

Monthly averages of wind data may not provide full information on wind effects because of large fluctuations during each month, and the short-term effects of some of the strong winds may have been averaged out. Short-term effects, however, are difficult to evaluate in the context of long-term changes because so many complex processes are involved. To gain additional insights into long-term variability, we analyzed one-year running averages of the meridional and zonal components of the wind in two study areas. Analysis of the components provides a means to sort out wind advection effects, especially to the north or to the west. The two study areas are (a) the western region (between 60°W to 40°W and called A1), where much of the summer ice cover is located; and (b) the eastern region between 40°W to 20°E (called A2), which is primarily in the seasonal ice region. Only wind data between 65°S to 72°S are analyzed in both areas.

One-year running averages of meridional and zonal components of the wind from 1978 through 1995 are shown in Figure 3, using the same set of data used in Figure 1. The data points in Figure 3 are relatively low compared to those in Figure 1 because each represents an average of monthly data over an entire year. While differences in the meridional wind distribution are apparent during the overlap period (Figure 3*a*), except for 1988, the values from the two sources (ABM and ECMWF) show a similar variability in A1 during this period. In A2, the values from the two sources during the overlap period agree very well (Figure 3*b*). Overall, the plots show that the one-year running averages of meridional winds provide distinct interannual variations

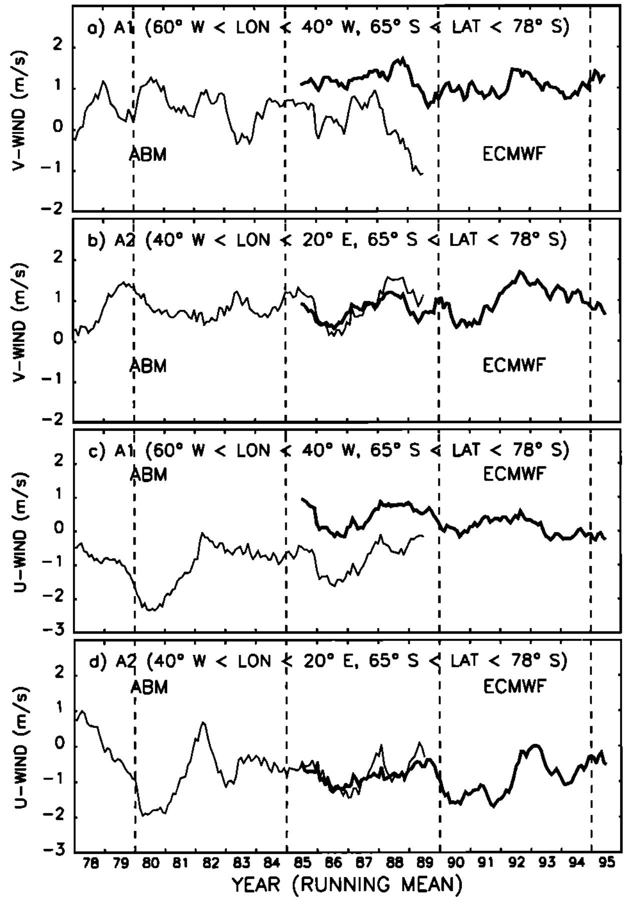


Fig. 3. Yearly-running averages of monthly meridional (*a* and *b*) and zonal (*c* and *d*) winds over sea ice in A1(65°S to 78°S, 60°W to 40°W) and A2(65°S to 78°S, 40°W to 20°E) study areas.

and other information that are not apparent from the monthly plots (Figure 1). In A1, ABM winds have peak values in 1979, 1980, 1982, 1984, and 1987, while the ECMWF wind data show peak values in 1988 and 1992, and 1995. In A2, enhancements in the ABM meridional winds are apparent in 1979, 1983, 1985, and 1988, while enhancements in the ECMWF winds are evident in 1988, 1989, and 1992. For completeness, the zonal components of the wind are also shown. Except for a few exceptions, the U-wind is generally westerly, and where it is easterly, as with ECMWF winds, there appears to be a bias with respect to the ABM values. The U-wind appears to be most prominent in 1980, as cited earlier, when the wind is relatively strong and negative in both A1 and A2 study areas and when ice extent was most extensive.

The years of occurrence of peak values in the winter ice extents (e.g., 1980, 1984, 1987, and 1992) are generally consistently close to those of peak values in the meridional winds. The relatively lower average ice concentrations during these periods (Table 3) are also consistent with wind effects. The smaller enhancement in the ice extent in 1984 compared to the other years may be associated with relatively lower wind speed during the year. The correlation of wind with ice extent is slightly better in A2 than in A1. This will be discussed in the context of coastal polynya areas in the next section.

We present the following hypotheses to explain the phenomenon of a "low summer minimum following a large winter maximum ice cover":

1. The Antarctic Circumpolar Wave (ACW) leads to greater winter ice coverage every 4 to 5 years [*White and Peterson, 1996*]. Increased brine release associated with more ice production causes the formation of more saline surface water, reducing the strength of the pycnocline and allowing greater exchange with the warmer deep water. This additional heat further reduces the ice cover during the summer minimum.

2. Exceptionally strong southerly winds result in higher ice velocities, pushing the ice edge further north. Increased lead and coastal polynya areas produce a larger percentage of the thinner ice than normal. This would make the ice cover more vulnerable to melting, leading to a less extensive summer ice cover.

3. Wind advection effects (regional wind stress curl) on the ocean may cause a spin up of the Weddell Gyre. An increase in wind speed during the year makes the gyre move faster while a decrease produces a slower gyre. In winter, a faster Weddell Gyre (stronger regional curl of the wind stress) moves more ice out of the cold southern region (where it "leaves room" for increased ice production) of the western boundary region, moving the winter ice edge further north than usual. By summer, the perennial ice field of the western Weddell Sea has been flushed out of the region by the stronger Weddell Gyre, into the melting zones to the north. A faster Weddell Gyre may thus produce greater differences between winter and summer sea ice cover.

A periodicity of approximately four years is apparent in the data, and matches the period of the Antarctic Circumpolar Wave [*White and Peterson*, 1996], lending support to Hypothesis 1. The observed wind effects also support Hypothesis 2 but it is not known which of Hypothesis 1 or 2 is more important. Wind effects could also lead to a vigorous Weddell Gyre (Hypothesis 3). It is apparent that the key factor is the influence of wind and that the three hypotheses are not independent of each other.

5. ROLE OF LATENT HEAT POLYNYAS IN ICE PRODUCTION

To understand the relationship of the ice cover to AABW, the relative influence of polynyas to total ice production should be evaluated. Two basic types of polynyas, each of which has different roles in ice/ocean/ atmosphere coupling, have been defined [e.g., *Gordon and Comiso*, 1988; *Comiso and Gordon*, 1996]. One type is the "latent heat polynya" induced by wind removal of newly formed sea ice. Latent heat polynyas usually form along coasts or obstructions (islands and big icebergs) and have been called coastal polynyas. The other type is the "sensible heat polynya", which is maintained by the upwelling of relatively warm deep water to the sea surface. Depending on size and surface conditions, the latter may be either convective or non-convective. In this study, we focus on the rôle of the latent heat polynyas because they are directly linked to the production of HSSW and ultimately to bottom water formation.

Coastal polynyas around Antarctica have been referred to as "ice factories" as the constant removal of newly formed ice by the wind results in the continuous formation of sea ice. During the slacking of the wind, the polynya may be covered by thin ice, but this would be removed with the next wind burst, once more exposing the ocean to the atmosphere. It has been inferred indirectly from sea ice core studies that a large fraction of the Weddell Sea ice pack may originate from sea ice formed in coastal polynyas [*Eicken and Lange*, 1989]. Examples of latent heat polynyas in the Antarctic coastal region have been cited and their net effects studied [*Zwally et al.*, 1985; *Cavalieri and Martin*, 1985; *Jacobs and Comiso*, 1989; *Darby, et al.* 1995; *Kottmeier and Sellmann*, 1996]. Estimates of salinization from polynyas in the Weddell Sea are also presented by *Markus et al.* [this volume] for the 1992 to 1994 period.

5.1. *Variability in the Areas of Coastal Polynyas*

Typical coastal polynyas in winter have widths of the order of less than one to several kilometers. The best resolution available from current satellite passive microwave systems is 12.5 km from the 85 GHz channels. Generally, even these channels cannot resolve most of the coastal polynya features and therefore the latter are represented in the data as reduced ice concentrations. Because of the high sensitivity to weather and other atmospheric effects as well as the high variability of the emissivity of the ice surface at this frequency [*Comiso et al.*, 1989], the 85 GHz channels have not been used to infer global sea ice concentration. When the conditions are good, however, they may provide better spatial details than other SSM/I channels [*Markus and Burns*, 1995]. Since satellite 85 GHz data are currently available only with the SSM/I sensor and for the period July 1987 to 1988 and from December 1992 to the present, they are presently not suitable for long-term studies. Our study makes use of ice concentrations derived from the 37 and 18 GHz (or 19 GHz) channels [*Comiso*, 1995]

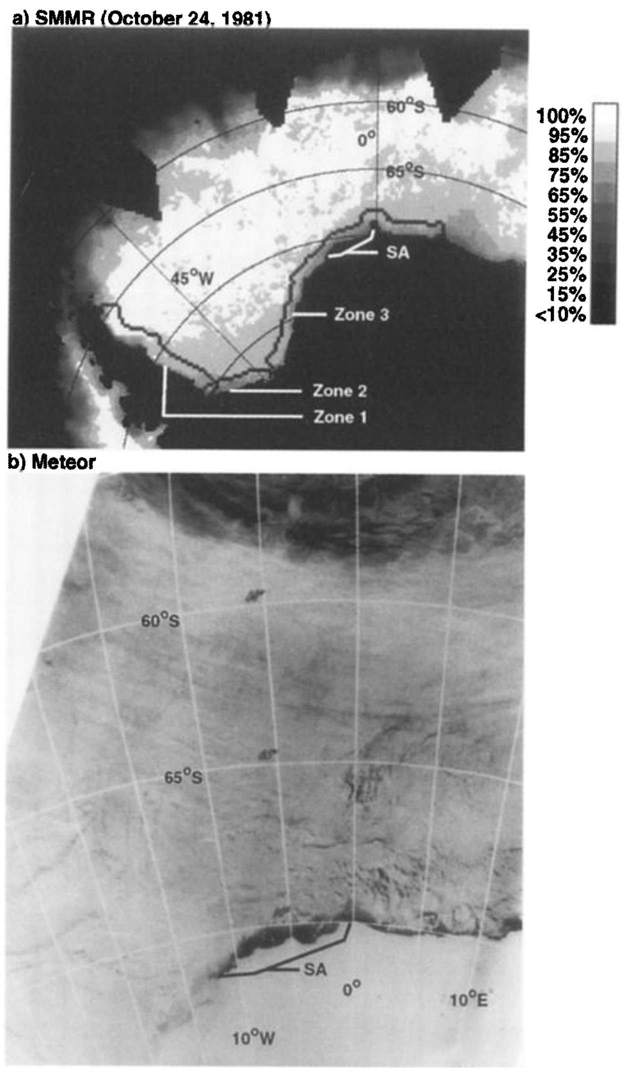


Fig. 4. Ice cover characteristics on October 24, 1981 as depicted by (*a*) a coded ice concentration map using SSM/I data and (*b*) a visible channel image from the Russian Satellite Meteor. Regions of Zone-1 through Zone-3 are indicated as well as a polynya study area (SA).

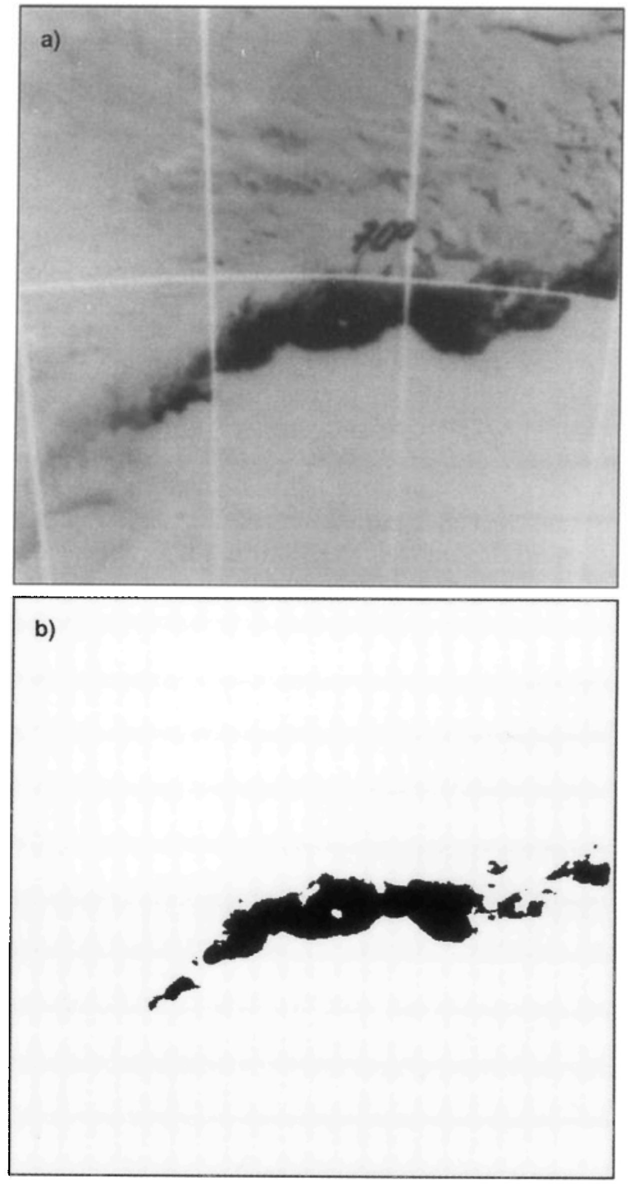


Fig. 5. (*a*) An enlarged visible channel image of Figure 4*b*, including SA, and (*b*) a binary image of ice and water using a thresholding technique on the image data in (*a*).

which provide consistent polynya area information for the period from 1979 to the present.

The overall error in our estimates of polynya area is difficult to quantify because of the lack of validation data sets in the region during winter. The relatively low emissivity of new ice compared to thick ice and lower surface ice temperatures than average in these regions (especially for young ice), causes overestimates in open water areas. However, polynyas are known to be covered predominantly by new and young ice [*Martin et al.*, 1992]. In polynya heat flux studies, the errors due to new and young ice are partly compensated because fluxes from new and young ice are known to be an order of magnitude lower than those of thick ice [*Maykut*, 1978; *Lytle and Ackley*, 1996]. A crude assessment of the accuracy of the area estimates during spring has been made through a comparative analysis of SSM/I ice concentration data (Figure 4*a*) and Russian Meteor satellite data in the visible channel (Figure 4*b*). The two data sets show similar features in the coastal regions, especially in the study area (SA) between 0° and 15°W. A thresholding algorithm based on the large contrast of the albedo of thick ice with snow cover and open water was applied to the visible channel image (magnified in Figure 5*a*), and the result is shown as a binary map in Figure 5*b*. The estimate of open water from SSM/I was 12,700 km^2 while the area indicated as open water in the binary map is 12,345 km^2. The thresholding technique may classify some forms of new ice (i.e., those below the threshold) as open water since new ice has an albedo closer to that of open water than thick ice [*Perovich, et al.*, 1986; *Allison et al.*, 1993]. The good agreement in the estimates (within 2.9%) indicates that the polynya areas inferred from SSM/I data reflect quantities associated with a real surface feature such as those in Figure 4*a* (labeled as SA) that may be partly frozen. Although the spatial details of the polynya as observed from the visible image is not reproduced in the SSM/I data because of the much coarser resolution of the latter, the inferred magnitude of the polynya size from the two systems are in reasonable agreement.

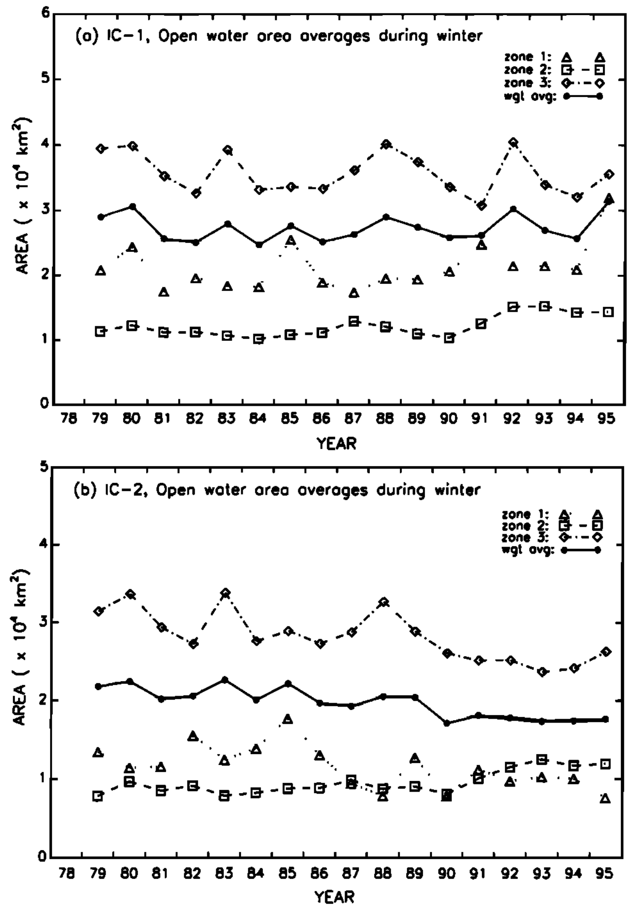


Fig. 7. Averages of daily coastal polynya open water areas during each winter from 1979 through 1995 using ice concentration values from (*a*) the standard Bootstrap Algorithm for the Antarctic (IC-1), and (*b*) the modified Bootstrap algorithm for the Arctic (IC-2). The number of days in the average depends on the length of winter which varied from year to year.

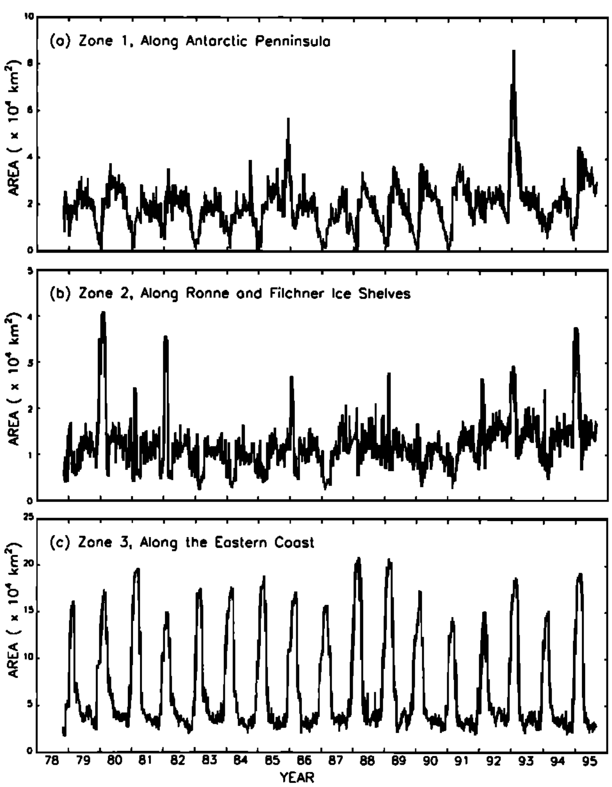


Fig. 6. Weddell Sea coastal polynya open water areas derived from SSM/I daily average data in (*a*) Zone-1, (*b*) Zone-2, and (*c*) Zone-3 from 1979 through 1995.

Estimates of daily open water areas along the coastline of the Weddell Sea study region are shown in Figure 6. The coastline is divided into three study areas: Zone-1, along the Antarctic Peninsula (64°S to 75°S);

Zone-2, along the Ronne/Filchner Ice Shelves (37°W to 60°W); and Zone-3, along the eastern coastline of the Weddell Sea (20°E to 37°W). The outlines of the three zones are indicated in Figure 4*a*. The width of the study areas is approximately the same and about 100 km (4 pixels) from the continental margin. The total areas of Zone-1, Zone-2, and Zone-3 are 16.06 x 10^4, 6.07 x 10^4, and 22.6 x 10^4 km^2, respectively.

The seasonal variability of open water areas in Zone-1 is shown to be quite large (Figure 7*a*). Apart from a few exceptions, open water areas are unexpectedly higher during winter than in summer. During spring and summer, the areas of open water in this zone are reduced to almost zero (consistent with *Markus et al.* [this volume]), suggesting that, during this time period, ice is advected towards the Antarctic Peninsula, probably due to the influence of wind (as observed in the 1988 and 1989 data) and the Weddell Gyre. The exceptions (when open water area are more substantial) are in the springs of 1985, 1992, and to some degree 1991. The pronounced peak starting in the spring of 1992 through the summer of 1993 was due to a large coastal polynya (see Plate 2). The presence of this polynya in summer is among the factors that led to the low minimum in 1993 which was preceded by a high winter maximum as pointed out earlier. The unusually dispersed features also suggest strong wind effects as described earlier. The occurrence of the peak value during the spring of 1985 coincided with the absence of ice near the eastern tip of the Antarctic Peninsula which may be associated with wind effects or possible intrusion of warm water masses from the north. During some years (e.g., 1982, 1983, 1992), the size of the coastal polynyas is essentially sustained during much of the growth period, while in other years (e.g., 1988, 1989, 1990) the size is enhanced in early winter and gradually decreases towards the summer. Persistently strong winds could cause the former while a decreasing wind intensity and a heavy ice cover could cause the latter. Short term (e.g., daily) variations are also apparent, likely caused by short term oscillations of wind effects.

The variability of the coastal polynya areas in Zone-2 (Figure 6*b*), is similar to that in Zone-1 but the summer values are not as consistently close to zero in this zone as in the latter, and there are more years when the coastal areas have substantial open water during the summer. It is also apparent that Zone-2 is more active (i.e., higher open water area per kilometer of coastline) during winter than Zone-1. In 1986, large icebergs about 12,000 km^2 in total surface area calved from the Filchner Ice Shelf (near 45°W) and were grounded near the coastline. The presence of the icebergs apparently caused a higher open water area than during previous years, except in 1990. A bias (estimated to be about 2,500 km^2) caused by the presence of the icebergs, which have lower emissivities than those of sea, has been removed. During the summer, the open water areas are shown to be relatively high in 1980, 1981, 1982, 1986, 1989, 1992, 1993 and 1995. This is partly due to the formation of polynyas and partly due to the seasonal retreat of the ice cover (see Plates 1 and 2).

The coastal polynya area distribution for Zone-3 (Figure 6*c*) is different from those in the other zones in that the coastal region is largely a part of the seasonal ice region. Some uncertainties are introduced in the retrieval of ice concentrations near coastlines because of instrumental (e.g., antenna pattern and side lobes) effects and contamination of the pixels by continental contributions. The yearly peak values were relatively low in 1982, 1991, and 1992, which are the years when much of the coastline was occupied by ice during the summer. Large interannual variations in winter are also apparent, and the total areas are slightly higher than those in Zone-1.

To evaluate the interannual variability of coastal polynya areas, averages of these open water areas during winter (arbitrarily defined as the period from April through November when the study areas were fully ice covered) were calculated for each zone and results are shown in Figure 7*a*. The numerical values are also given in Table 3. The percentages of open water in winter in Zone-1, Zone-2, and Zone-3 are 12%, 20%, and 16%, respectively, indicating that Zone-2 has the most polynyas per unit area among the three. In Zone-1, polynya areas are relatively enhanced in 1980, 1985, and 1992. In Zone-2, the polynya areas are slightly higher than average in 1980 and 1987, but significant increases in area occurred in the 1992, 1993 and 1994 period. In Zone-3, distinct peaks in 1980, 1983, 1988, and 1992 are apparent. These years coincide approximately with years of enhanced ice extent and meridional winds as discussed previously. The coherence is even better when the net impact from all three zones are taken into account as indicated by the weighted averages of the polynya areas shown as bold lines in Figure 7*a*.

Our estimates of polynya areas are in general agreement with those of *Markus et al.* [this volume] during the summer, when validation data are available. However, we found large discrepancies between our estimates and those of *Markus et al.* [this volume] in the winter period. The difference is attributed to the use of different sets of SSM/I channels, as indicated earlier, which have different sensitivities to new ice and atmospheric effects. To gain insights into the difference, ice concentrations were derived using the Arctic version of the Bootstrap algorithm [*Comiso*, 1995] in which the vertically and horizontally polarized channels at 37 GHz (called the HV37 set) are utilized for highly consolidated ice areas. The use of this set minimizes surface temperature and ice sheet contamination effects where they are applied. *Markus et al.* [this volume] also uses the 37 GHz channel in combination with the 85 GHz channels for deriving ice concentration.

The results of the use of ice concentrations (IC-2) from the Arctic algorithm are plotted in Figure 7*b* and values are given (in parenthesis) in Table 3. These results show considerably lower polynya areas than the previous ones. The average percentage differences between the two techniques are 42%, 22% and 20%, in Zone-1, Zone-2, and Zone-3, respectively. The discrepancies are believed to be mainly due to the presence of new and young ice, since the difference is caused by the use of the HV37 set which is more sensitive to these types of ice surfaces. Assuming that this is the case, the results from the two techniques can be used to assess the effect of having new and young ice cover instead of open water. Since heat and salinity fluxes are very different for new and young ice surfaces compared to those of thick ice, ability to detect them as part of a polynya feature is an important consideration. The percentage difference can thus be used as a guide in readjusting the estimates presented in Table 3. The use of the HV37 also minimizes the bias due to contamination from the continental ice sheets. However, overall, the distributions from the two results are similar except for the years after 1991. This may mean more thin ice production in the region in recent years than previously.

The polynya areas derived from the Arctic algorithm are closer to those of *Markus et al.* [this volume] but still significantly higher. The use of the 85 GHz data has its advantages due to higher resolution but has not been validated during adverse weather conditions. The NOAA-AVHRR images in Figure 8 illustrate that polynya sizes can be relatively large (and comparable to our results) in the western Weddell region. The images also show substantial atmospheric effects in the region. Such effects are usually opaque to the 85 GHz signal and can cause large errors in ice concentration estimates when 85 GHz data are used. The strength of our technique is the temporal consistency in the estimates because we use the 19 GHz data (in combination with a 37 GHz data), which are less vulnerable to atmospheric and surface effects. A weakness is the coarser resolution of the 19

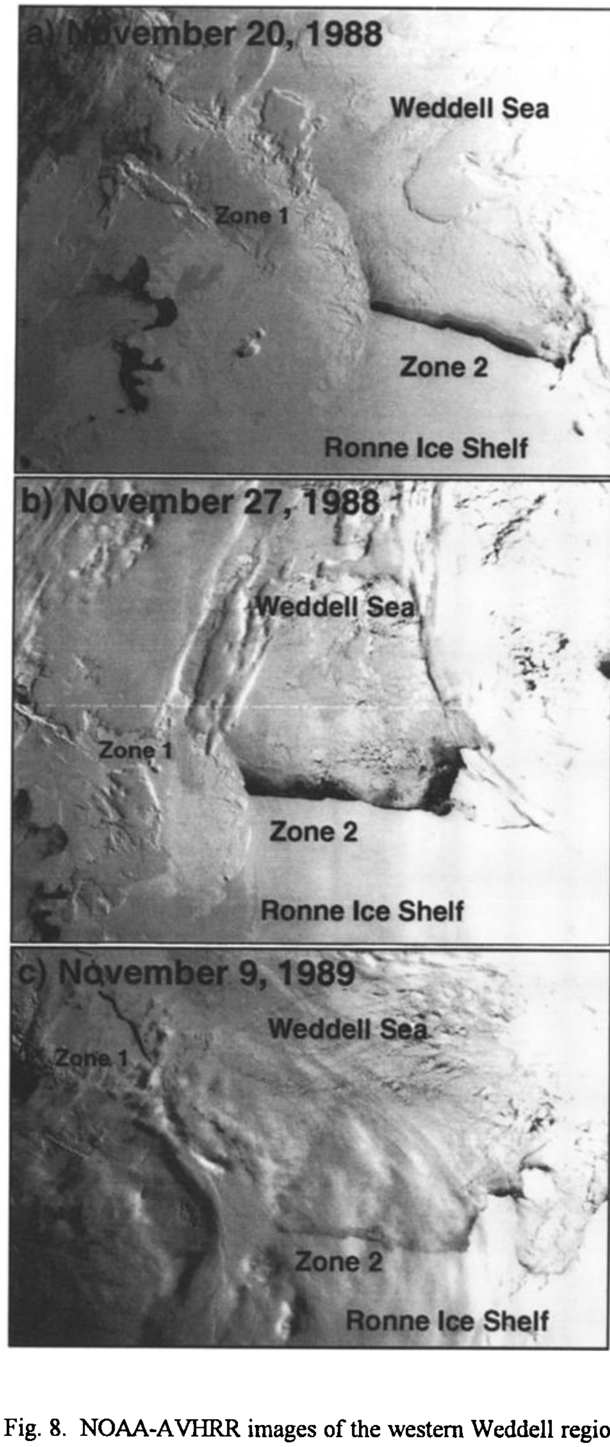


Fig. 8. NOAA-AVHRR images of the western Weddell region on (*a*) November 20, 1988, (*b*) November 27, 1988, and (*c*) November 9, 1989. Polynya features in Zone-1 and Zone-2 are apparent but sometimes they are hidden by clouds that can adversely affect retrievals from the 85 GHz data.

GHz data, which may cause some contamination of the polynya area by the continental ice sheet, and hence a bias, as pointed out in *Zwally et al.* [1985]. The Arctic algorithm reduces the bias and may provide a better estimate of actual open water area but a fraction of new and young ice is classified as thick ice. Further studies are needed to establish the accuracy of the various techniques, especially during winter.

5.2. Oceanographic Significance of the Coastal Polynyas

Coastal polynyas are formed as wind blowing off Antarctica sweeps clear the ice from adjacent ocean [e.g., *Smith et al. 1990*]. They facilitate the production of high salinity shelf water [HSSW, *Foster and Carmack*, 1976*a,b*; *Foldvik et al.*, 1985], through production of vast amounts of sea ice [*Zwally et al.*, 1985]. The total ice production within a coastal polynya can be quite high, perhaps tens of meters per winter season, as newly formed ice within the polynya is continuously removed by the wind exposing the ocean to the very cold atmosphere allowing continued ice production. In the Weddell Sea, HSSW is exported to the deep ocean within the convective plumes over the continental slope to feed the saline variety of the Antarctic Bottom Water observed in the western rim of the Weddell Sea [*Gordon et al.*, 1993]; a similar process occurs in the Ross Sea [*Jacobs et al.*, 1985]. Additionally, HSSW migrates below the ice shelves, where melting glacial ice emerges as slightly fresher Ice Shelf Water (ISW) with temperatures well below the one atmospheric pressure freezing point [*Carmack and Foster*, 1975; *Foldvik et al.*, 1985]. The fresher ISW flows into the deep ocean to feed a low salinity variety of the Antarctic Bottom Water in both the Weddell and Ross Seas [*Gordon et al., 1993; Jacobs et al., 1985*]. The partitioning of HSSW that flows directly off the shelf versus that which passes through the ice shelf contact is not known. One might expect that an increase in HSSW directly adjacent to the shelf ice barrier would ultimately contribute to increased Ice Shelf Water production.

The premise relating coastal polynyas to Antarctic Bottom Water production is: coastal polynyas result in more ice production, enhancing the production of HSSW, with commensurate increases in slope plumes of HSSW and of ISW leading to the formation of more Antarctic Bottom Water. Enhancement of shelf salinity depends on the existence of a broad continental shelf, allowing for accumulation of HSSW. In Zone-3, where the brine release may be considerable, bottom water formation appears to be suppressed [*Fahrbach et al.*, 1994], because of the narrow width of the continental shelf. Zones-1 and Zone-2 may be more effective in leading to bottom water production.

Zwally et al. [1985] estimated the added ice production stemming from Antarctic coastal polynyas as 0.10 to 0.17 m/day with an increase in shelf water salinity of 0.2 to 0.4 ‰, making coastal polynyas the major contributor to the creation of HSSW. Although it is just a crude estimate, we use the *Zwally et al.* relationship to determine the salinity increase within the Weddell Sea coastal polynyas as a simple and consistent indicator of the interannual changes in HSSW production that is most likely linked to coastal polynya processes. More sophisticated techniques require the use of accurate and temporally consistent wind and temperature data which, as indicated earlier, are available only in a few stations. The *Zwally et al.* [1985] equation, which relates increasing shelf water salinity to polynya ice production is

$$\Delta S = sTA_rR_i/0.1\ h, \quad (2)$$

where ΔS is the salinity increase resulting from ice formation in the coastal polynya; s is the salt rejection in g cm^{-2} for each meter of sea ice formed (a value of 2.5 is used); 0.1 in the denominator is a scaling factor to yield ΔS values in parts per thousand; T is the duration in days of the winter period, taken as 240 days for Zone-1 and Zone-2 and varied from 180 to 216 days in Zone-3; A_r is the area ratio of open water to total area of the shelf (in our case, the study area is used as an approximation since the dilution factor is not known); R_i is the rate of ice formation within the polynya in m d^{-1}; h is the water column thickness (a 518 m average is used for the glacially depressed Weddell Sea Shelf). Using the open water polynya areas over the continental shelf (Figure 7a) the associated boost to shelf water salinity is calculated (Table 3). The R_i value used is 0.14 m d^{-1}, the mean of the estimated range of *Zwally et al.* [1985]. As we are mainly interested only in the interannual variations of shelf water production, the exact value of R_i is not critical, though we assume it to be a constant. The derived ΔS values are high compared to previous values [e.g., *Zwally et al.*, 1985] because the areas of each zone, instead of the larger, total shelf area, is used in the denominator of A_r

The 1979 through 1995 mean salinity increase for the coastal zones of the Weddell Sea is 0.232 ‰ with a standard deviation of 0.021 ‰. With the Arctic algorithm, the corresponding value is 0.157 ‰. Relatively high values are encountered in 1980, 1988, 1992, and 1995, which represent the years following a low summer minimum extent, which, as discussed above, follow the high winter maximum occurrence associated with passage of the Antarctic Circumpolar Wave [ACW, *White and Peterson,* 1996].

The bottom water connection may be best associated with Zones-1 and -2, as Zone-3 is mostly over a narrow shelf, prohibiting the accumulation of HSSW. Zone-1 shows maximum production of saline shelf water in 1980, 1985, and 1991 while Zone-2 shows high values in 1980, 1988, and for the years 1991 to 1995. An intriguing possibility exists that the passage of the ACW may be related to increased bottom water formation.

Instead of causing an increase in shelf water salinity, enhanced sea ice production within the coastal polynyas may lead to increased production of HSSW of constant salinity. Assuming that the entrainment ratio of brine to resident surface water of the winter mixed layer remains the same, increased sea ice production is expected to be linearly related to HSSW volume production of constant salinity. Hence, the interannual variations in HSSW production rate would be directly proportional to polynya areal extent, similar to the salinity increase listed in Table 3.

6. RELATIONSHIPS TO THE ANTARCTIC BOTTOM WATER

Among the key results of the Ice Station Weddell project [*Gordon et al.*, 1993] is the identification of two types of Weddell Sea Bottom Water (WSBW) forming in the western Weddell Sea: a salty denser type that draws water directly from the HSSW; and a slightly fresher, less dense water type that is drawn from Ice Shelf Water. The two types of WSBW are found within the lower 300 meters of the water column. At many sites, both WSBW types occur in the same benthic layer. In the northwestern Weddell Sea, the benthic layer has mixed upward into the water column removing the complex salinity stratification.

The T/S relationship of all station pairs in 1° latitude by 1° longitude bins in the western Weddell Sea (Plate 5) indicates that in 1992 and 1993, the WSBW is colder and fresher than that of previous years. During the 1960s and 1970s, the -0.8° to -1.0° C bottom water is markedly more saline than that observed in 1992-1993. All but one station in the western rim of the Weddell Sea are from 1992 and 1993. That station (black circle) represents the 1960s period; it has a bottom T/S that is clearly more saline, and warmer than that observed in 1992/93 (red circle). In the northwestern corner of the Weddell Sea the data array representing a wider range of years, also shows the 1992/93 bottom water (red triangles) as being fresher and colder than that observed in previous years (e.g., black triangles). While the time series is far from complete, it strongly suggests that WSBW observed in 1992 and 1993 is both fresher and colder than that observed in earlier years. The movement towards fresher and colder water is indicative of an increased Ice Shelf Water contribution.

The relationship of increased coastal polynya area and associated greater HSSW production to increased ISW escape from the continental margin is not known and numerical model research is encouraged. One possibility that should be investigated is that increased HSSW production is expected to occur during more extensive coastal polynya periods. This may lead to a thicker layer of HSSW which would in turn lift the ISW layer to a shallower depth, providing less impeded overflow of the outer shelf topography. However, a factor that must be considered is that the HSSW and ISW water types that feed WSBW have residence times measured in years. *Mensch et al.* [in press] estimate the residence time of HSSW in the Weddell Sea as 5 years, and that the ISW is renewed from the HSSW on a time scale of 14 years. A direct year-by-year connection of ice extent and coastal polynyas with the variability of WSBW may not be obvious or expected, as lower frequency thermohaline events may determine the availability of the shelf water for bottom water formation. Other processes such as wind-induced shelf water circulation changes may influence higher frequency changes in the escape of shelf water to the deep ocean. For example, wind changes may control the spreading of HSSW, determining the percentage of HSSW that flows directly into the deep sea versus that component which spreads below the glacial ice to form ISW. From the continuity equation, an increase of the HSSW percentage flowing under the shelf ice would be expected to force increased escape of ISW.

Although no imaging passive microwave satellite data were available before 1973, some visible channel data indicate that the areal extent of Antarctic sea ice was higher in the early 1970s com-pared with later years [*Zwally et al.*, 1983*a*]. This is compatible with a saltier and colder bottom water (Plate 5) for these years and as observed by *Foster and Carmack* [1976*b*]. However, *Foster and Middleton* (1979) also indicated that the year to year variability in the bottom water of the Weddell Sea can be significant. Needless to say, improved monitoring of the Weddell thermohaline stratification and the sea ice cover is required to gain a meaningful statistical relationship between sea ice and WSBW.

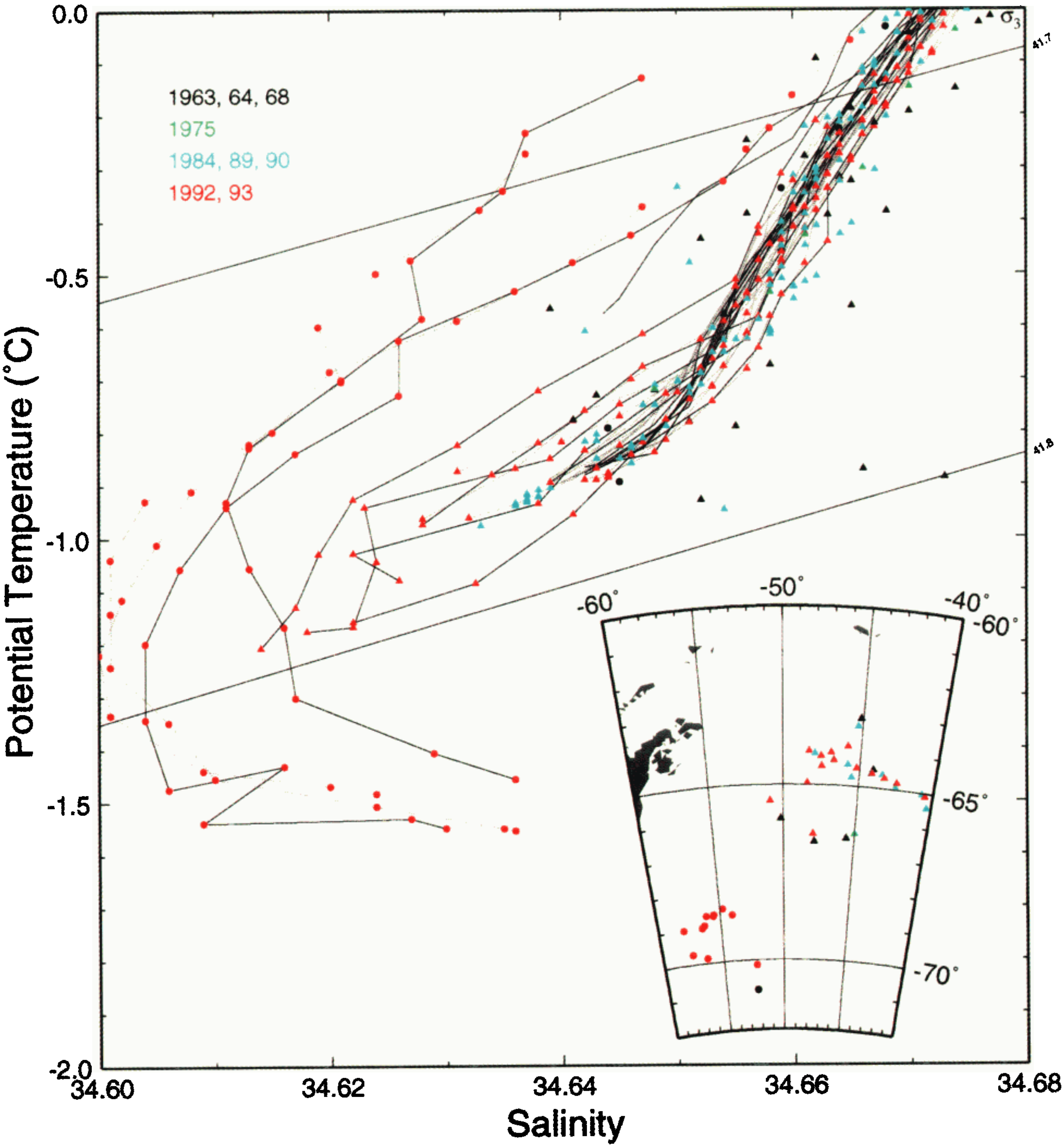


Plate 5. The potential temperature-salinity relationship for the lower water column in the Weddell Sea derived using hydrographic stations from different years within 1° latitude by 1° longitude bins. The water column progressively gets colder as the sea floor is approached. For a station to qualify for this figure, the deepest T/S value has to be less than 50 m off the sea floor and there must be at least one other station within the same bin from a different year. When there was more than one station from a particular year, only one was used, so as not to over represent any specific year in the T/S scatter. Symbols, shown in the insert, are keyed to specific year intervals represented in the figure. The stations used are shown in the map insert, using the same symbol notation. Solid lines and dotted lines represent data from 1992 and 1993 stations, respectively. The circles represent the western rim of the Weddell Sea while the triangles represent the northwestern corner. Both of these areas are along the primary pathway for the escape of newly formed bottom water from the Weddell Sea (*Gordon et al., 1993; Muench and Gordon, 1995*).

7. SUMMARY AND CONCLUSIONS

The characteristics and interannual variability of the sea ice cover in the Weddell Sea from 1979 through 1995 have been examined. Our results indicate a highly variable summer sea ice cover confined mainly in the western Weddell Sea but covering different areas of the region during different years. The summer ice extent has been shown to vary by as much as 6.5 x 10^5 km^2 during the 17 year period with summer ice in the 1990s significantly more extensive than in earlier years. However, summer ice minimum extent does not correlate well with winter parameters and is highly correlated only with the length of summer, with a correlation coefficient of -0.88, confirming the effect of increased solar heating when summer occurs early. It is also weakly correlated with net ice production, and ice expansion rate, with correlation coefficients of -0.42, and -0.30, respectively. The negative signs for these coefficients are unexpected, since more extensive summer minima were expected to cause a conditioning in the ocean that would enhance ice production and ice areal expansion rate.

Our analysis shows that unusually high ice extents during the winter are followed by unusually low extents during the summer. These optimum winter events, which happened in 1980, 1984, 1987, and 1992, are shown to be correlated with meridional winds, which are coherent with the observed passages of the Antarctic Circumpolar Wave [*White and Peterson*, 1996]. Good correlation of the ice cover with available surface temperature data is not as apparent in the Weddell as in the Bellingshausen Sea. A hysteresis loop is observed in the relationships of surface temperature and ice extent, which may partly explain the lack of strong correlation. Also, the average temperature in the western Weddell Sea is a lot lower than that of the Bellingshausen Sea [*King*, 1991].

The areal extent of coastal polynyas in the Weddell sector also has been analyzed in three zones and our results indicate a good correlation of polynya areas with ice extent and meridional winds. The coherence of the occurrence of peak values of areas of coastal polynyas and ice extent confirms that polynyas play a strong role in the production of sea ice and hence of cold, saline, dense water. The polynyas in the eastern Weddell Sea is comparable in size with those in the western region and are slightly better correlated with wind and ice extent. While one might expect production of HSSW in the eastern region, the narrow shelf prohibits accumulation of HSSW and thus suppresses the formation of dense bottom water [*Fahrbach et al.*, 1994].

Large interannual variability of WSBW from 1963 through 1993 has been observed from available hydrographic data. We suggest, but cannot prove with the limited hydrographic data set, that the WSBW variability is related to the large interannual variability in the sea ice cover. The fresher, colder WSBW of 1992 and 1993 than in earlier years (e.g., 1970s) suggests a changing ratio of HSSW to Ice Shelf Water-derived WSBW varieties. Quantitative analysis of the sea ice - WSBW link is complicated by other factors such as changing shelf water circulation in response to wind variability, though this factor is also expected to be reflected in sea ice distribution, shelf water mass residence times, and associated glacial ice melting.

Acknowledgments. We gratefully acknowledge Larry Stock of Caelum and Rob Gersten of Hughes STX for programming support in the analysis of wind and satellite data. Members of the Goddard sea ice group (D.J. Cavalieri, P. Gloersen, C. Parkinson, J. Zwally, and one of the authors [JCC]) were responsible for producing the consistent time series of SMMR and SSM/I data used in this paper. The critical and valuable comments by Stan Jacobs and four anonymous reviewers are very much appreciated. We also thank Rob Massom and Per Gloersen for providing very useful suggestions. This research was supported by the Cryosphere Program at NASA Headquarters and by NSF Grant OPP 93-13700 to Lamont-Earth Observatory of Columbia University. Lamont-Doherty Earth Observatory contribution number 5710.

REFERENCES:

Ackley, S. F., and E. T. Holt, Sea ice data buoys in the Weddell Sea, *CRREL REP. 84-11*, 18 pp.,1984.

Allison, I., R. E. Brandt and S. G. Warren, East Antarctic sea ice: albedo, thickness distribution, and snow cover, *J. Geophys. Res., 98(C7)*, 12,417-12,429, 1993.

Carmack, E. C. and T. D. Foster, Circulation and distribution of oceanographic properties near the Filchner Ice Shelf, *Deep-Sea Res.,22*, 77-90,1975.

Cavalieri, D. J. and S. Martin, A passive microwave study of polynyas along the Antarctic Wilkes Land coast, *Antarc. Res. Ser., 43*, 227-252, 1985.

Comiso, J. C., Surface Temperatures in the Polar Regions using Nimbus-7 THIR, *J. Geophys. Res., 99(C3)*, 5181-5200, 1994.

Comiso, J. C., SSM/I Concentrations using the Bootstrap Algorithm, *NASA Ref. Publication- 1380*, 40pp, 1995.

Comiso, J. C., and S. Ackley, Antarctic sea ice passive microwave signatures during summer and autumn, *IEEE IGARSS'94 Digest, Vol. 1*, 143- 146, 1994.

Comiso, J. C., and A. L. Gordon, The Cosmonaut Polynya in the Southern Ocean: Structure and Variability, *J. Geophys. Res., 101(C8)*, 18,297-18313, 1996.

Comiso, J. C., T. C. Grenfell, D. L. Bell, M. A. Lange, and S. F. Ackley, Passive Microwave In Situ Observations of Winter Weddell Sea Ice, *J. Geophy. Res., 9(C8)*, 10891-10905, 1989.

Darby, M. S., A. J. Willmott, and T. A. Somerville, On the influence of coastline orientation on the steady state width of a latent heat polynya, *J. Geophys. Res., 100(C7)*, 13,525-13,633, 1995.

Eicken, H., and M. A. Lange, Development and properties of sea ice in the coastal regime of the southeastern Weddell Sea, *J. Geophys. Res., 9(C6)*, 8193-8206, 1989.

Fahrbach, E., R. G. Peterson, G. Rohardt, P. Schlosser, and R. Bayer, Suppression of bottom water formation in the southeastern Weddell Sea, *Deep-Sea Res., 41(2)*, 389-411, 1994.

Fahrbach, E., G. Rohardt, N. Scheele, M. Schroder, V. Strasss, and A. Wisotski, Formation and discharge of deep and bottom water in the northwestern Weddell Sea, *J. Marine Res., 53*, 515-538, 1995.

Foldvik, A., T. Gammelsrod, and T. Torreesen, Circulation and water masses on the southern Weddell Sea, *Antarct. Res. Ser., 43*, 5-20, 1985.

Foster, T. D, and E. C. Carmack, Frontal zone mixing and Antarctic bottom water formation in the southern Weddell Sea, *Deep-Sea Res., 23*, 301- 317, 1976*a*.

Foster, T. D., and E. C. Carmack, Temperature and salinity structure in the Weddell Sea, *J. Phys. Oceanog., 6*, 36-44, 1976*b*.

Foster, T. D., and J. H. Middleton, Variability in the bottom water in the Weddell Sea, *Deep-Sea Res., 26A*, 743-763, 1979.

Gloersen, P., W. Campbell, D. Cavalieri, J. Comiso, C. Parkinson, H. J. Zwally, Arctic and Antarctic Sea Ice, 1978 -1987: Satellite Passive Microwave Observations and Analysis, *NASA Spec. Publ. 511*, 1992.

Gordon, A. L., Two stable modes of Southern Ocean winter stratification, in *Deep Convection and Water Mass Formation in the Ocean*, edited by J. Gascard, and P. Chu, Elsevier Publisher, pp. 17- 35, 1991

Gordon, A. L., and J. C. Comiso, Polynyas in the Southern Ocean, *Scientific American, 258*, 90-97, 1988.

Gordon, A. L., B. A. Huber, H. H. Hellmer, and A. Ffield, Deep and bottom water of the Weddell Sea's western rim, *Science, 262*, 95-97, 1993.

Jacka, T. H., and W. F. Budd, Detection of sea ice and temperature changes in the Antarctic and Southern Ocean, in *International Conference on the Role of the Polar Regions in Global Change*, Geophysical Institute and Center for Global change and Arctic System Research, University of Alaska Fairbanks, 1, 63-70, 1991.

Jacobs, S. S., and J. C. Comiso, Satellite passive microwave sea ice observations and oceanic processes in the Ross Sea, Antarctica, *J. Geophys. Res., 94(C12)*, 18195-18211, 1989.

Jacobs, S. S, and J.C. Comiso, A recent sea-ice retreat west of the Antarctic Peninsula, *Geophys Res. Letter, 20(12)*, 1171-1174, 1993.

Jacobs, S. S., and J.C. Comiso, A climate anomaly in the Amundsen and Bellingshausen Seas, *J. Climate, 10(4)*, 697-709, 1997.

Jacobs, S. S., R. Fairbanks and Y. Horibe, Origin and evolution of water masses near the Antarctic continental margin: Evidence from $H_2{}^{18}O/H_2{}^{16}O$ ratio in seawater, *Antarctic Research Series, 43*, 59-85, 1985.

King, J. C., Recent climate variability in the Antarctic Peninsula, *Proceedings of the 5th Conference Climate Variations*, Denver, Oct. 14-18, 1991, Boston: American Meteorological Soc., pp. 354-357, 1991.

Kottmeier, C., and L. Sellmann, Atmospheric and oceanic forcing of the Weddell Sea ice motion, *J. Geophys. Res., 101(C9)*, 10,809-20,824, 1996.

Lytle, V. I., and S. F. Ackley, Heat flux through sea ice in the Western Weddell Sea: Convective and conductive transfer processes, *J. Geophys. Res., 101(C4)*, 8853-8868, 1996.

Markus, T., and B. Burns, A method to estimate subpixel-scale coastal polynyas with satellite passive microwave data, J. Geophys. Res., 100(C3), 4473-4488, 1995.

Markus, T., C., Kottmeier, and E. Fahrbach, Ice formation in coastal polynyas in the Weddell Sea and their impact on oceanic salinity, *Antarct. Res. Ser. (this volume)*.

Martin, S., K. Steffen, J. Comiso, D. Cavalieri, M. R. Drinkwater, and B. Holt, Microwave remote sensing of polynyas, edited by F. Carsey, *AGU Geophysical Monograph Series, 68*, 303-311, 1992.

Massom, R. A., Observing the advection of sea ice in the Weddell Sea using buoy and satellite passive microwave data, *J. Geophys. Res., 97(C10)*, 15,559-15,572, 1992.

Maykut, G. A., Energy exchange over young sea ice in the central Arctic, *J. Geophys. Res., 83(C7)*, 3646-3658, 1978.

Mensch, M., R. Bayer, J. Bullister, P. Schlosser, R. Weiss, The distribution of Trituim and CFCs in the Weddell Sea during the mid 1980's, *Progress in Oceanography* (In press).

Muench, R. D., and A. L. Gordon, Circulation and transport of water along the western Weddell Sea margin, *J. Geophys. Res., 100(C9)*, 18503-18515, 1995.

Perovich, D. K., G. A. Maykut, and T. C. Grenfell, Optical properties of ice and snow in the polar oceans, 1: Observations, *Proceedings of SPIE: Ocean Optics VIII, 637*, 232-241, 1986.

Smith, S., R. Muench, and C. Pease, Polynyas and leads: An overview of physical processes and environment, *J. Geophy. Res., 95(C6)*, 9461-9479, 1990.

Smith, R. C., S. E. Stammerjohn, and K. S. Baker, Surface air temperature variations in the western Antarctic Peninsula region, *Antarct. Res. Ser., 70*, 81-104, 1996.

Trenberth, K. E., J. E. Olson, and W. G. Large, A global ocean wind stress climatology based on ECMWF Analyses, NCAR/TN-338, National Center for Atmospheric Research, Boulder Colorado, 93 pp., 1989.

Weatherly, J. W., J. E. Walsh, and H. J. Zwally, Antarctic sea ice variations and seasonal air temperature relationships, *J. Geophys. Res., 96(C8)*, 15,119-15,130, 1991.

White, W. B. and R. G. Peterson, An Antarctic circumpolar wave in surface pressure, wind, temperature, and sea-ice extent, *Nature, 380*, 699-702, 1996.

Zwally, H. J., J. C. Comiso, and A. Gordon, Antarctic offshore leads and polynyas and oceanographic effects, *Antarc. Res. Ser., 43*, 203-226, 1985.

Zwally, H. J., J. C. Comiso, and C. L. Parkinson, Variability of Antarctic sea ice and changes in carbon dioxide, *Science, 220*, 1005-1012, 1983*a*.

Zwally, H. J., J. C. Comiso, C. L. Parkinson, W. J. Campbell, F. D. Carsey, and P. Gloersen, Antarctic Sea Ice 1973-1976 from Satellite Passive Microwave Observations, *NASA Spec. Publ. 459*, 1983*b*.

J. C. Comiso, Laboratory for Hydrospheric Processes, Code 971, NASA/Goddard Space Flight Center, Greenbelt, MD 20771.

A. L. Gordon, Lamont-Doherty Earth Observatory of Columbia University, Route 9A, Palisades, NY 10964-8000.

(Received November 15, 1996;
accepted August 5, 1997)