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Recurring Polynyas Over the Cosmonaut Sea and the Maud Rise

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Two polynyas over the deep ocean were observed in the Antarctic region during the winter of 1980: one near 43°E, 66°S (Cosmonaut polynya) and another near 2°E, 64°S (Maud Rise polynya). The time history of these two polynyas was examined on an alternate day basis using ice concentration maps from the Nimbus 7 scanning multichannel microwave radiometer (SMMR). A quantitative analysis of a study area around it shows that the totally enclosed Cosmonaut polynya attained a maximum size on July 25, 1980, with an open water area of as much as 137,700 km^2. This polynya lasted for a few weeks, disappeared on August 16, 1980, and was not observed for the rest of the winter. Similar polynyas in the same region have occurred for several years, including 1973, 1975, 1979, 1982, and 1986. The Maud Rise polynya, on the other hand, was observed as a reduction in ice concentration to about 37% within the SMMR resolution of about 900 km^2. However, the open water area in the region amounted to 92,800 km^2 on July 20, and the polynya recurred several times during the same winter period. It is proposed that both polynyas are products of deep-reaching convection which introduces warmer deep water into the surface layer. In this way, they are viewed as sensible heat polynyas in that they are maintained by oceanic heat. The oceanographic settings of these two polynyas are similar. The hydrographic data at both sites indicate the existence of localized doming of the pycnocline. This brings warmer, saltier deep water closer to the sea surface, which has been demonstrated to be an effective preconditioner for deep-reaching convection. It is probable that the polynyas are terminated by "invasion" of sea ice from the sides, which attenuates convection. The capability of a polynya to survive an entire winter period may be related to its size; the larger polynyas are better protected from convergence of the surrounding sea ice. For example, a simple model shows that a polynya with a diameter of about 100 km or greater is much more likely to survive a winter season than a smaller one.

1. INTRODUCTION

After almost a decade of absence since its appearance for three consecutive years (1974–1976), the large winter Weddell polynya remains a mysterious and intriguing phenomenon. Examination of the southern ocean sea ice cover from 1979 to the present using data from the Nimbus 7 scanning multichannel microwave radiometer (SMMR) has shown no evidence of a similar winter polynya that persisted throughout the season. This is also true for 1977 to 1978, as can be inferred from the National Oceanic and Atmospheric Administration (NOAA)/Navy biweekly ice maps. Polynyas of smaller size and shorter duration, however, have been reported along the coastal regions of Antarctica [*Bromwich and Kurtz*, 1982; *Zwally et al.*, 1985; *Cavalieri and Martin*, 1985].

Coastal polynyas are probably maintained by the wind, which removes sea ice as it forms. Ocean-to-atmosphere heat loss is supported by the latent heat of fusion, and coastal polynyas are considered as latent heat polynyas. In this manner, coastal polynyas would be the sites for the generation of sea ice and salinization of shelf water [*Zwally et al.*, 1985]. On the other hand, polynyas over the deep ocean are likely to be maintained by deep-reaching convection, which induces heat into the surface layer [*Gordon*, 1982]. Such deep ocean polynyas [e.g., the large Weddell polynya in the mid-1970s] can be considered sensible heat polynyas and would be located in areas where large reservoirs of relatively warm water occur immediately below the shallow and weak pycnocline [*Martinson et al.*, 1981]. Upwelling and entrainment of this heat into the mixed layer is an important factor in the formation of such polynyas, as was pointed out by *Gordon and Huber* [1984].

This paper is focused on two remarkable deep ocean polynyas observed in the Antarctic region during the winter of 1980: a recurring polynya at about 43°E, 66°S, which will be referred to as the Cosmonaut polynya since the area is located over the Cosmonaut Sea (as shown in GEBCO bathymetric sheet 5.18 [*Vanney and Johnson*, 1985]); and a polynya at about 2°E, 64°S, which will be called the Maud Rise polynya, in view of its proximity to the Maud Rise topographic feature. The Maud Rise polynya is located in the region where the large Weddell polynya was observed in the mid 1970s. The relationship of the size and location of these polynyas to the oceanographic and meteorological data is presented. A possible relationship between the two polynyas is suggested in that both are in the eastern margins of the Weddell Sea.

2. SATELLITE MICROWAVE OBSERVATIONS OF THE POLYNYAS

To examine the existence, persistence, and spatial variabilities of polynyas in the southern hemisphere, a data set of 2-day-averaged ice concentration maps, covering several years of SMMR data, were generated using the procedure discussed by *Comiso et al.* [1984] and *Comiso and Sullivan* [1986]. Two-day averages were used instead of orbital or daily data because complete spatial coverage of the polynya regions is important for this study, and substantial data gaps in the maps would occur otherwise. These 2-day averages actually cover 3 days because the SMMR sensor operates on an alternate-day

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basis only. Figure 1 shows a sequence of color-coded 2-day ice concentration maps from SMMR observations in 1980. The days indicated in the images are days between actual observations. The series of images shows the initial stages of the ice cover over the Cosmonaut Sea and the Maud Rise during fall, and the formation and recurrences of the polynyas in the winter through spring.

2.1. *Cosmonaut Polynya*

The Cosmonaut Sea had little ice cover until June 28, when an embayment of ice-free water started to form at about 65°S and 45°E. The sequence of images in Plate 1 shows the formation of an opening within the ice pack, the initial stages of which are similar to those of the large Weddell polynya [*Carsey*, 1980; *Martinson et al.*, 1981]. The embayment of open water persisted for several weeks until about July 16, when ice began to encircle the feature, causing the formation of the Cosmonaut polynya on July 22. The time of complete enclosure also seems to coincide approximately with the time of maximum size for the open water. During the days that followed, slight distortions of its shape could be observed, but the most obvious change with time is the shrinking of its size until its complete disappearance on August 17. Except for a slight reduction in concentration in the vicinity from August 30 (not shown) to September 2, the Cosmonaut polynya did not recur during the rest of the winter.

To quantify the variability of the ice cover in the Cosmonaut Sea during the formation of the polynya, a rectangular study area which was about 285,000 km^2 in size, and which enclosed the polynya region, was analyzed. The corners of the study area are 66.3°S, 31.4°E; 62.62°S, 43.8°E; 64.2°S, 48.5°E; and 68.8°S, 35.8°E. Within this study region, Figure 1 shows a time series of the minimum and maximum ice concentration (Figure 1*a*); the average ice concentration, including one standard deviation (σ) above and below this average (Figure 1*b*); and the area of open water and the number of data elements (pixels) below 85% ice concentration (Figure 1*c*).

The plot for minimum concentration (Figure 1*a*) shows that before July 27, the study area was partly covered by the ice-free region beyond the edge of the ice (see Plate 1). This is indicated in the plot by a consistently low value of less than 8% ice concentration. The minimum concentration increased to 21% on July 30 after the polynya was formed, then to 44% on August 5, but it dropped back to 8% on August 9. During the apparent disappearance of the Cosmonaut polynya on August 16, the minimum ice concentration was about 71% in the study region. However, these values are associated with areas close to the marginal sea ice region where it is normal to find ice concentrations significantly lower than 100%. The plot for maximum concentration shows that ice cover in the study region generally includes areas of consolidated ice, with 95% representing the lowest value after July 11. The maximum ice concentration is sometimes shown as slightly greater than 100% because of underestimates in the emissivity of consolidated ice. Such high values in ice concentration are compensated by underestimates in ice concentration in some other areas as described by *Comiso and Sullivan* [1986]. This minimizes the possible statistical bias in the quantification of areal open water cover in the study regions. The average concentration, on the other hand, shows a gradual increase until September 27, when it was approximately 97%. The average concentration was about 52% when the polynya was formed and was approximately 88% when the Cosmonaut polynya disappeared. The standard deviation is observed to decrease with time during the same winter period except for a few cases (e.g., July 31, August 4, and August 6). Such decrease indicates less spatial variability because of the gradual increase in ice concentration.

Figure 1*c* shows the variation of the actual amount of open water within the study region with time. This was accomplished by determining the sum of the product of the area and the fraction of open water within each grid element over the entire study area. In the calculation of open water area, an 8% ice concentration threshold was used because ice-laden water with low concentration could not be unambiguously discriminated from ice-free water [*Comiso and Sullivan*, 1986]. Thus derived ice concentrations with values less than 8% were considered ice free. The areal distribution of open water (see Figure 1*c*) exhibits slightly fluctuating values but a trend indicating a definitive decrease in open water area throughout most of the winter. The only exceptions occurred on August 5 and August 7, when significant increases were observed. On August 7 the amount of open water in the polynya region was about 61,640 km^2 compared with 53,870 km^2 on August 5. During the entire winter period the open water area was least on September 4, with an areal cover of about 13,580 km^2. Assuming that during nonpolynya conditions, the areal cover of open water in the region is about 13,580 km^2, the amount of open water introduced on July 24, 1980, when the estimate of open water was 134,700 km^2, can be as much as 121,120 km^2. For comparison, daily averages were similarly analyzed giving areal cover of 10,800 km^2 on September 5 and 137,700 km^2 on July 25, for a difference of 126,900 km^2. This indicates that the effect is further enhanced, on account of less averaging, if near-instantaneous observations were used.

The distributions in Figure 1*c* show a gradual decrease in the amount of open water within the polynya from July 24 to August 17. However, from August 5 through August 11, significant increases in open water are obvious, especially on August 7 (Julian day 220), when peaks in number of pixel and area occurred. This is accompanied by enhancements in standard deviations (Figure 1*b*) and a dip in open water in the minimum ice concentration distribution.

To further examine the variability of the size of the polynya with time, transects along a horizontal line going through the study region were studied. The transects started at 67.8°S, 33.9°E and ended at 62.4°S, 48.5°E. The average of two data elements was taken along the transect for an effective width of about 60 km. The distributions of ice concentrations along the transect for different time periods before, during, and after the occurrence of the polynya are shown in Figure 2. The distributions show ice concentrations decreasing as the location approaches the polynya region centered at about 65.3°S, 42.0°E, increasing at the other side of the polynya, and decreasing again near the marginal sea ice region and the ice free ocean. The plots from July 6 to July 14 show the distribution during the period when there was only an embayment (see Plate 1). The polynya became completely surrounded by ice on July 18 and, as indicated, the size was approximately 510 km lengthwise at this time. By August 15 the distribution was approximately uniform indicating that the polynya was completely closed.

The distribution of ice concentration northeast and southwest of the Cosmonaut polynya shows substantial variability especially during the period of embayment. Maximum wind velocities for each day taken from a nearby Syowa Station, located at 69°S, 39°E are listed in each of the plots. The data

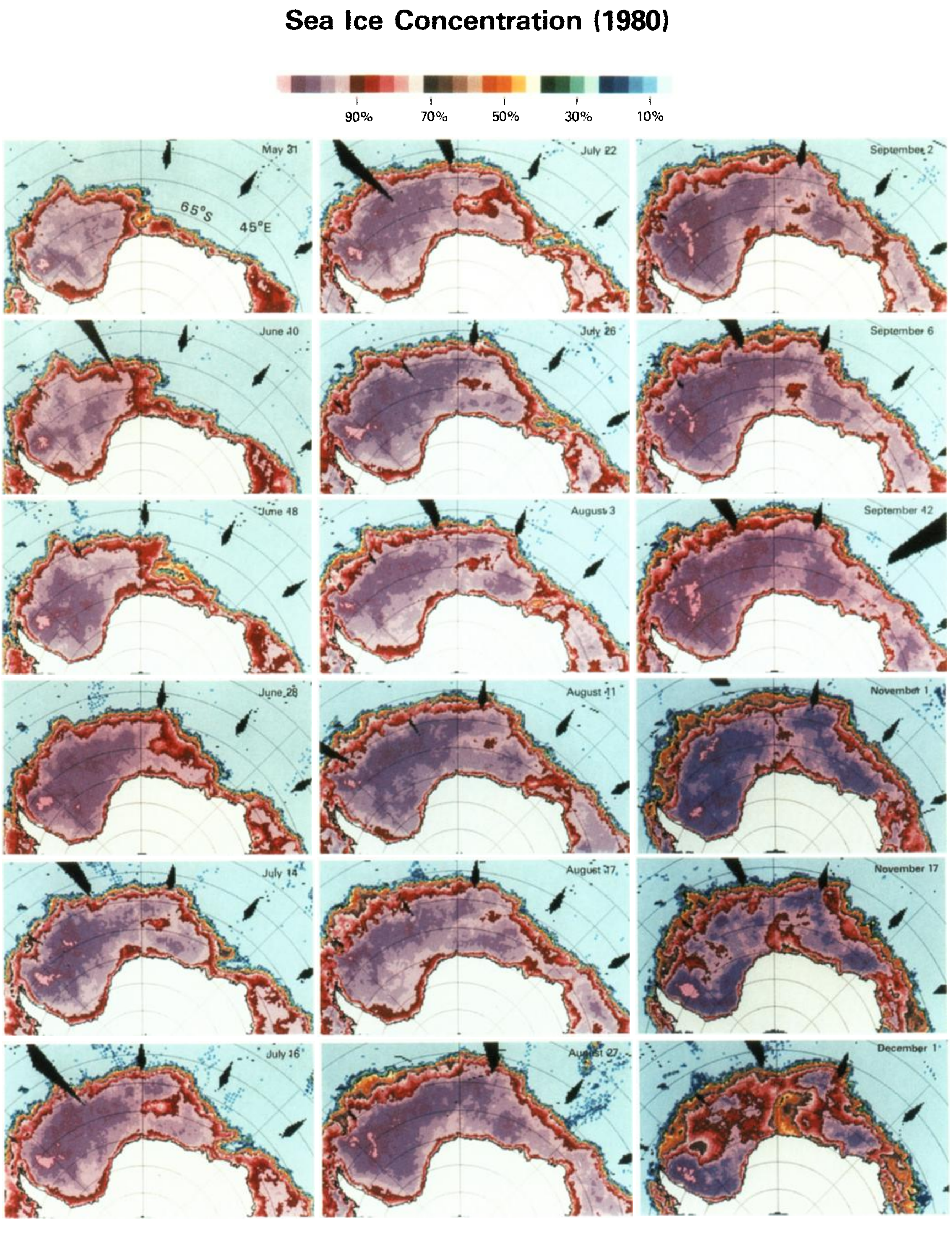


Plate 1. Color-coded sea ice concentration maps from May 31 to December 1, 1980. Each color image is an average of two daily SMMR maps.

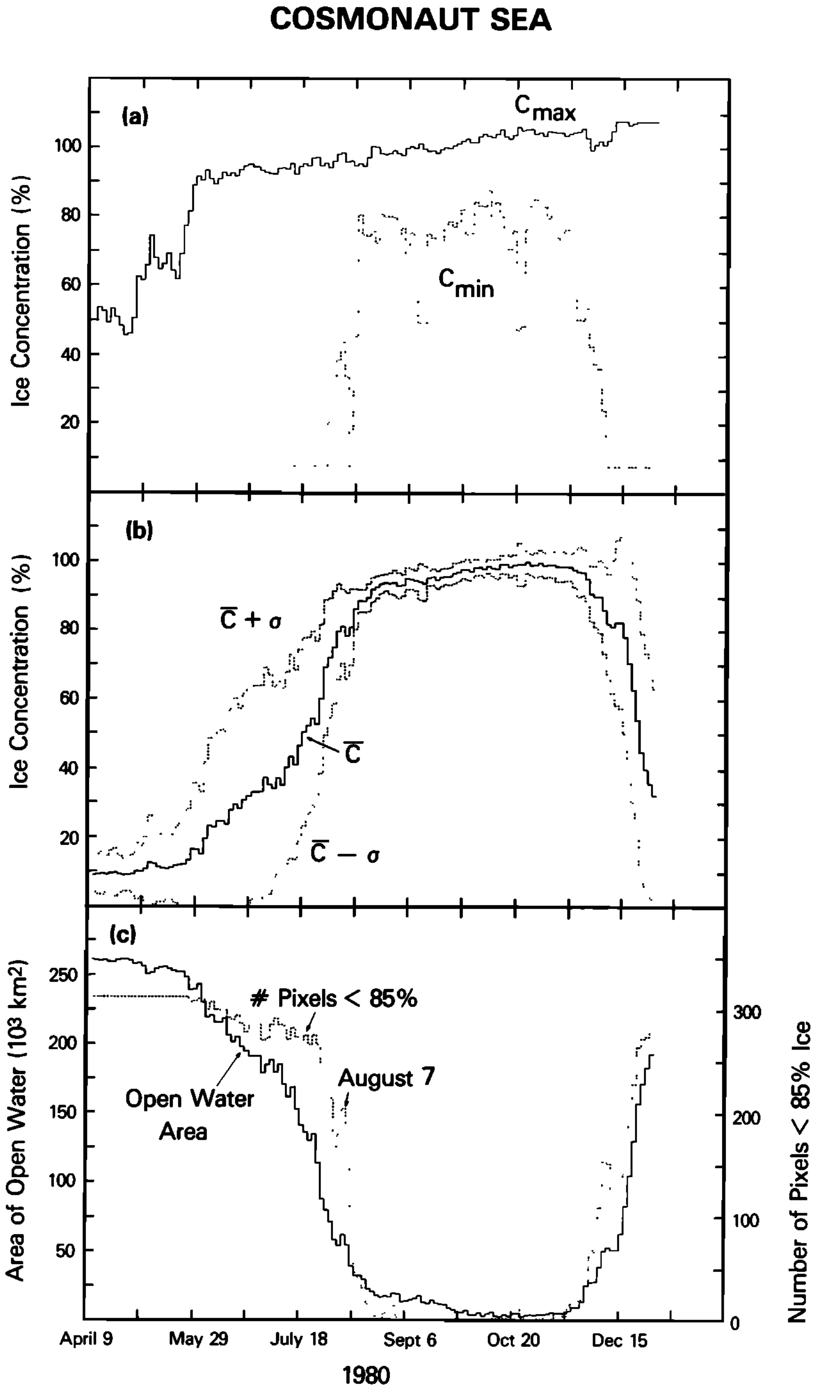


Fig. 1. Time series distributions from 1980 SMMR maps of (*a*) minimum and maximum sea ice concentration, (*b*) average ice concentration and a standard deviation below and above the average, and (*c*) area of open water and number of data elements (pixels) with less than 85% ice concentration within the Cosmonaut Sea study region.

show possible effects of wind on the size of the polynya. For example, significant increase in wind velocity (13.3 m/s to 20.8 m/s) from July 6 to July 8 corresponds to an increase in the sea ice concentration gradient to the southwest of the Cosmonaut polynya and substantial reduction in ice concentration to the northeast. When the wind decreased to 12.1 m/s on July 10, the ice concentration distribution became similar to the July 6 distribution. A slight change in shape also occurred on July 12, when the wind decreased to 3.4 m/s and changed direction. On July 14 a strong wind (25.5 m/s) drastically changed the characteristics of the ice distribution to the northeast of the polynya. After the polynya was formed, the large change in wind velocity from August 3 to August 7 (from 6.4 m/s to 34.2 m/s) corresponded to significant reductions ice concentration minimum and size and an overall increase in open water area as indicated in Figure 1. This immediately preceded the termination of the polynya.

2.2. *Maud Rise Polynya*

The Maud Rise polynya activities displayed more sporadic occurrence than did the Cosmonaut polynya during the winter months of 1980 (see Plate 1). On May 31 a quasi-polynya was

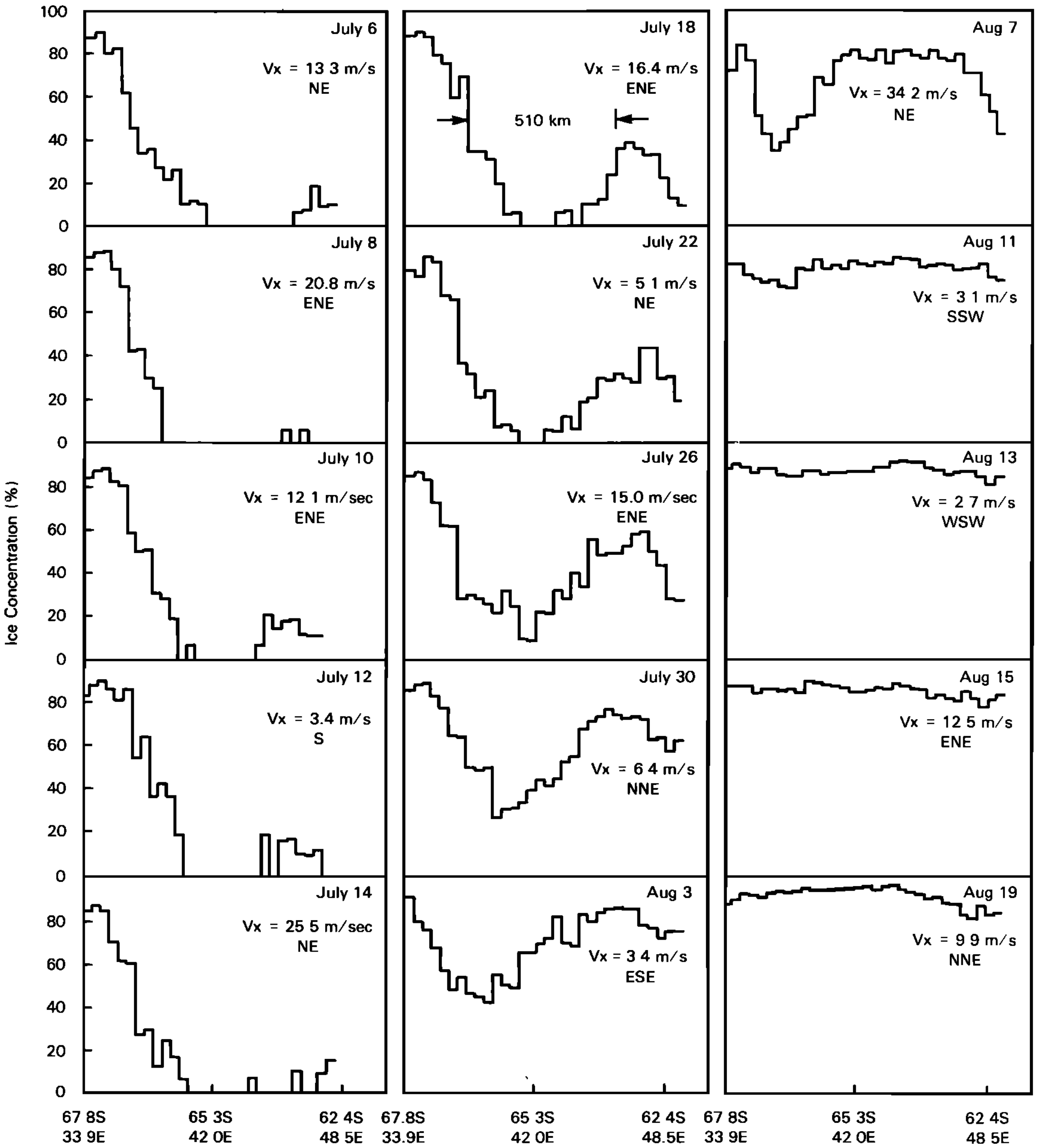


Fig. 2. Ice concentration distributions along a transect across the Cosmonaut polynya and from 67.8°C, 33.9°E to 62.4°S, 48.5°E.

formed near the Maud Rise region. This was followed by the formation of a substantially larger polynya on June 18 centered about 65°S, 6°E. Subsequently, the concentration in the area increased as the ice cover advanced northward as shown on June 28. From July 5 to July 9, no evidence of open water is observed from the satellite data. However, reductions in ice concentration became observable again on July 11 and lasted for several weeks. The open water area reached a maximum size on July 19 and then apparently got frozen on August 13 to August 15. Variations in the size and shape of the reduced concentration region are also observable in Plate 1, especially on July 14, July 16, July 22, and July 26. On July 22, significantly reduced ice concentrations comparable in size to those of the large Weddell polynyas in the 1970s can be observed over the Maud Rise region. In the region, however, the ice concentration varied from 55% and higher, with a mean value close to 90%. Further evidences of significant open water in the region were observed on August 17, but this time, the center is located at about 63°S, 13°E, which is a considerable displacement from the previous observations. Also, similar occurrences of open water in the study region were observed from August 31 until September 8.

The period from November 1 to December 1 shows (see Plate 1) a recurrence of the Maud Rise polynya in early spring and a decay pattern in the vicinity which shows a probable relationship to the Weddell gyre [*Hibler and Ackley*, 1983]. On November 1, reductions in ice concentration were apparent over both the Maud Rise and the Lazarev Sea, along the continental coastline. Subsequent days showed rapid expansion of low-concentration ice from the Lazarev Sea to the Riiser Larsen Sea which eventually led to a merging of the coastal polynya and the Maud Rise polynya on November 17. By December 1 the ice concentration has decreased to about 30% over the Maud Rise and the adjacent coastal regions,

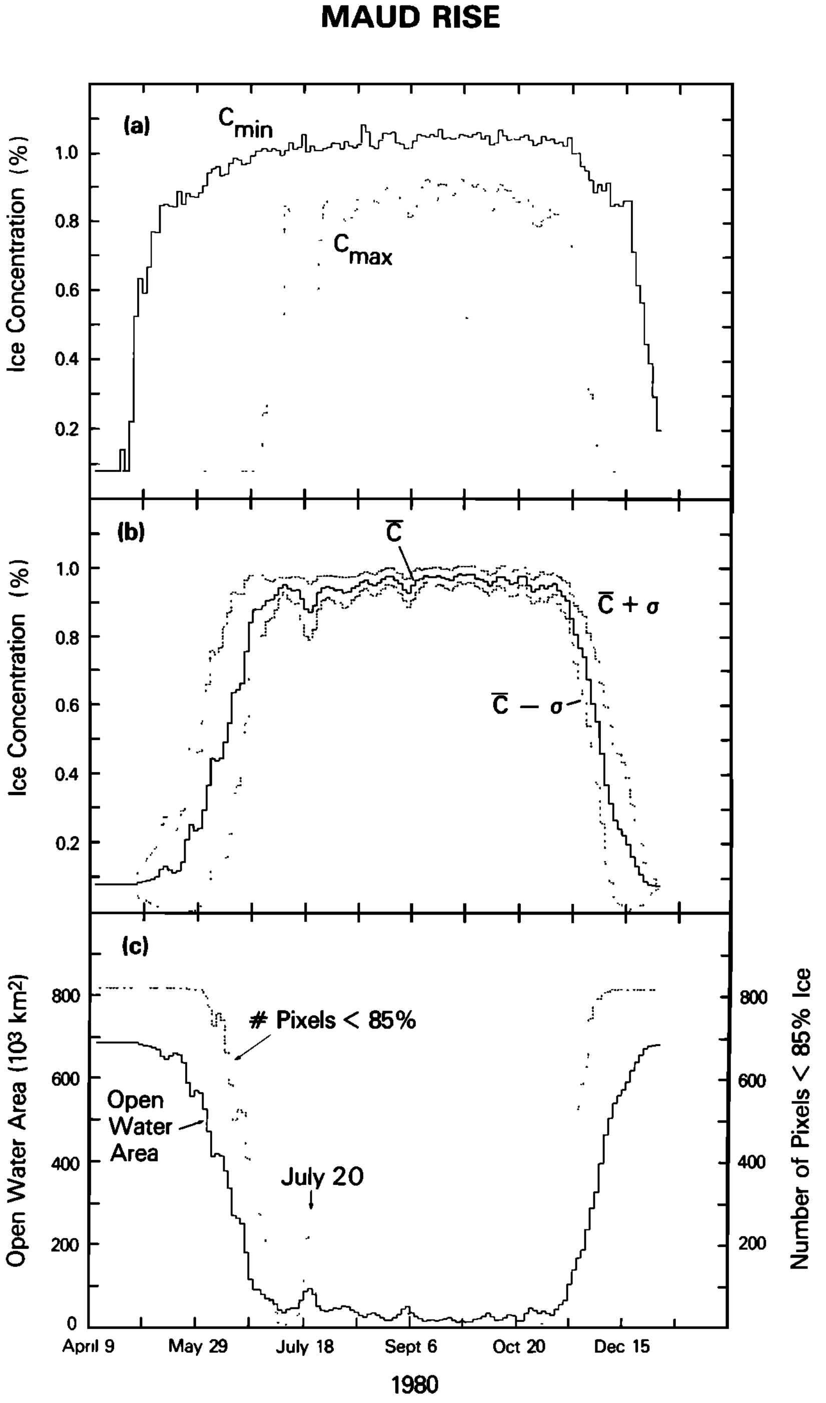
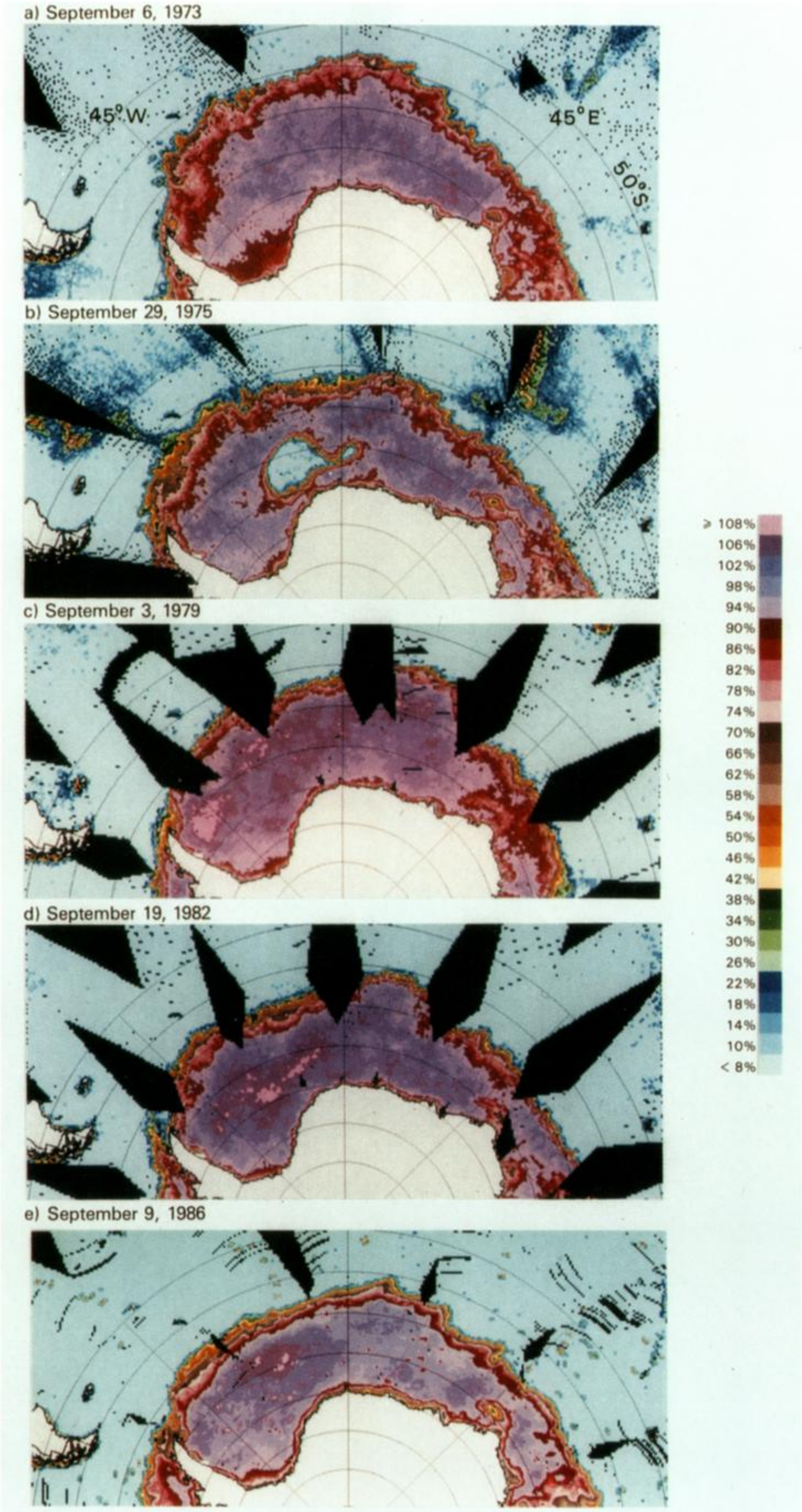


Fig. 3. Time series distributions from 1980 SMMR maps of (*a*) minimum and maximum sea ice concentration, (*b*) average ice concentration and a standard deviation above and below the average, and (*c*) area of open water and number of data elements (pixels) with less than 85% ice concentration within the Maud Rise study region.

while ice cover in most other areas in the vicinity was still nearly consolidated.

The results of a quantitative analysis of sequential data similar to those made over the Cosmonaut Sea but for data over the Maud Rise are presented in Figure 3. A rectangular study region with a total area of 743,000 km^2 and corner points located at 61.5°S, 4.9°W; 60.7°S, 14.3°E; 66.7°S, 18.2°E; and 67.7°S, 5.1°W was used. The distribution of the minimum ice concentration (Figure 3*a*) shows that the study region started to be completely ice covered on June 28. The most obvious dip in ice concentration in midwinter occurred on July 18, but significant dips also occured on August 5, August 13, September 4, and September 16. The distribution for maximum ice concentration shows relatively uniform values close to 100% with some undulations from June 20 to July 24. The average ice concentration within the study area climbed steadily to about 91% on June 28 and fluctuated from 88% to 98% thereafter. The changes in the standard deviations above and below the average also show spatial variability of the ice cover, a good example of which is that associated with the reduction of ice concentration on July 19.

The open water areal cover distribution (Figure 3*c*) shows



a) September 6, 1973

b) September 29, 1975

c) September 3, 1979

d) September 19, 1982

e) September 9, 1986

Plate 2. Sea ice concentration maps showing Cosmonaut polynyas during 1973, 1975, 1979, 1982, and 1986.

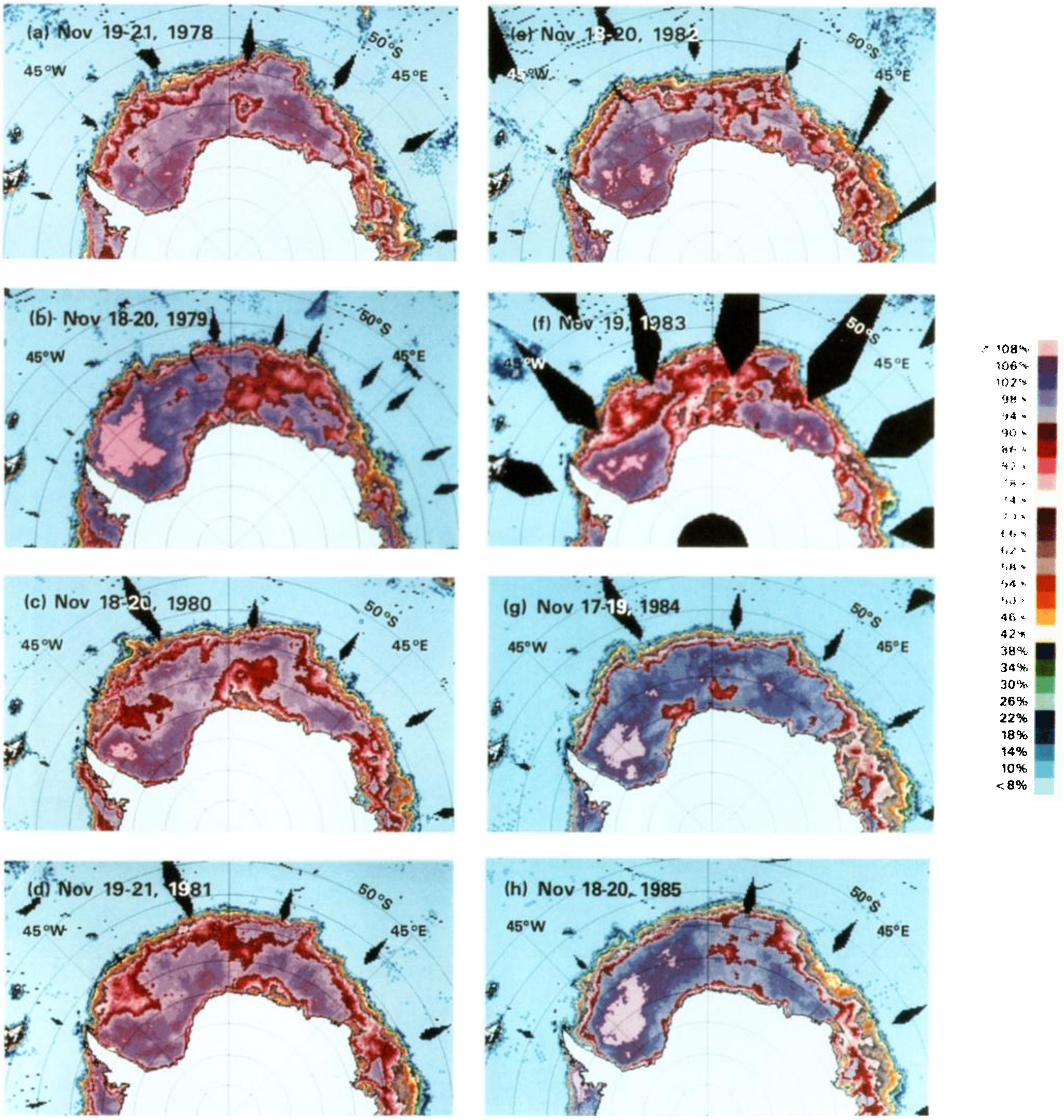


Plate 3. Sea ice concentration maps showing spring breakup in November over the Maud Rise from 1978 to 1985.

basically the same enhancement observed in the standard deviation distribution. Although the open water coverage was about 66,000 km^2 on July 2, it subsequently decreased to 34,520 km^2 on July 8 when no localized open water area was discernible from the images. On July 12 an isolated open water area near the Maud Rise became apparent again, increasing to as much as 92,800 km^2 on July 20. Thus approximately 58,280 km^2 of open water were introduced in the study region during the recurrence of this polynya. The area of open water within the study region also increased from 37,840 km^2 on July 28 to 50,690 km^2 on August 5; from 23,920 km^2 on August 15 to 34,410 km^2 on August 19; from 17,070 km^2 on August 27 to 50,400 km^2 on September 4; from 14,930 km^2 on September 12 to 24,320 km^2 on Septemer 24; from 13,240 km^2 on October 2 to 34,420 km^2 on October 12; and from 16,250 km^2 on October 26 to 47,400 on November 3. The area of open water subsequently decreased to 30,340 km^2 on November 11 but steadily increased thereafter until the ice breakup.

2.3. *Years of Polynya Occurrences Other Than 1980*

Polynya formations in the vicinity of these two areas were also observed in some other years. For example, the Cosmonaut polynya was observed on September 6, 1973, and September 29, 1975, as shown in Plates 2*a* and 2*b* using the Nimbus 5 electrically scanning microwave radiometer (ESMR) data. During these years the Cosmonaut polynyas were comparable in size to the 1980 polynya. Furthermore, an embayment similar to that of the 1980 Cosmonaut polynya occurred during the early part of winter (June to July) in 1973. Also in 1973, a recurring polynya similar to the 1980 Maud Rise polynya was observed during the winter period. In 1975 the Cosmonaut polynya appeared during the occurrence of the large Weddell polynya which persisted throughout the winter. Since a continuous series of winter data is not available for 1973 and 1975 because parts of these data are either poorly calibrated or not recorded [see *Zwally et al.*, 1983], it is not possible to examine in detail the time sequence for the formation and disappearance of the 1973 and 1975 polynyas. Other Cosmonaut polynyas were also observed on September 9, 1979 [*Martinson et al.*, 1981]; September 19, 1982; and September 9, 1986 from SMMR as shown in Plates 2*c* 2*d* and 2*e*. During these three years, however, events leading to the formation of these polynyas were different from those in 1980 because the initiation of these Cosmonaut polynyas was not preceeded by embayments. Instead, like the Maud Rise polynya in 1980, they showed up as a phenomenon after the area had been completely covered by ice. The 1986 polynya, however, was considerably larger than those in 1979 and 1982 and is comparable in size to the 1980 polynya. It was also an unusually persistent Cosmonaut polynya, occurring from August 23 to October 7, 1986.

Since 1976 the only Maud Rise polynyas observed other than the one in 1980 are those that occurred during the spring and summer. Early breakup near the Maud Rise is common almost every year and often causes an acceleration of the decay of the Weddell Sea ice pack. This suggests that the winter heat input from the ocean deep layer may be larger in the Maud Rise polynya area than in other areas, which allows more rapid removal through melting in the spring.

The images in Plate 3 show the early stages of spring polynya formations during November from 1978 until 1985. Reductions in ice concentration over the Maud Rise to as low as about 50% are evident. Although the ice concentration could be significantly less by December, as is shown in Plate 1, the initial stages of breakup in November reveal early signals and give more specific locations where strong oceanographic forcings could be occurring. It is expected that there is no preferential atmospheric warming over the polynya region at this time except for feedback effects from these regions. It is apparent that the size, shape, and location of the spring polynyas vary considerably from one year to another. However, it is evident that the ice breakup occurs at about the same area every year from 64°S to 66°S and from 0°E to 6°E. Sometimes the area of spring breakup is very well defined, as in 1978, 1983, 1984, and 1985. Other times, the area of breakup is larger and less isolated, as in 1979, 1980, 1981, and 1982. The cause for the apparent differences in size of the spring polynyas from one year to the next is not known but is partly associated with the differences in length of winter seasons.

The presence of significant open water in the western region of the Weddell Sea is also apparent in Plate 3 images, suggesting the possible location of a significant body of warm water in these regions, as was mentioned earlier. Low-concentration areas are evident near the coastal regions at about 20°W in 1979, at about 3°E in 1980, and at about 20°E in 1981 and 1982. Over the deep ocean regions, open water areas are also observable in various places including those at about 20°W and 65°S in 1979, at about 41°W and 67°S in 1980 and 1981, at about 15°W and 63°S in 1982, at about 20°W and 68°S in 1983, and at about 20°W and 70°S in 1984. There is no obvious trend in the migration characteristics of these reduced concentration areas, which might be associated with a large body of warm water. It can be observed however, that the location of such occurrences could be displaced by as much as 1200 km in a year.

2.4. *Error Analysis*

The errors associated with the quantification of the sizes of the polynyas are difficult to evaluate primarily because of large variability of the microwave emissivities of sea ice in the polynya regions. One primary source of uncertainty is that associated with the formation of new ice and the refreezing of leads. An exponential dependence of emissivity with thickness has been observed by *Grenfell and Comiso* [1986] during the early stages of ice growth. Such factor makes nilas and other forms of new ice difficult to distinguish from low-concentration ice within the 30-km resolution of the satellite sensor. Thus the satellite microwave data could be interpreted as low-concentration ice although the actual concentration is considerably higher but covered mostly by newly formed ice. Furthermore, under midwinter conditions, ice formations over polynyas and leads occur so rapidly that during the period in which 2-day-averaged data are collected, the ice cover could undergo several stages of development. For example, a region covered by thin ice during a satellite orbit could actually be covered by open water during a previous few orbital coverages. The several channels of SMMR do not allow an unambiguous discrimination of new ice from the thicker ice when the latter is in low-concentration regions. If the presence of thin ice is not significant within the study region, the error in the determination of areas is less than 5% based on known fluctuations of the emissivities of first-year ice and open water. Otherwise, the error could be considerably larger. The primary objective of this paper, however, is to evaluate presence and persistence of polynyas in the study regions. The satellite data enable a good identification of the location of these polynyas and a determination of their temporal variability in size. Also, the persistence of low-concentration ice regions inside the ice pack in midwinter is consistent with continuous activity due to either (or both) oceanographic or atmospheric forcings.

Another souce of error is the effect of bad weather conditions. Despite the use of a combination of 18-GHz and 37-GHz channels to minimize the weather effects over ice-free oceans, as described by *Comiso et al.* [1984] and *Comiso and Sullivan* [1986], low-concentration ice several hundred kilometers beyond the marginal ice region could still be observed from the color-coded ice concentration images (Plates 1, 2, and 3). This effect reflects the difficulty in differentiating between emissions from low-concentration ice regions and those from the atmosphere during adverse weather conditions, and it is more apparent in 1973 and 1975 (see Plate 3) because the data are derived from the one-channel (19 GHz) ESMR sensor. If the weather effects could be minimized, the size of polynyas derived from the data would be larger. The time series analysis, however, indicates relatively stable areal distributions of open water, suggesting minimal effect of weather on the calculated size of the polynyas.

3. OCEANOGRAPHIC SETTING OF THE TWO POLYNYA REGIONS

Both the Maud Rise and Cosmonaut Sea are located along the eastern margins of the Weddell gyre [*Deacon*, 1979] (Figure 4). Maud Rise is near the apex of an anticyclonic bend in the relative geostrophic streamlines. The Cosmonaut Sea is positioned at the eastern terminus of a zonally elongated cyclonic trough in the sea level over the southern extreme of the deep Weddell basin. The oceanographic environment at both sites is remarkably similar, in that both areas are associated with isolated patches of a relatively shallow pycnocline. Inspection of the temperature and salinity distribution on the 100-m surface (Figure 5; see also *Gordon and Molinelli* [1982, Plates 11 and 27] reveals an isolated region of water warmer than 0.0°C and saltier than 34.5‰ (Cosmonaut Sea) to 34.6‰ (Maud Rise). This is significantly saltier than the summer surface water and therefore can only be attributed to doming of warmer and saltier deep water.

The Maud Rise pycnocline dome, extending from 5°W to 15°E along 65°S to 67°S, is larger and better represented by the data set. The Cosmonaut Sea feature, seen in both temperature and salinity only from 38°E to 47°E along 66°S, is based only on a few *Discovery* stations and hence is not well resolved.

The shallowing of the pycnocline layer separating the temperature minimum and deepwater masses in the Maud Rise area is seen in hydrographic sections in Figure 6 (reproduced from *Gordon and Huber* [1984]; also see Plates 188–123 of *Gordon and Molinelli* [1982]). Associated with the pycnocline doming is thinning of the temperature minimum layer, and directly below the shallowed pycnocline, the deep water attains its warmest, most saline condition for the region. In addition, the isopycnals below the temperature maximum of the deep water are depressed, thus acting to compensate in a baroclinic sense the elevated isopycnals of the pycnocline. This leads to a maximum of geostropic current near the temperature maximum layer (relative to a deeper reference level [*Gordon and Huber*, 1984].

The shallowed pycnocline across the Cosmonaut Sea area is not as well covered by series of hydrographic stations. The *Conrad* hydrographic and expendable bathythermograph (XBT) sections along 37°E and 33°E, respectively [*Jacobs et al.*, 1980; *Gordon and Molinelli*, 1982, Plates 126–131] fall to the west of the shallowed pycnocline region. However, they do reveal shallowed pycnocline near 64°S, although the 0°C isotherm is deeper than 100 m.

The southern ocean pycnocline, which separates the base of the winter mixed layer (which in summer is the temperature minimum layer) from the warm Weddell deep water, is quite weak. The σ_0 differential across the pycnocline is only 0.2 [*Gordon*, 1981; *Gordon and Huber*, 1984]. This makes the pycnocline particularly susceptible to static instability during the winter. Instability results in convective overturning, which would effectively exchange warm deep water with cold surface water, thus inhibiting sea ice formation. Significant cooling of deep waters to depths of 3000 m occurred during the 1970s, supporting the hypothesis that convective overturning was the primary mechanism responsible for maintenance of the Weddell polynya during the mid-1970s [*Gordon*, 1982]. In this regard, the Weddell polynya can be considered as a sensible heat polynya, held open by oceanic heat, which was then vented to the atmosphere.

The probability of convective overturning between the cold surface and warm deep layers for a given sea-air buoyancy flux is much greater for the thin, mixed-layer, shallow pycnocline conditions [*Martinson et al.*, 1981]. This suggests that continued, wind-induced upwelling of the pycnocline eventually preconditions an area for convection and polynya generation. The localized shallow pycnocline may be a climatic situation, but temporal variability would be expected which can trigger a polynya. In a general sense, a balance is achieved between the regional Ekman-induced upwelling and downward entrainment of the mixed layer into the warmer deep water. *Gordon et al.*, [1984] report that the regional entrainment rate for the Weddell gyre is approximately 30 m per year, matching the Ekman upwelling. Doming of the pycnocline would result in greater entrainment [*Martinson et al.*, 1981; *Gordon and Huber*, 1984].

The stability of the stratification depends on the amount of fresh water introduced to the surface layer. Should the entrainment rate increase or the temperature and salinity of the deep water change, the heat and salinity balance of the surface layer would be altered. Associated also in that doming are warmer, saltier deepwater compounds, which are the thermohaline effects on the surface layer. *Gordon and Huber* [1984] point out that unless there is an increase in freshwater introduction (excess precipitation over evaporation and a net convergence of sea ice) to the mixed layer, pycnocline doming, with the associated enhanced upward heat and salt flux, would tend to destabilize the water column. They suggest that wind induced "spin-up" of the Weddell gyre may play a role in increasing the inflow of deepwater heat and salt into the gyre and further doming of the pycnocline. During the convective mode, these polynyas will ventilate the deep ocean.

There is the obvious question as to polynya-terminating factors. As *Martinson et al.* [1981] point out, the convection can be stopped only if sufficient fresh water is introduced to the area. The convection within an active polynya is self-perpetuating in that as the newer exposed deep water cools it becomes denser and sinks, forcing further convection. The convection would cease in spring as the atmosphere no longer removes heat, or at any time that the area is flooded by fresh

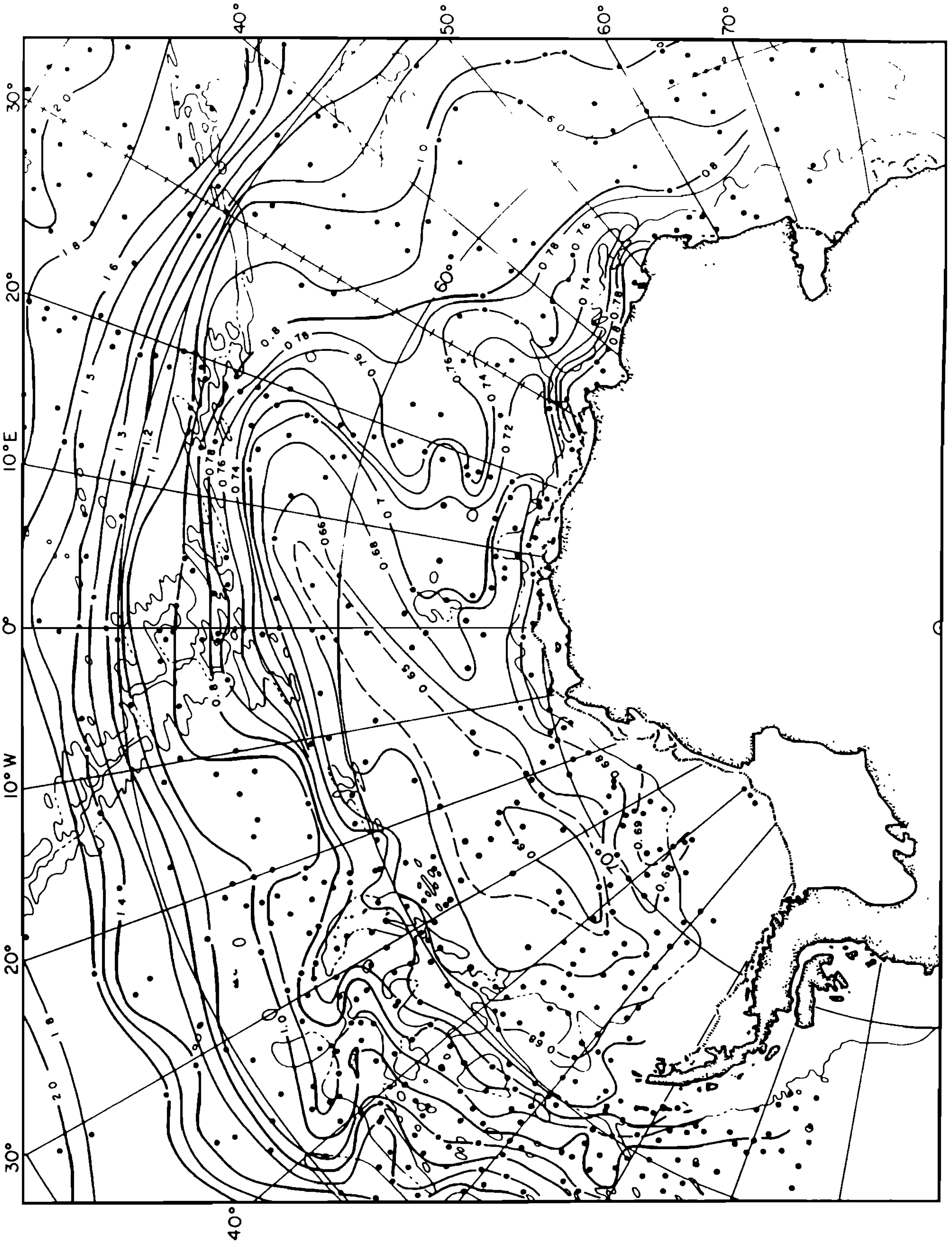
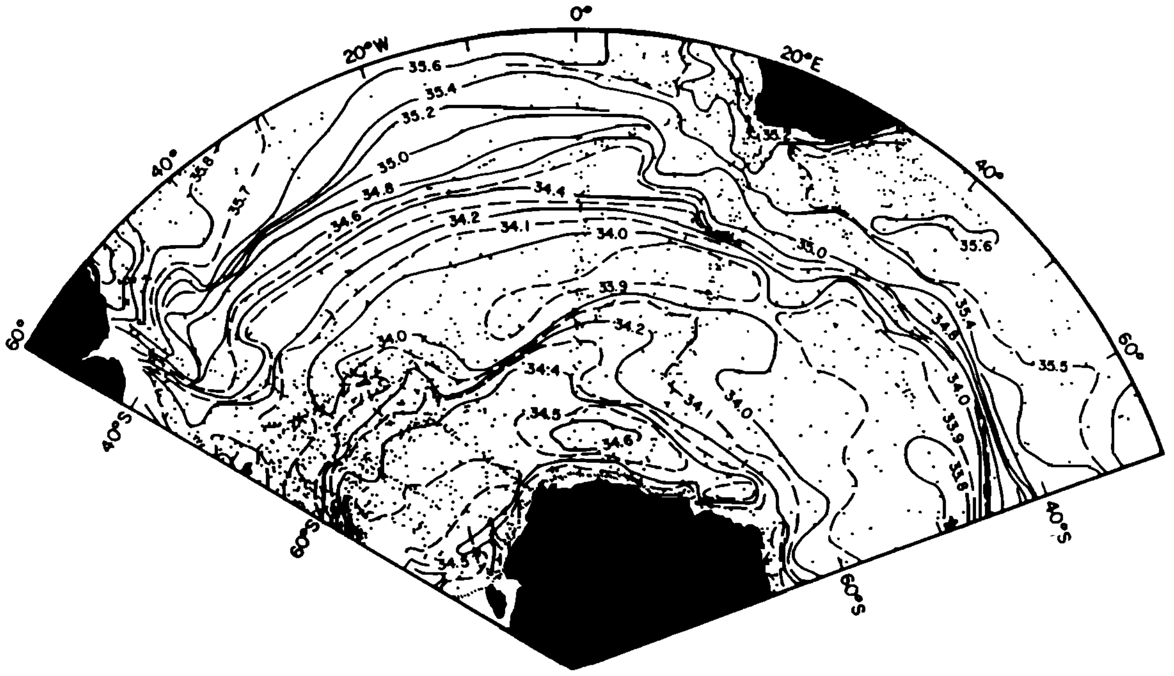
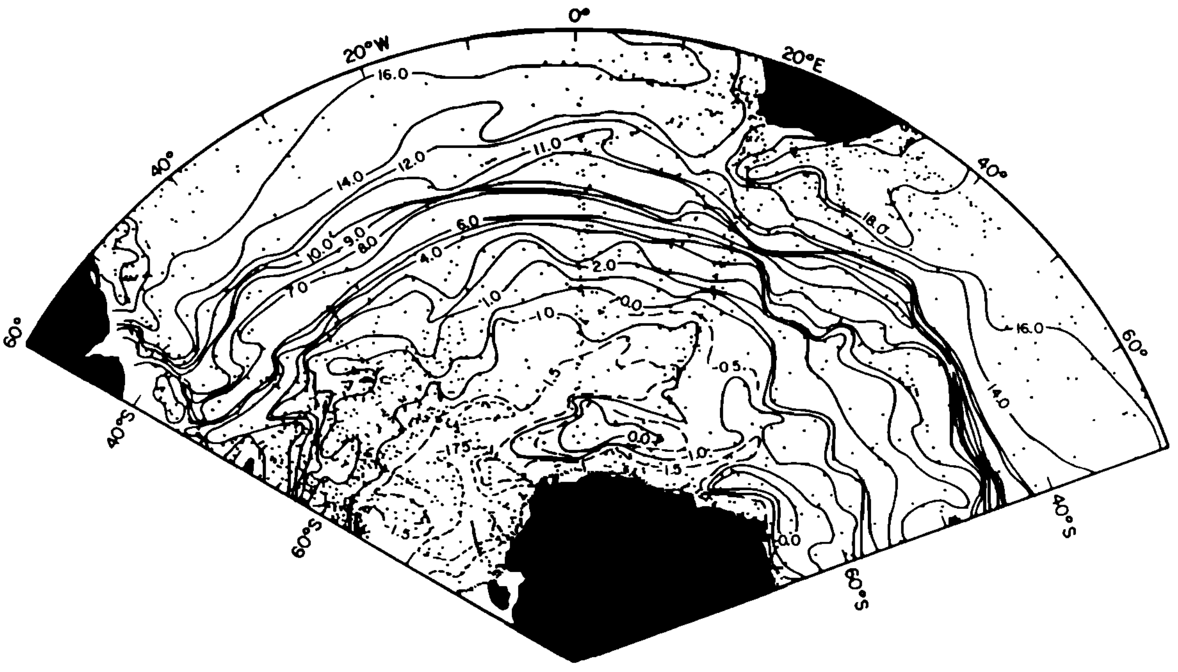


Fig. 4. Dynamic height anomaly of the sea surface relative to 2500 dbar (in dynamic meters). The hydrographic data used for this figure are derived from the pre-1976 data set.



SALINITY ‰



POTENTIAL TEMPERATURE °C

Fig. 5. Potential temperature and salinity at the 100-m level within the Weddell gyre region (taken from Plates 11 and 27 of *Gordon and Molinelli* [1982]).

water [*Martinson et al.*, 1981]. The low-salinity "cap" stabilizes the water column, supressing convection. Since the amount of fresh water required to stop the convection is approximately double the excess regional precipitation over evaporation [*Martinson et al.*, 1981; *Gordon and Huber*, 1984], the most reasonable mechanism is net convergence of sea ice with a thickness of slightly under 1 m [*Clarke and Ackley*, 1984], i.e., ice exceeds precipitation as a freshwater source if it can converge into the polynya and melt.

4. POLYNYA SIZE VERSUS PERSISTENCE

The recurring polynyas of the Maud Rise and the Cosmonaut Sea regions differ from the Weddell polynya of the mid-1970s, which was larger and persisted for the entire winter. During each winter, and for the three consecutive winters of its existence, the Weddell polynya slowly drifted to the west [*Carsey*, 1980]. This drift is attributed to the general circulation advecting the convective regime [*Gordon*, 1982].

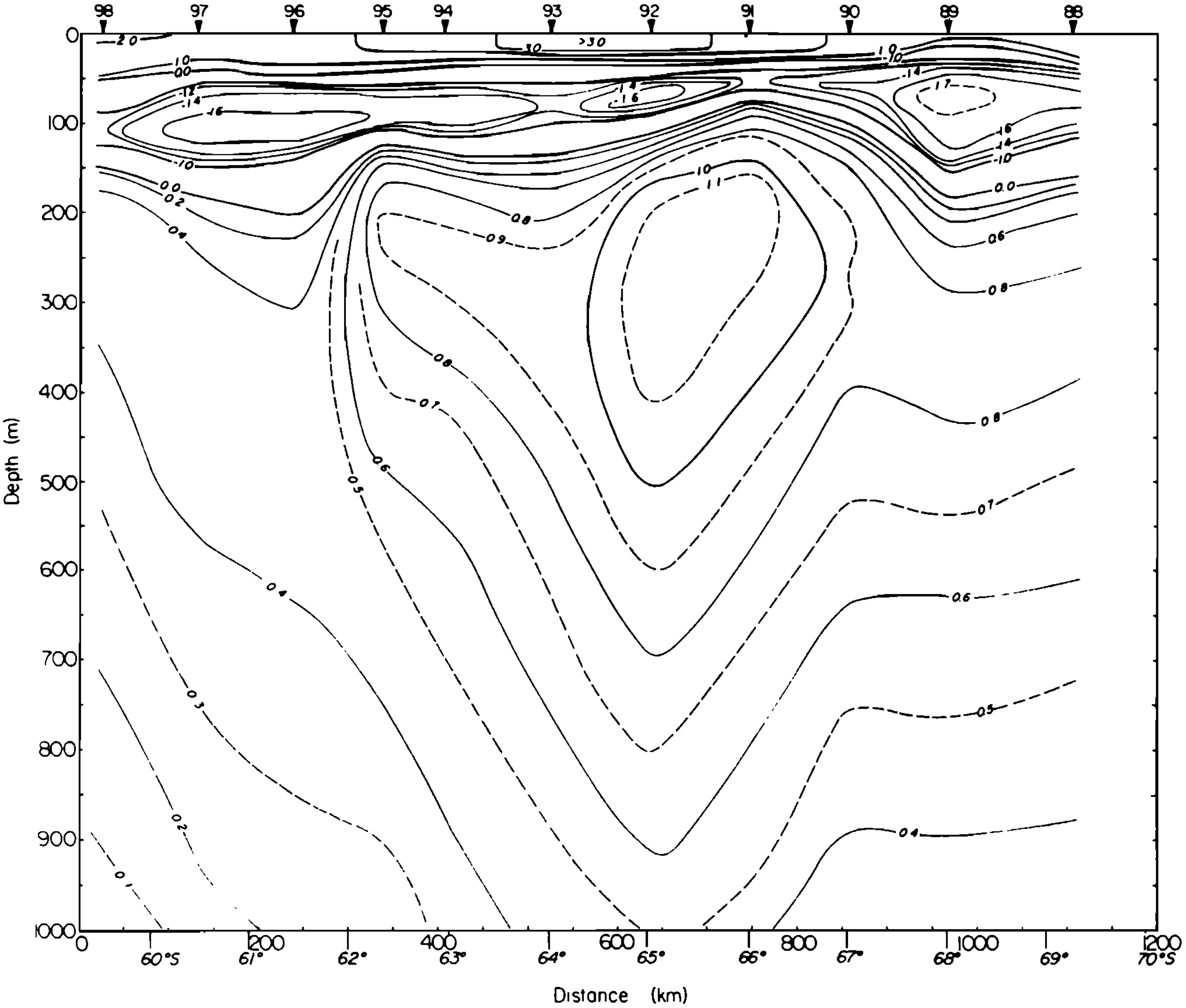


Fig. 6. Potential temperature section along 10°E, traversing the domed pycnocline of the Maud Rise region. Taken from *Gordon and Huber* [1984].

The termination of the Weddell polynya and of the recurring polynya is probably related to net convergence and melting of sea ice, as was discussed previously. The larger the convective region of the polynya, the greater must be the rate of ice injection to attenuate convection. The polynya area grows with the square of the mean radius, while the polynya ice edge grows linearly with the radius. Thus the larger the polynya, the less "apparent" is the boundary and the better protected is the convective interior region from the ice.

We suggest that the larger the size of a sensible heat polynya, the greater the probability of persistence and the less change of sufficient sea ice inflow. Polynyas must attain a certain threshold size before they can persist for long periods. The recurring polynyas at Maud Rise and the Cosmonaut Sea are relatively small and are hence damped out by sea ice inflow.

Sea ice may move into the convective region of the polynya by two processes: random diffusion of ice floe relative to the ocean, or wind-induced advection relative to the ocean. The steady state advection-diffusion equation is

$$(K_x/\rho)d^2C/dx^2 - udC/dx = m \qquad (1)$$

where C is the ice concentration; m is the melting rate; K_x is the horizontal diffusion coefficient, assumed to be constant; ρ is the ice density; and u is ice advective velocity. For the nonadvective case, $u = 0$, and therefore

$$R_d = (2K_x/\rho m)^{1/2} \qquad (2)$$

where R_d is the distance for which C decreases from 1.0 (100% ice concentration) to 0.0. For the nondiffusive case, $K_x = 0$, and

$$R_a = u/m \qquad (3)$$

where R_a is the distance traveled by the advecting ice floe before melting.

For a melt rate $m = 10^{-5}$ to 6×10^{-6}%/s (ice melt completed in 1 to 2 days, respectively) and a diffusion coefficient K_x/ρ of 10^4 to 10^5 cm^2/s (a value expected for a polynya ice edge scale of 1 to 10 km [see *Okubo*, 1971]), R_d would have a range of 0.5 to 2.0 km. For an advective velocity of 1 to 50 cm/s (a value near 10 cm/s may be characteristic [*Ackley*, 1981]; *Thorndike* [1986] finds mean displacement of sea ice induced by synoptic weather system of 7 km/d (8 cm/s)), R_a

ranges from 1 to 80 km. The ratio of R_a to R_d varies from approximately 0.5 to 160. Using midrange for m, and K_x, and 10 cm/s for u, yields a ratio of 11, suggesting that ice advection relative to the ocean is the more important mechanism delivering ice into the polynya convective regime.

Distortion of the convective region by horizontal shear in the polynya regime may constrict an axis of a persistent polynya, making it susceptible to closure by sea ice invasion. This may have been the case for the large Weddell polynya, which drifted into a region of stronger shear within the Weddell gyre.

Although the model provides only a first approximation to the effects of sea ice transport to the persistence of a sensible heat polynya, a more comprehensive and quantitative model needs to be developed. Two points are evident: (1) Wind-induced ice advection into the polynya is more effective than random diffusion of ice in supplying fresh water to attenuate polynya convection. The relation of wind speed to the Cosmonaut polynya shape and size (section 2.1) supports this conclusion. (2) The minimum characteristic diameter of a sensible heat polynya of about 100 km is necessary to protect the convective region from the freshwater source for all but the most intense wind-forced ice advection.

With the case of the 1980 Cosmonaut polynya, although the length of basically ice-free water was about 510 km, the width was only about 100 km (see Plate 1 and Figure 2). A polynya of this size was able to survive about 4 weeks. However, the gradual reduction in size made it more and more vulnerable to termination. As for the Maud Rise polynya, even when the size was maximum, the data elements had, at most, 63% open water. This polynya recurred several times during the same winter, suggesting that the doming of the pycnocline persisted and reinitiated the polynya.

5. SUMMARY AND CONCLUSIONS

Two areas of recurring deep ocean polynyas in 1980 over the southern ocean have been identified: one over the Cosmonaut Sea (Cosmonaut polynya) and another over the Maud Rise (Maud Rise polynya).The Cosmonaut polynya was observed to have occurred in early winter about the same time, and in a similar manner as the Weddell polynya in the mid-1970s. This polynya had a maximum open water area of about 137,000 km^2 and lasted for about 4 weeks. It is also observed to have recurred for several years including 1973, 1975, 1979, 1982, and 1986. The Maud Rise polynya, on the other hand, is the first significant area of open water over the Maud Rise since the large Weddell polynyas. Although the satellite shows it as a reduction in ice concentration to only about 37%, within the SMMR resolution of about 900 km^2, the total area of open water in the region was about 92,800 km^2 on July 20, 1980. Furthermore, the Maud Rise region is the scene of early spring ice breakup almost every year.

It is proposed that these deep ocean polynyas are products of deep-reaching convection which introduces warmer deep water into the surface layer. In this way they are viewed as sensible heat polynyas in that they are maintained by oceanic heat. The oceanographic settings of these two polynyas are similar in terms of the pycnocline depth. The hydrographic data at both sites indicate the existence of localized doming of the pycnocline. The observed pycnocline shallowing at the Maud Rise and Cosmonaut Sea areas preconditions these regions for polynya generation. Enhanced doming of the pycnocline (relative to a climatic condition) induced by the direct wind effect or by ocean circulation spin-up by the larger-scale wind field, would be expected to trigger the polynya. The polynya would then be maintained by ocean convection. This is an effective precondition for deep-reaching convection.

The sporadic nature of these polynyas in contrast to those in the mid-1970s suggests that the size of the polynya is related to persistence. The primary mechanism for the termination of these polynyas is wind-induced ice influence to the convective region. The characteristics of the Cosmonaut polynya correspond to changes in wind field at the adjacent coastal station (Syowa). However, the meteorological data at the coastal station may not be representative of the data in the open ocean, and therefore a more detailed comparison is not warranted at this time.

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