A Possible Link between the Weddell Polynya and the Southern Annular Mode*

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ABSTRACT

Shortly after the advent of the first imaging passive microwave sensor on board a research satellite an anomalous climate feature was observed within the Weddell Sea. During the years 1974–1976, a 250×10^3 km^2 area within the seasonal sea ice cover was virtually free of winter sea ice. This feature, the Weddell Polynya, was created as sea ice formation was inhibited by ocean convection that injected relatively warm deep water into the surface layer. Though smaller, less persistent polynyas associated with topographically induced upwelling at Maud Rise frequently form in the area, there has not been a reoccurrence of the Weddell Polynya since 1976. Archived observations of the surface layer salinity within the Weddell gyre suggest that the Weddell Polynya may have been induced by a prolonged period of negative Southern Annular Mode (SAM). During negative SAM the Weddell Sea experiences colder and drier atmospheric conditions, making for a saltier surface layer with reduced pycnocline stability. This condition enables Maud Rise upwelling to trigger sustained deep-reaching convection associated with the polynya. Since the late 1970s SAM has been close to neutral or in a positive state, resulting in warmer, wetter conditions over the Weddell Sea, forestalling repeat of the Weddell Polynya. A contributing factor to the Weddell Polynya initiation may have been a La Niña condition, which is associated with increased winter sea ice formation in the polynya area. If the surface layer is made sufficiently salty due to a prolonged negative SAM period, perhaps aided by La Niña, then Maud Rise upwelling meets with positive feedback, triggering convection, and a winter persistent Weddell Polynya.

1. Introduction

With the advent of scanning passive microwave sensors on board polar orbiting satellites in late 1972, the polar community entered the era of viewing sea ice conditions poleward of the outer ice edge with near-synoptic clarity. The waxing and waning of the seasonal sea ice cover in the Southern Ocean, whose northern ice edge was previously observed only sporadically from ship, was now exposed in its entirety. The satellite sensors in their second year of operation revealed a large ice-free region during the winter near the Greenwich meridian and 65°S, which is referred to as the Weddell Polynya (Zwally and Gloersen 1977; Carsey 1980; Gordon and Comiso 1988; Fig. 1). The Weddell Polynya, averaging 250×10^3 km^2 in size, was present during the entire austral winters of 1974, 1975, and 1976.

The Weddell Polynya formed just south of the central axis of the cyclonic (clockwise) flowing Weddell gyre. The Weddell gyre, which dominates the circulation of the Weddell Sea, stretches from the Antarctic Peninsula to roughly 20° or 30°E and from the southern limits of the Antarctic Circumpolar Current near 58°S to the margins of Antarctica [Klatt et al. (2005) provide

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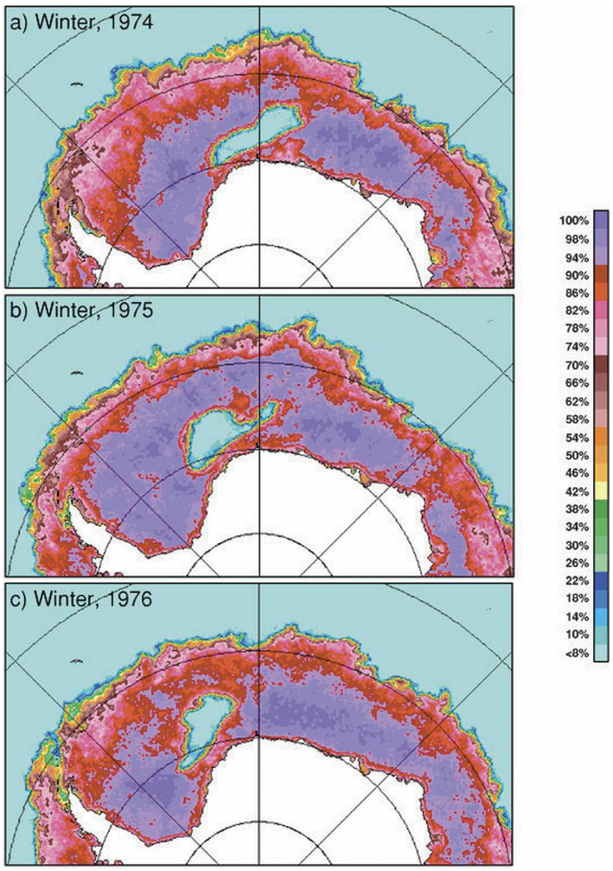

FIG. 1. Color-coded sea ice concentration maps derived from passive microwave satellite data in the Weddell Sea region during (a) 30 Aug 1974, (b) 30 Aug 1975, and (c) 29 Aug 1976. The Weddell Polynya is the extensive area of open water (in blue) near the Greenwich meridian roughly between 65° and 70°S. (Adapted from Gordon and Comiso 1988.)

the most recent overview of the Weddell gyre]. The stratification within the Weddell gyre is characterized by a thick layer of relatively warm, saline deep water drawn from the lower Circumpolar Deep Water. Along the southern limb of the gyre the warm deep water is >1.0°C, with salinity >34.7. The warm deep water is capped by the ~100-m-thick surface layer of near-freezing temperature in the winter. In the summer a warmed surface layer induces a temperature minimum near 50–100 m marking a residue of the winter condition. The surface layer is separated from the warmer deep water by a weak pycnocline (density gradient). Below the warm deep water are the Weddell Sea Deep Water and Weddell Sea Bottom Water, both cooled and freshened relative to the warm deep water by input from the continental margins of Antarctica.

During each winter, the polynya area shifted westward at a rate of 0.013 m s^{-1}, the approximate barotropic flow within the Weddell gyre once away from the topographic effects of the continental margins and Maud Rise (Gordon 1978, 1982). As the Weddell Polynya was observed near the very start of the satellite-based time series one might have reasonably expected that a winter persistent polynya was the norm, but since 1976 a winter-long polynya has not been observed. What has been observed are much smaller (10×10^3 km^2), sporadic polynyas with characteristic time scale of 1 week in the vicinity of Maud Rise near 65°S, 2°E (Comiso and Gordon 1987; Lindsay et al. 2004) induced by circulation-topographic interaction (Gordon and Huber 1990).

The Weddell Polynya of the mid-1970s represents an anomaly relative to the last three decades of direct sea ice observations. Comparison of water column characteristics before and after the Weddell Polynya indicates that it was maintained in the cold winter months by ocean convection reaching to a nearly 3000-m depth that injected relatively warm deep water into the surface water (Gordon 1978, 1982; Fig. 2). The Weddell Polynya is an example of a sensible heat polynya (the ocean to atmosphere heat flux is maintained by lowering the surface water temperature) in contrast to latent heat polynyas (where ocean to atmosphere heat flux is maintained by latent heat release of forming sea ice, which is subsequently removed by the wind) that form along much of the coastline of Antarctica. An estimate of the 3-yr average winter ocean heat lost to the atmosphere within the Weddell Polynya is 136 W m^{-2} (Gordon 1982). This ocean heat loss is supported by deep reaching ocean convection of 1.6 to 3.2 Sv (1 Sv $\equiv 10^6$ m^3 s^{-1}) that exchange freezing-point surface water with relatively warm Weddell Deep Water. Moore et al. (2002) using National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) data find that buoyancy loss within the Weddell Polynya is larger than determined by Gordon (1982) so that the ocean convection may have been significantly more vigorous. However, the NCEP freshwater flux estimate does not include the convergence of freshwater into the polynya associated with the movement of sea ice floes (e.g., by wind stress associated with passing weather systems) with subsequent melting. Gordon (1982) and Comiso and Gordon (1987) suggest that the influx of sea ice from the polynya edges acts to dilute the deep-water salt injected into the surface layer and therefore is a factor in modulating the convective intensity.

The sea surface salinity measured in the austral summer of 1977 shows that in the area of the Weddell Polynya the surface water was markedly saltier than that of the surrounding area and relative to the regional climate average (Fig. 3). It is reasonable to conclude

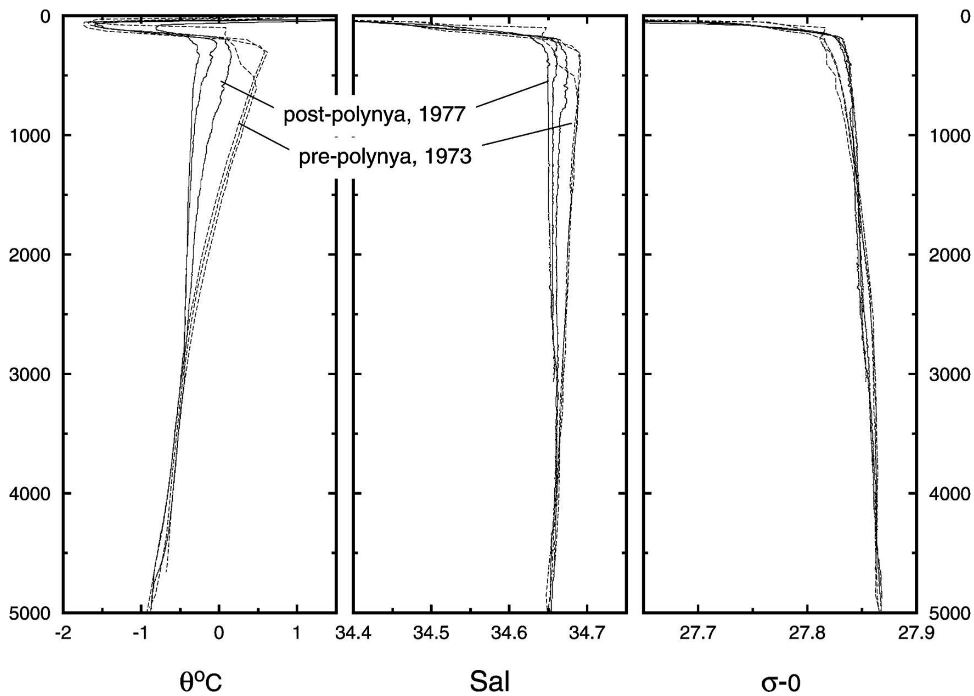

FIG. 2. Profiles of potential temperature (θ°C), salinity (Sal), and density (σ0) before (1973) and after (1977) the occurrence of the Weddell Polynya (from Gordon 1982).

that the salty surface layer is a consequence of the upward mixing deep-water salt during the winter months coupled with the lack of summer sea ice melt. Salty surface water preconditioned the region for a repeat of the polynya the following year. It is hypothesized (Gordon 1978, 1982) that the slow drift westward of the convective region with the overall circulation of the Weddell gyre by the winter of 1977 carried it into the high shear (dv/dx) of the western boundary current of the Weddell gyre, where reduced east–west dimensions enabled surrounding sea ice drift by synoptic weather systems to flood the area with meltwater thus shutting down the potential for deep reaching convection (Comiso and Gordon 1987).

There has been significant rebound in deep-water temperature since the Weddell Polynya. Smedsrud (2005) finds that the area affected by the Weddell Polynya warmed by $\sim 14 \times 10^9$ J m^{-2} from 1977 to 2001. The warming rate within the southern westward flowing limb is about the warming rate observed within the Antarctic Circumpolar Current of 0.034°C decade^{-1} (Gille 2002), indicating that the Weddell Sea Deep Water warming is an advective effect. At the Greenwich meridian the Weddell Deep Water was warmest at the end of the 1990s, decreasing slightly since 1998 (Fahrbach et al. 2004), particularly in the vicinity of Maud Rise (Smedsrud 2005).

Using observational data we present the hypothesis that the Weddell Polynya was primarily the consequence of a prolonged negative phase of the Southern Annular Mode (SAM), with a possible contributing role of the La Niña phase that preceded the polynya. After a brief review of the ocean stratification, meridional overturning circulation, and sea ice cover of the ocean south of the Antarctic Circumpolar Current, we explore our hypothesis by first reviewing the SAM time series then inspect the observational data within the central Weddell Sea for stratification trends and their relationship to SAM and the possible role of ENSO. We then review the Maud Rise effect, which we believe acts as the trigger for generation of a persistent Weddell Polynya if the surface layer is preconditioned by being made sufficiently salty.

2. Southern Ocean stratification, meridional overturning, and sea ice

The Antarctic Circumpolar Current, carrying some 130 Sv eastward (Olbers et al. 2004), serves as the primary deep-water interocean connection. Additionally, there is a substantial circulation along the meridional plane. Through isopycnal processes mediated by an intense eddy field, the Southern Ocean meridional overturning circulation is the primary mechanism exposing the World Ocean's deep water to the atmosphere (Gnanadesikan 1999; Marshall and Radko 2003).

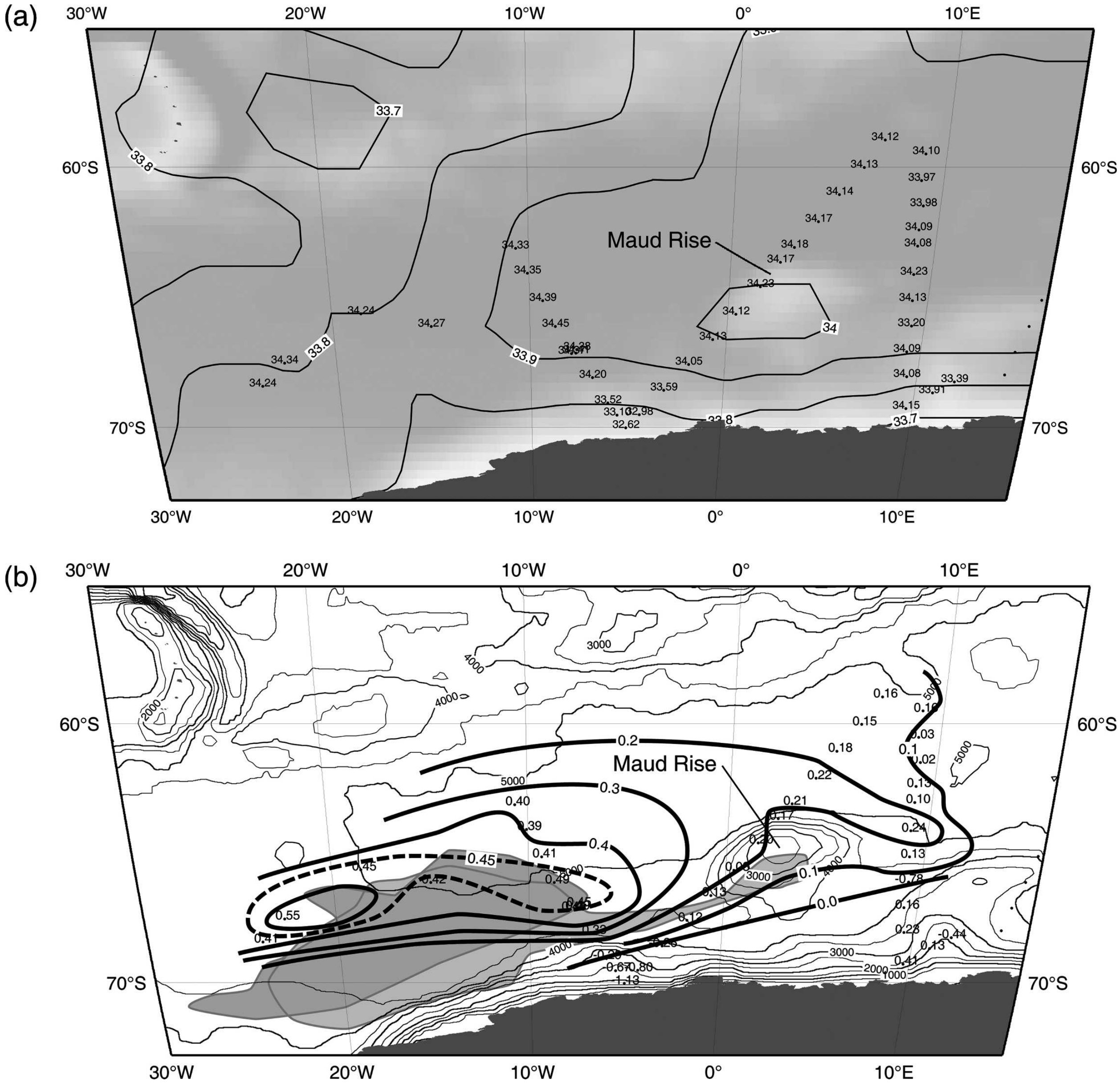

FIG. 3. Surface layer salinity of the eastern segment of the Weddell Sea. (a) The average salinity of the surface 20 m of the ocean from the archived hydrographic data (Conkright et al. 2002). The smaller numbers are specific surface salinity values at hydrographic stations obtained from the *Islas Orcadas* cruise 12, which took place in January–February 1977, the austral summer following the 1976 occurrence of the Weddell Polynya. The gray tone denotes ocean depth; lighter tones are shallower. Antarctica is the dark gray south of ~70°S. Maud Rise is the relatively shallow region near 65°S, 2°E. (b) The difference of *Islas Orcadas* surface salinity values from the climatic surface layer salinity values shown in (a). The position of the Weddell Polynya in the austral winters of 1975 and 1976 (see Fig. 1) is shown as gray tones. Seafloor depths are in meters.

Within the meridional plane, relatively warm, salty circumpolar deep water spreads southward and upward, eventually interacting with the polar atmosphere of the region (the Antarctic zone) south of the Antarctic Circumpolar Current. There may be as much as 50 Sv of deep water flowing southward across the Antarctic Circumpolar Current (Sloyan and Rintoul 2001). Based on winter period data from the central Weddell Sea, Gordon and Huber (1990) estimate that 24 ± 5 Sv of deep water enters into the Antarctic surface layer, about half of the poleward flux of Circumpolar Deep Water. The component that does not reach into the surface layer is entrained into the descending limbs of the meridional circulation associated with Antarctic

Bottom Water and Antarctic Intermediate Water. The deep water that does enter into the surface layer is eventually converted to the surface water types that feed the descending limbs. Recent estimates of the amount of surface water lost to varied forms of Antarctic Bottom Water formation is ~10 Sv (5.4 Sv of shelf water and 4.7 Sv of surface water; Orsi et al. 2001, 2002). Estimates of the contribution of Antarctic surface water to Antarctic Intermediate Water is less well defined, but one may assume from continuity that it amounts to the balance of the deep-water input to the surface layer, about 10 Sv.

The circumpolar deep-water temperatures range from +0.5° to +2°C and so represent a very large reservoir of heat relative to Antarctic zone surface layer, which is close to the seawater freezing point (~−1.9°C) during the winter. Separating the surface layer from the deep water is a shallow, rather weak pycnocline. The central Weddell Sea pycnocline from 100 to 200 m has a density increment of only 0.1 kg m^{-3} (a gradient closer to that of the deep ocean than the main pycnocline of the World Ocean). Removing the Antarctic zone pycnocline by increasing the surface water density would allow deep ocean heat to freely enter into the winter surface layer. The upward flux of heat associated with the removal of the pycnocline would inhibit the formation of sea ice, producing an open ocean convective mode of Southern Ocean overturning, as represented by the Weddell Polynya (Gordon 1991). However, stability of the Southern Ocean stratification is fairly robust (Martinson 1990), endowed with a network of negative feedbacks associated with the freshwater storage in the sea ice cover.

Antarctic zone mixed layer density is increased by heat loss to the atmosphere, estimated as 16 W m^{-2} (Gordon and Huber 1990), but this is compensated by the input of freshwater. On a seasonal time scale the freshwater balance is dominated by the sea ice waxing and waning cycle, but at annual and longer time scales the surface salinity is a consequence of a balance between the addition of freshwater input by precipitation minus evaporation ($P - E$) and continental runoff (glacial ice melt) with the salt input from the relatively salty deep water. The residence time of the surface layer, set by the Ekman divergence, is estimated to be less than 3 yr (~2.5 yr; Gordon and Huber 1990). The annual addition of freshwater into the seasonal sea ice zone is not well known but can be estimated from the salinity of the 24 ± 5 Sv deep-water entrainment into the surface layer (Gordon and Huber 1990). The deep-water salinity of 34.66 with a surface layer salinity of 34.0 implies a freshwater input of 0.8 m yr^{-1}. However, as pointed out by Gordon and Huber (1990), about half of the deep water is removed from the surface layer without a significant change in salinity as part of the Antarctic Bottom Water process, so accounting for the resident surface layer requires only 0.4 m yr^{-1}, which is within the range of values suggested in the literature (0.3–0.5 m yr^{-1}; see Gordon 1981). A 15% reduction in freshwater input (~6 cm yr^{-1}) leads to +0.1 higher equilibrium sea surface salinity. As discussed in section 4, this is a common value for the anomaly of sea surface salinity (δSSS observed minus the climate average) and so represents the likely range of fluctuation of freshwater input. A loss of freshwater of this amount on the annual basis, particularly if sustained for 2 or 3 yr, is sufficient to remove the pycnocline in the Weddell Polynya region where surface salinities are already elevated by topographically induced upwelling at Maud Rise (see section 7), triggering a persistent winter polynya.

The sea ice cover of the Antarctic zone exhibits significant seasonality, and over past decades, interannual variability. Using historical passive microwave data [Scanning Multichannel Microwave Radiometer (SMMR) from November 1978 to July 1987; Special Sensor Microwave Imager (SSM/I) on varied satellites from August 1987 through the present] the trends in the extent and area of the Antarctic ice cover have been quantified by different investigators (e.g., Bjorgo et al. 1997; Zwally et al. 2002; Comiso 2003). Bjorgo et al. (1997) used data from 1978 to 1996 and inferred a negative but insignificant trend in the total Antarctic sea ice cover, while Zwally et al. (2002) used data from 1979 to 1998 and inferred a positive trend of 0.98% ± 0.37% $decade^{-1}$. Also, Comiso (2003) used data from January 1979 to December 2000 and found a positive but insignificant trend of 0.4% ± 0.3% $decade^{-1}$ for the entire Antarctic region. An updated version of the Comiso (2003) analysis that includes data up to December 2004 shows a positive trend of 0.5% ± 0.2% $decade^{-1}$. The trends in the various sectors around the Antarctic region are mainly insignificant except in the Ross Sea and the Bellingshausen/Amundsen Seas sectors, where a 6% to 7% $decade^{-1}$ positive trend in the former is basically offset by a 7% to 8% $decade^{-1}$ negative trend in the latter. In the Weddell Sea sector and using the same technique, Zwally et al. found a 0.89% ± 0.88% trend $decade^{-1}$ while Comiso (2003) inferred −1.2% ± 0.8% $decade^{-1}$ with the difference mainly because of a significant drop in the ice cover in 1999 and 2000. Following a rebound in the ice extent in this sector in 2003 and 2004, the updated value of Comiso (2003) is 0.5% ± 0.5% $decade^{-1}$. The sea ice extent within the Weddell sector does not display a significant difference in the decades of the 1980s compared to that of the

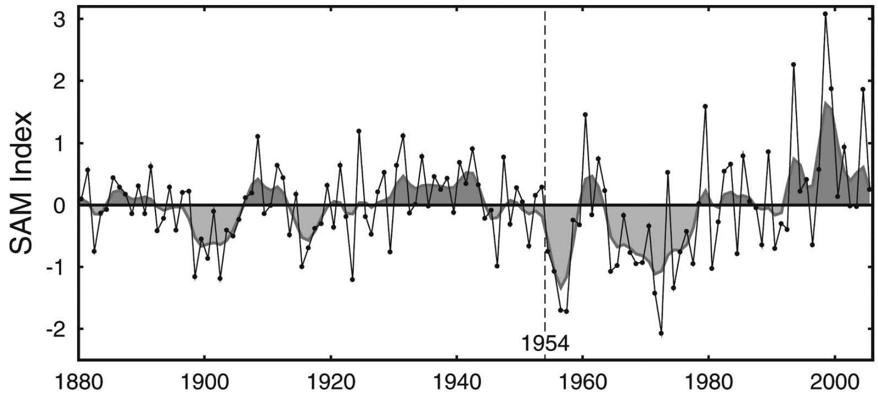

FIG. 4. SAM time series based on SLP indices for various sectors of the Southern Ocean. Yearly values are shown as the black line connecting annual values. The thicker gray line and gray pattern denotes the 5-yr low-pass-filtered data. The index prior to 1954 (dashed line) is computed without Antarctic SLP stations and thus is more uncertain.

1990s, though some increases in the amount of open water inside of the pack of ~3.2% decade^{-1} was observed. Sea ice changes in one sector tend to balance variability in other sectors of the Southern Ocean, so that the regional or sector differences are larger than the full Southern Ocean differences. The sector-to-sector variability is in part influenced by the Antarctic dipole (Yuan and Martinson 2000), but it would be intriguing if the extent (total and Weddell sector) continues to increase as in the last two years, as may be expected from shifting of the SAM index (discussed below).

3. Southern Annular Mode (SAM)

The atmospheric conditions associated with the SAM or Antarctic Oscillation is described by Gong and Wang 1999 and Thompson and Wallace 2000 and its impact on the ocean and sea ice is described by Hall and Visbeck 2002. Zonally symmetric fluctuations of the midlatitude westerly winds are associated with changes in the sea level air pressure difference between 40° and 65°S. SAM is the primary mode of atmospheric variability poleward of 30°S (Visbeck and Hall 2004) and may also account for much of the variability in ocean circulation and sea ice in this region. Hall and Visbeck (2002) used a coupled ocean–atmosphere model to explore how SAM influences ocean circulation and sea ice variability on interannual to century time scales. They find that the maximum westerlies shift southward during positive SAM and to the north in negative SAM. The atmosphere over the seasonal sea ice zone (between the maximum westerlies and Antarctica) becomes more convergent during the positive SAM, leading to an increase in rising motion within the air column, perhaps associated with poleward migration of cyclonic eddies, which increase the poleward moisture flux and would induce greater precipitation. During negative SAM the opposite conditions prevail, those of reduced rising motion and drier conditions, as the drier conditions of Antarctica extend over the adjacent seas, such as the Weddell Sea. Karoly (2003) shows the same pattern in a model-based map of the relation between SAM variations and rainfall in the Southern Hemisphere.

The ocean's response to the shifting SAM is mostly through the Ekman transport. Positive SAM increases upwelling near 65°S close to the Antarctic margins and decreases upwelling near 45°S (see Lefebvre et al. 2004). This has the effect of increasing the tilt of the isopycnals and the strength of the Antarctic Circumpolar Current. Negative SAM has the opposite effect. The results of Hall and Visbeck (2002) are in general agreement with the model findings of Lefebvre et al. (2004) and Gupta and England (2006) showing that positive SAM spins up the meridional overturning circulation of the Southern Ocean and that the Weddell Sea experiences decreased sea ice with increased winds from the north (warmer); during negative SAM there is increased Weddell Sea ice cover with colder air brought in with the enhanced south wind.

The SAM index from 1880 to 2002 (Fig. 4) was calculated using a two-step selection algorithm. A complete presentation of the procedure is under preparation by M. Visbeck. A summary is as follows. In a first pass all stations on Antarctica and on the subpolar islands and southern ends of the continents that had more than 75% of valid monthly data between 1970 and 2000 and with a height below 950 hPa were selected from the hemispheric sea level pressure (SLP) dataset kindly provided by P. Jones from the Climatic Research Unit (CRU) (Jones 1991; Jones et al. 1999). The remaining stations were sorted into four regions: a polar region between 90° and 60°S and three subtropical ring segments between 60° and 20°S from 10°W to 80°E (South Africa, AF), 80°E to 120°W (Australia/New Zealand, AU), and 120° to 10°W (South America, SA). For each region normalizing the mean SLP anomaly with the standard deviation generated an SLP-based index. From that a preliminary SAM index was constructed by computing the difference between the mean subtropical indices (SA + AF + AU)/3 and Antarctica (AA). In a second step only stations with correlations between the station pressure anomalies and the preliminary SAM index >0.3 for the subtropical regions and correlations >0.7 for the Antarctic zone were retained and a new set of regional averaged pressure anomalies and indices constructed. From the remaining 11 stations for Antarctica, 7 for South Africa, 12 for Australia/New Zealand, and 10 for South America, a final station-based SAM index was derived covering the time span from 1954 to 2005. Prior to 1954 the SAM index was estimated without any SLP data from Antarctica. For the <1954 period the Antarctic SLP was approximated from the subtropical regions using AA (proxy) = −(SA + AF + AU)/3. This "proxy" for Antarctica has a correlation with the observed AA SLP between 1954 and 2005 of 0.74. This allows an estimation of the SAM index prior to 1954. Our index for the recent 50 yr compares well to that of Marshall (2003), who have constructed their SAM index from the same station dataset with the goal to match as closely as possible the EOF-based index based on the NCEP–NCAR reanalysis data (Gong and Wang 1999). For the purpose of this paper a calendar-year-averaged SAM index was used with equal contribution from all months. Prior to the late 1970s the SAM index was mostly negative. Since then the SAM index is closer to neutral (zero), tending to more positive values since the early 1990s, with some return toward zero values since 2000.

4. Weddell stratification variability

Observations are sparse within the Weddell gyre, but we believe adequate to provide a reasonable glimpse of the trends of surface, pycnocline, and deep-water characteristics over the last decades (Figs. 5–7), which support the supposition of association between the Weddell Polynya to larger-scale climate features, notably SAM.

a. Surface layer

The salinity within the upper 100 m is taken as the surface layer, as it approximates the winter mixed layer thickness (Gordon and Huber 1990). All observations within the central axis of the Weddell gyre (Fig. 5a) are used to define a climatic mean surface salinity (SSS) for 5° longitude bins, each divided into a northern and southern part at the midlatitude of 63.75°S. As may be expected the preponderance of the data is from the spring, summer, and fall season. Stations in the immediate region of Maud Rise (63°–67°S, 2°W–6°E) are omitted as local processes affect the upper ocean stratification (see section 7). The SSS anomaly (δSSS; Fig. 5b) is determined by differencing the SSS for specific years from the binned-averaged SSS. To qualify, a station must have four or more levels with salinity observations in the 0–100-m interval, each level separated by at least 10 m.

Much of the scatter represented by individual stations may be attributed to local effects. Examination of underway surface layer data records (not shown) of the *Polarstern* within the central Weddell Sea indicates that in summer there is much spatial variability of salinity (amplitude of ~0.2 salinity) at 10–100-km length scales. These features, which are likely products of pools of sea ice meltwater, are not expected to extend below the seasonally warmer surface layer of the upper 30 m. Additionally, to the west of Maud Rise some stations are obtained in small eddies spun off Maud Rise (Gordon and Huber 1995). The average of the δSSS for specific years is shown as a large, black dot when there are six or more stations in a bin, and gray dot when there are two–five stations.

The δSSS (Fig. 5b) values from 1954 to 1975 are mostly positive (saltier than the climate mean) with close tracking to the SAM index. From the late 1970s the δSSS values exhibit mostly near-zero to negative δSSS. More specifically from 1954 to 1975, there are 16 yr with two or more observations. Of these, 14 have a positive δSSS. The average δSSS of the full 16 yr is $+0.09 \pm 0.06$. From 1965 to the time of the Weddell Polynya the average δSSS value is $+0.13 \pm 0.02$, with 2 yr with six or more stations. Directly after the Weddell Polynya occurrence the δSSS tends to have more zero values. From 1977 to 2002, the average δSSS is negative for 10 yr represented by two or more stations; 2 yr with near-zero δSSS; and 10 yr represented by two or more stations, with a positive δSSS. The average δSSS for the period 1977–2002 is -0.01 ± 0.08. The surface layer was on the whole saltier (denser) in the years leading up to the Weddell Polynya than after the polynya. A linear regression of SAM versus δSSS (Fig. 5c) shows a trend, albeit weak, of saltier SSS with negative SAM.

As discussed in section 2 a freshwater input of 85% (representing a net reduction of 6 cm yr^{-1}) of the climate norm would impose an increase of the equilibrium

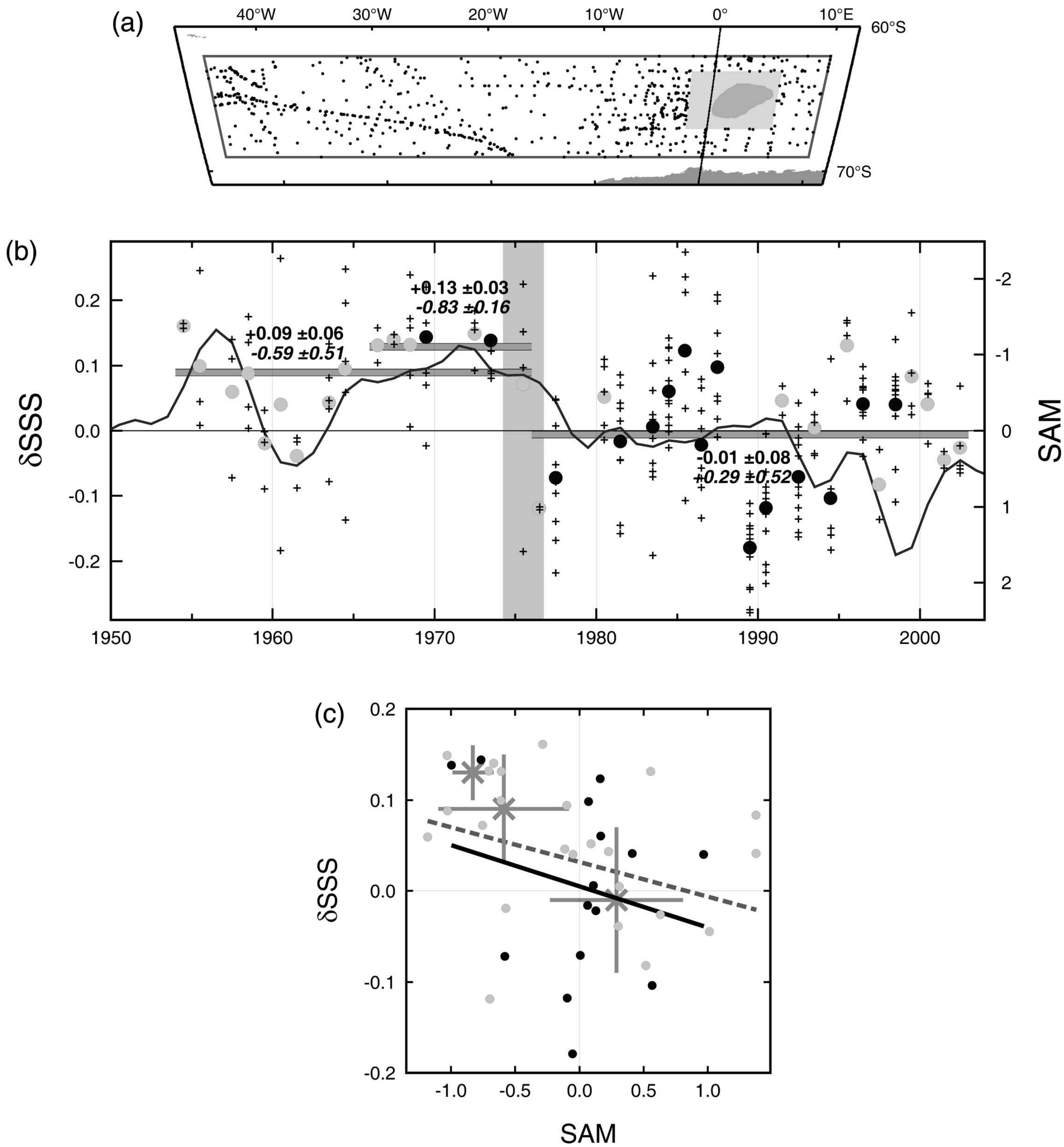

FIG. 5. (a) The location of the oceanographic stations used to construct a time series of the salinity of the upper 100 m within the central Weddell Sea. The dark gray area is Maud Rise. Data from the lighter-tone gray bracketing Maud Rise are omitted in construction of the salinity time series. (b) Time series of the surface layer (upper 100 m) salinity anomaly (δSSS) relative to climate mean within the central region of the Weddell Sea. The gray-tone band marks the period of the Weddell Polynya. Each station used is represented by +; yearly average values are shown as a large black dot when there are six or more stations; large gray dot when there are between two and five stations. The solid line is the 5-yr low-pass-filter SAM index taken from Fig. 4. The mean and standard deviation values for δSSS and SAM (italics) for specific periods are shown in the figure (see section 4a of the text). (c) The relationship of the yearly averaged δSSS to the SAM index [large dots in (b)]. Linear regression of δSSS to the SAM index is shown: the black line is constructed from the large black dots shown in (b); the dashed line is based on all of the gray and black dots. The positions of the mean and standard deviation for specific periods shown in (b) are placed in the δSSS/SAM scatter.

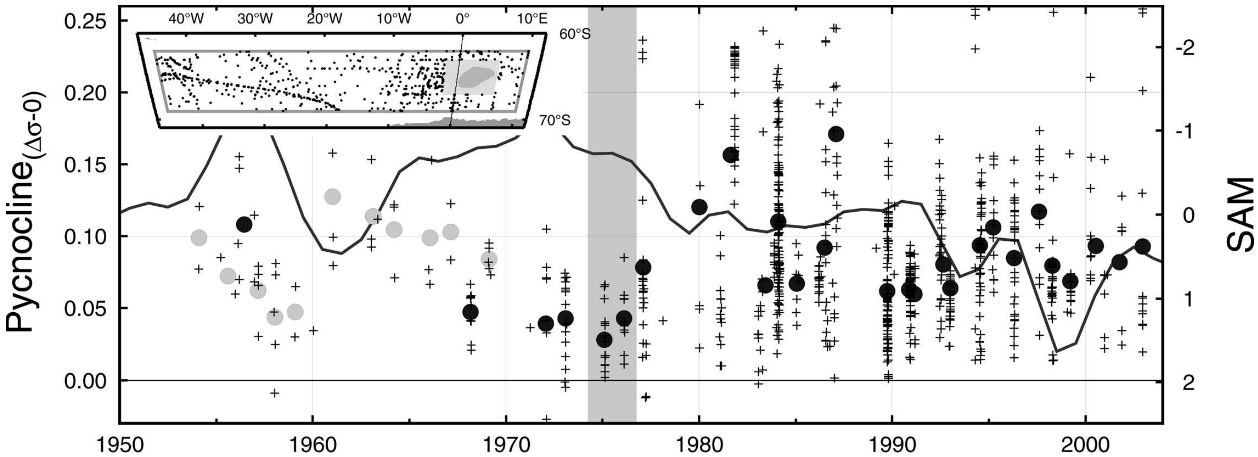

FIG. 6. The pycnocline strength, as given by the change of density in kg m^{-3} between 100 and 200 m ($\sigma 0$), within the central region of the Weddell Sea (see map insert for station positions). The period of the Weddell Polynya is marked by a gray tone. Each station used is represented by a small +; yearly average values are shown as a large black dot when there are six or more stations and as a large gray dot when there are between two and five stations. The solid line is the 5-yr low-pass-filter SAM index taken from Fig. 4.

surface layer salinity by 0.1. A prolonged negative SAM will allow the surface layer to attain the higher equilibrium salinity, as after the 2.5 yr of the estimated surface layer residence time, the "historical memory" of the past wetter years is lost. As the δSSS was about +0.13 just before the appearance of the Weddell Polynya (Fig. 5b), a reduction of ~8 cm in the annual $P - E$ can account for the observed SSS increase. Thus small changes in net freshwater input can have a sizable effect on surface salinity. In view of the paucity of direct observations in the central region of the Weddell Sea, we believe that a relationship between surface salinity and SAM is a reasonable conjecture.

b. *Pycnocline*

Exchange between the deep water and surface layer is inversely related to the strength (stability) of the pycnocline. A strong, intense pycnocline acts to attenuate vertical exchange. A weakened pycnocline would lead to greater upward mixing of deep-water heat and salt into the surface layer. Removal of the pycnocline leads to convective overturning. Using the same stations shown in Fig. 5a (again omitting the stations in the Maud Rise region) we calculate the strength of the density change between 100 and 200 m, which defines the central Weddell Sea pycnocline (Fig. 6). The pycnocline weakened in the late 1950s, strengthened around 1961, and then weakened steadily into the era of the Weddell Polynya. The sigma-0 ($\sigma 0$) difference between 100 and 200 m was only 0.04 in the early to mid-1970s. Since then the pycnocline has been more intense, with average value of $\Delta\sigma 0$ of about 0.08.

c. *Weddell Deep Water*

The Weddell Deep Water properties (200–500-m interval; again omitting the stations in the Maud Rise region; Fig. 7) display a warming trend since the late 1970s into the mid-1990s. The coldest deep water occurred in the mid-1970s, a direct consequence of the Weddell Polynya (Gordon 1982). The trends in salinity are generally density compensating (cooler deep water is coupled to fresher deep water), so the density time series is rather flat, the yearly mean of which varies by less than 0.01. Changes in Weddell Deep Water have been studied by Robertson et al. 2002, Martinson and Iannuzzi 2003, and Fahrbach et al. 2004, suggesting linkage to ENSO. The Southern Oscillation index (SOI) values (dashed line on the temperature panel of Fig. 7) reveal a predominance of an El Niño phase since the late 1970s, with neutral to La Niña before the mid-1970s. A significant La Niña occurred during the Weddell Polynya period. Robertson et al. (2002) show that the Weddell Deep Water within the outer limbs of the Weddell gyre has warmed over the decades at a rate of 0.012°C yr^{-1} from the late 1970s to 2000 since the Weddell Polynya. Additionally, they show (their Fig. 8) that within the southern limb of the gyre, along the base of the continental slope from 0° to 20°W the deep water warmed from 0.6°C in the late 1970s to 0.9°C in 1995, about 0.018°C yr^{-1}, cooling slightly since then. Robertson et al. (2002) speculate that the Weddell Deep Water warms when the Weddell front (the northern defining front of the Weddell gyre) shifted southward, which may come about with changes in SAM or Antarctic Circumpolar Wave.

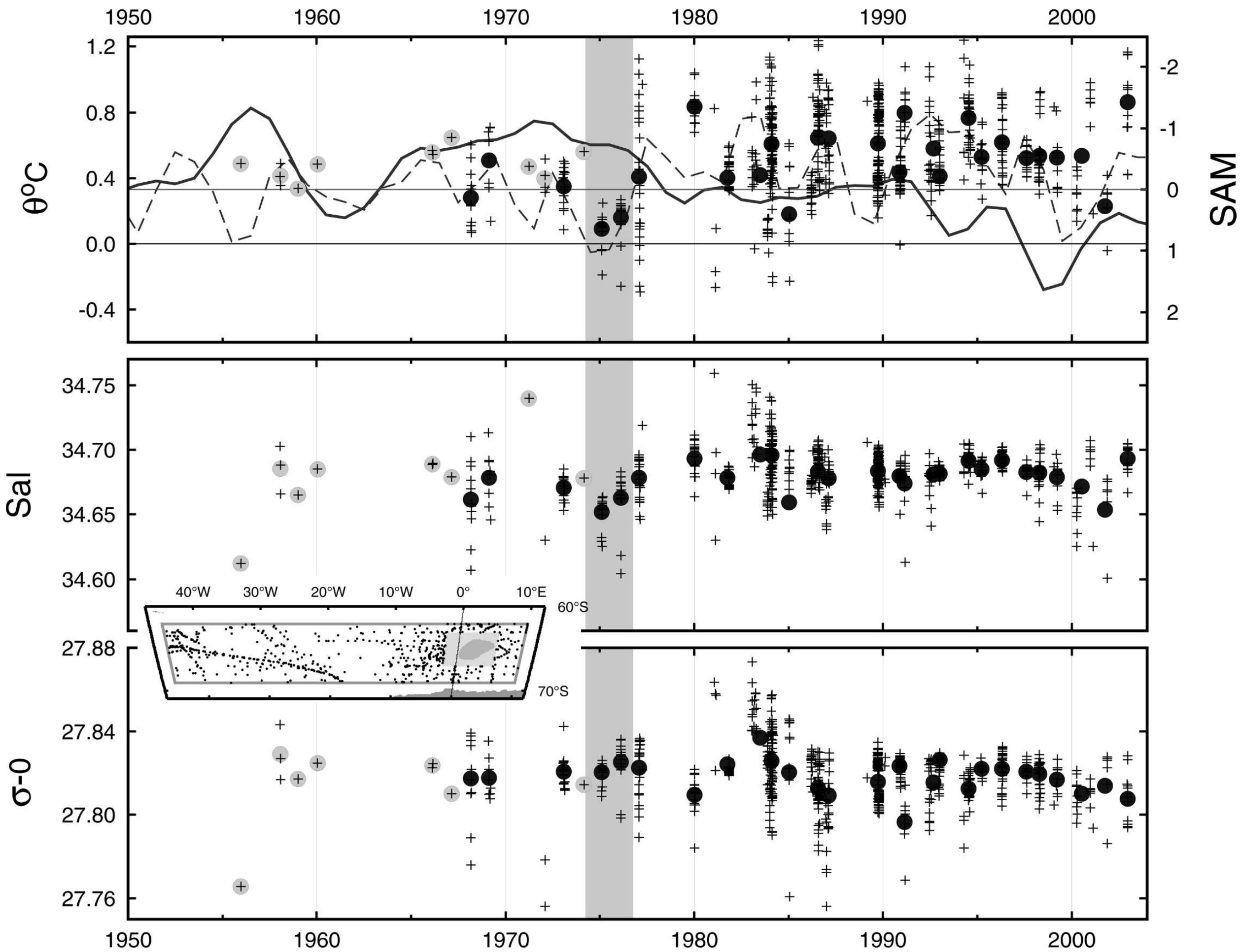

Fig. 7. (top) Time series of Weddell Deep Water potential temperature (θ°C); (middle) salinity (Sal); and (bottom) density (σ0) within the central region of the Weddell Sea. The stations used are shown in the map insert. The period of the Weddell Polynya is marked by the gray tone. Each station used is represented by a small +; yearly average values are shown as a large black dot when there are six or more stations and as a large gray dot when there are between two and five stations. The solid line in the top panel is the 5-yr low-pass filter SAM index taken from Fig. 4. The dashed line in the top panel is the 2-yr running mean of the SOI.

Fahrbach et al. (2004) return to this point, suggesting that increased inflow of Circumpolar Deep Water into the Weddell gyre occurs during the southward displacement phase of the Antarctic Circumpolar Wave (White and Peterson 1996). That the Antarctic Circumpolar Wave was more intense in the 1980s and early 1990s (Carril and Navarra 2001) may explain the deep-water warming during that period. Fahrbach et al. (2004) also suggest that changes of the cyclonic wind field over the Weddell gyre may alter the strength of the gyre and the inflow of warm deep water. Using the European Centre for Medium-Range Weather Forecasts (ECMWF) 1986–2002 data they find that the intensity of the atmospheric low pressure over the eastern Weddell Sea, centered at 65°S, decreased from the mid-1980s to the mid-1990s. They hypothesized that this led to a weaker Weddell gyre and increased intrusions of warm circumpolar deep water from the north. Since the mid-1990s the low pressure field has intensified.

5. Weddell time series and SAM

To summarize the above, ship-based observational data for the central region of the Weddell Sea suggest significant decadal thermohaline variability. From the mid-1950s to mid-1970s the surface layer was generally saltier than the longer-term mean. This is particularly the situation in the late 1960s to the time of the Weddell Polynya in the mid-1970s, when the pycnocline attained is at its weakest condition in the approximately 50 yr of archived observations. During the 1990s the reverse occurred: fresher surface water and strengthening pycnocline. The trends are indicative of increased surface salinity during negative SAM and decrease during positive SAM. The relationship of SAM to precipitation since 1979 within the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP), which is based on station observations and estimates drawn from satellite data (CMAP version 2, November 2004; Xie and Arkin 1997) over the Weddell, reveals a positive, albeit weak, correlation of precipitation with SAM. Karoly (2003) also shows this trend.

For the central Weddell gyre the regression of 0.05–0.10 mm day^{-1}, or 1.8–3.7 cm yr^{-1} less precipitation for a SAM index of -1, about the value of the negative SAM in the decade proceeding the polynya. As discussed above a reduction of annual freshwater input ($P - E + R$) of ~8 cm is needed to explain the elevated SSS of ~0.13 prior to the Weddell Polynya. This is higher than the CMAP precipitation value, but other SAM-related factors govern the surface layer salinity, such as the freshwater export by sea ice divergence over the Antarctic zone. This may account for the larger reduction of freshwater input implied from the SSS values in comparison to the CMAP reanalysis data. During negative SAM the band of low air pressure around the Antarctic, the Antarctic trough, shifted northward, which may have led to increased export sea ice (freshwater extraction) from the Weddell Sea into the southern limbs of the Antarctic Circumpolar Current.

In view of the uncertainties in a negative SAM-induced reduction of freshwater within the Weddell Sea, such as that associated with $P - E$, with sea ice export and variability of the deep-water injection into the surface layer as pycnocline weakens, it is reasonable to deduce that a negative SAM from the mid-1960s to the mid-1970s led to saltier (denser) surface water, weakening the pycnocline, and deep-reaching convection associated with the Weddell Polynya.

6. An ENSO connection

There may also be a connection of ENSO with the Weddell Polynya. Martinson and Iannuzzi (2003) find that the Weddell gyre spins up (contracts) during El Niño and expands during a La Niña phase. The La Niña expansion of the gyre may enable increased export of sea ice with commensurate elevation of Weddell surface layer salinity, as hypothesized above for the negative SAM phase. There may also be a compounding influence on sea ice formation in the Maud Rise region. Kwok and Comiso (2002) (also see Yuan and Martinson 2000) show that for the Weddell sector west of the prime meridian La Niña is associated with warmer temperatures and with less extensive ice cover, while El Niño induces a colder, more extensive ice cover in western Weddell. However at the Greenwich meridian and in the Maud Rise area where the Weddell Polynya initiated, the conditions are slightly colder with more sea ice in La Niña than in El Niño. The Weddell Polynya occurred during a La Niña period. Additionally, the El Niño (albeit weak) of the 1960s that preceded the Weddell Polynya may have lead to a warmer Weddell Deep Water (as in the 1990s; Robertson et al. 2002; Fahrbach et al. 2004) increasing the susceptibility to polynya development once the surface layer salinity increased sufficiently.

A competing aspect of El Niño Weddell gyre spinup is doming in the center of the Weddell gyre that might encourage the formation of a polynya by thinning the protective buoyant surface layer. However, the Weddell Polynya did not form in the shallower pycnocline along the gyre's central axis but rather in the region between the central axis and the continental margin area, where gyre spinup would deepen the pycnocline. Hence the polynya occurs in a region where the pycnocline displacement due to gyre spinup would be small. A more potent feature is the local upwelling induced by Maud Rise.

7. The role of Maud Rise

One further piece of information is needed to properly understand the environmental forces leading to the Weddell Polynya: Maud Rise. Maud Rise is a seamount with a 1700-m peak near 65°S, 2°E. An area of reduced sea ice concentration often forms, lasting about a week, in the vicinity of Maud Rise (Comiso and Gordon 1987; De Veaux et al. 1993). A distinctive 300-km circular halo of low sea ice concentration has been observed most clearly for the months July–November, above the Maud Rise seamount in the eastern Weddell Sea (Lindsay et al. 2004). The mean ice concentration in the halo is just 10% less than in the center, where it is very near 100%. The halo may reflect the existence of a Taylor cap circulation over the seamount or other topographically induced mechanisms (Lindsay et al. 2004). The Maud Rise Polynya with sea ice concentrations of <92% seems to be occurring at increased frequency since 1991 (Fig. 8), with pronounced occurrences observed in 1991, 1992, 1994, and 2004, which may have led to cooling of the deep water in that region during the last decade (Smedsrud 2005).

Comiso and Gordon (1987) suggest that these small "openings" in the sea ice pack are closed when wind of the synoptic weather systems directs sea ice from the surrounding region over the Maud Rise region, which upon melting damp out convection. That is, if there is enough freshwater in the surface layer of the surround-

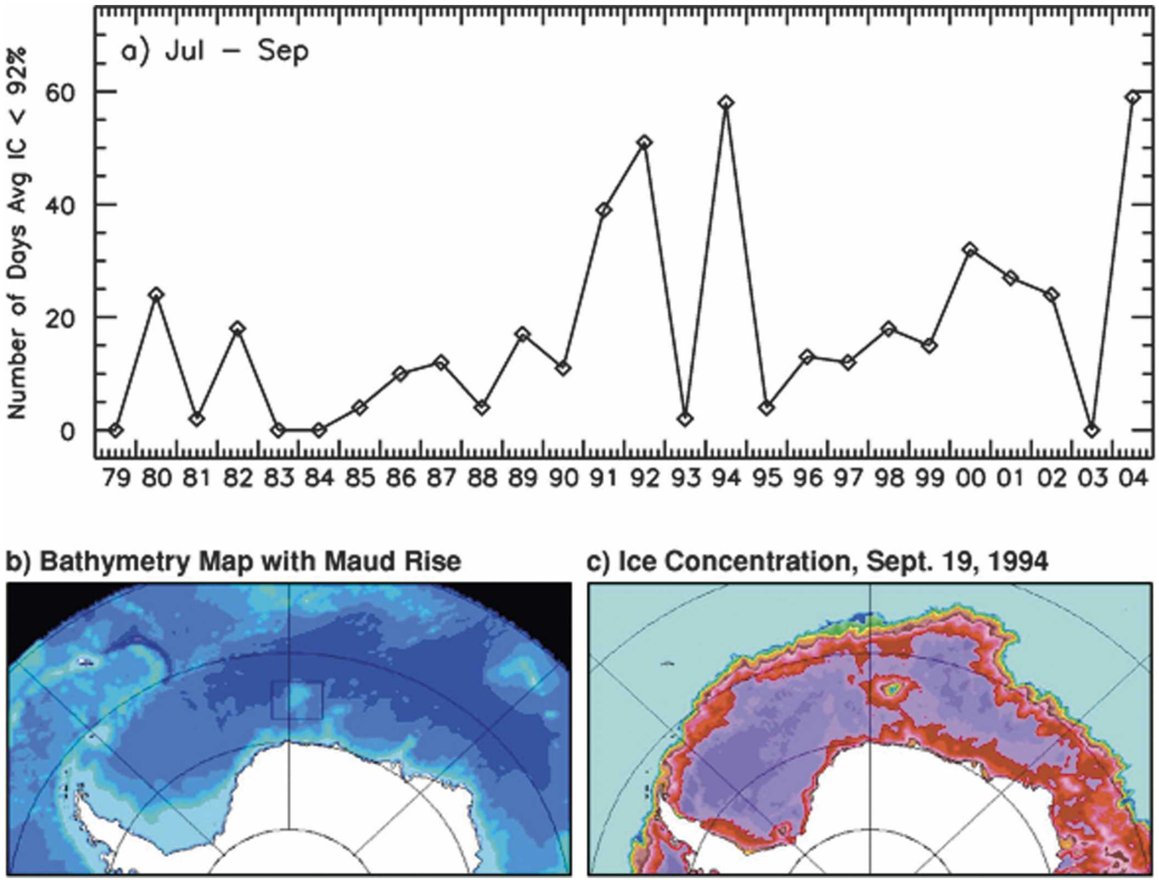

FIG. 8. (a) Number of days from 1979 to 2004 when the ice concentration average within the Maud Rise region [smaller box on the map in (b)] is less than 92%; (b) bathymetry of the Weddell Sea region including the Maud Rise (box); and (c) ice concentration map on 19 Sep 1994 showing a Maud Rise polynya. The year 1994 was one of the years when the Maud Rise Polynya reoccurred frequently during the winter.

ing region, including that within the sea ice, the Maud Rise upwelling would not spark a Weddell Polynya. If there is inadequate freshwater in the surface layer, then an upwelling event over Maud Rise could initiate a persistent Weddell Polynya. Comiso and Gordon (1987) surmise that there is a threshold size for a polynya to trigger a winter-long persistent feature; the threshold is determined by the distance that sea ice may be translated during a wind event, one that is large enough not to be damped out by synoptic systems.

The Maud Rise effect on sea ice is due to enhanced upwelling of warm deep water as induced by circulation/topography interaction over the flanks of Maud Rise (Gordon and Huber 1990; Bersch et al. 1992). Slight increases in the mixed layer density could trigger a convective mode and generation of a polynya, perhaps aided by the thermobaric effect (McPhee 2000). A more vigorous Weddell gyre may be expected to increase Maud Rise–induced upwelling, leading to more frequent short-lived polynyas over and near Maud Rise. Holland (2001) proposes a more dynamical link of Maud Rise to the local polynya events: that reduced sea ice cover is initiated by cyclonic eddies shed from the northeast flank of Maud Rise, which transmit divergent Ekman stress to the sea ice cover.

8. Conclusions

We present the provocative hypothesis that the Weddell Polynya of the mid-1970s resulted from a prolonged period of negative SAM. The negative SAM starved the Weddell surface water of freshwater through a reduction of precipitation and increased export of sea ice from the Weddell Sea into the Antarctic Circumpolar Current, making for a saltier surface layer. Winter cooling of the saltier surface destabilized the ocean pycnocline, allowing the development of deep-reaching ocean convection that delivered into the sea surface layer the "heat" of the Weddell Deep Water, thus inhibiting winter sea ice formation, resulting in the polynya state. ENSO may also have played a supporting role in that the strong La Niña of the mid-1970s produced a colder period over the Maud Rise region, allowing the destabilizing effect of more sea ice formation. We base our conjecture on observational data, which admittedly are sparse within the remote Weddell Sea, but we think sufficiently convincing to warrant further (most likely model based) research.

While in this research we focus on the well-documented Weddell Polynya of the mid-1970s, there may have been a polynya in 1960. Gordon (1982) reports that two hydrographic stations obtained by the Argentine ship *San Martin* in 1961 reveal the absence of the warm deep water, similar to conditions encountered in the 1977 *Islas Orcadas* stations. The SAM index (Fig. 4) indicates a prolonged negative SAM in the decade prior to the possible polynya in the winter of 1960. Furthermore, except for the 5-yr period centered on 1910, a negative or neutral SAM index persisted from the 1890s into the first three decades of the twentieth century (Fig. 4). Might the Weddell Polynya been common then?

Will a winter-long Weddell Polynya happen again? The conditions recorded at the beginning of the passive microwave data time series could not have been so unique that it caught a one-time feature. The Weddell Polynya must have formed before the mid-1970s and will occur again, but when? According to our proposed mechanism, it will happen once the SAM enters into a period of prolonged negative phase, so as to build up the salinity of the surface layer. Fyfe et al. (1999) and Cai et al. (2005) find that under increasing atmospheric CO_2 concentrations climate models predict a more positive value of the SAM. Fyfe and Saenko (2006) link this trend with strengthening and poleward shift of the Antarctic circumpolar current. The future of SAM depends on the stratospheric ozone levels as well as greenhouse gas concentration, which have opposing effects on surface climate (Shindell and Schmidt 2004). Shindell and Schmidt (2004) find that surface temperature trends of the southern polar region may become increasingly decoupled from the SAM index, as the greenhouse domination over the ozone effect grows. These simulations of future climate change suggest that the Weddell Polynya may become less frequent in the coming decades. However, the occurrence of a strong La Niña event or changing relationship of SAM to ENSO is also a consideration in predicting the future of the alternate deep ocean ventilation processes associated with the Weddell Polynya. The Maud Rise forcing upwelling of warm deep water is the trigger, but the regional surface layer salinity needs to be high enough for the local trigger to produce a winter-long persistent Weddell Polynya. So our advice to Maud Rise: keep trying! A Weddell Polynya once initiated eventually disappears if the SAM index returns to neutral or positive values and as the affected area advects westward into the western boundary current of the Weddell Sea.

If the proposed link between SAM and the Weddell Polynya proves to be robust, then one can consider the feedback to the SAM index and regional-scale meteorology of the exposure to the polar winter atmosphere of the polynya's 250×10^3 km^2 surface ocean "hot" spot and associated open ocean convection, as well as the Weddell Polynya's impact on the present, past, and modeled future climate and ventilation of the global ocean.

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