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# Warm Weddell Deep Water west of Maud Rise

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**Abstract.** A pool of relatively warm (>1.0°C) Weddell Deep Water (WDW) immediately west of Maud Rise appears to be a quasi-stationary feature. The "warm pool" is derived from the flow of warm WDW around the flanks of Maud Rise. An austral spring 1989 expedition of the R/V *Akademik Fedorov* obtained detailed measurements of the warm pool. It displays the general regional relationship of temperature maximum ($t$-max) warmth to shallowness of the pycnocline, as well as mixed layer oxygen concentration well below full saturation. Depression of oxygen values is a product of injection of WDW into the mixed layer during the ice-covered winter period. Associated with this transfer are high vertical fluxes of heat and salt which limit the thickness of the sea ice cover. In the winter the atmosphere is sufficiently cold to remove the WDW heat without massive sea ice melting, though the regional ice thickness is restricted. In the spring the atmospheric conditions cannot remove the ocean heat, and ice melting ensues before the atmospheric heat budget alone can account for the ice melt. This is clearly seen in the warm pool as very low mixed layer oxygen, which is a reflection of high WDW entrainment and vertical heat flux and is normally associated with high mixed layer salinity. Here it is coupled instead with reduced salinity, a result of approximately 0.5 m of ice melt. The *Fedorov* data confirm the role of oceanic heat flux in early removal of Southern Ocean sea ice at the end of winter, in that the region of highest WDW entertainment is associated with greater amounts of melt water.

## Introduction

A dominant feature of the Weddell Gyre is the relatively warm (>0°C) deep water immediately below the pycnocline. This deep water forms a local temperature maximum ($t$-max) and comprises a core layer referred to as the Weddell Deep Water (WDW). WDW is drawn into the eastern margin of the Weddell Gyre from the circumpolar deep water [*Orsi et al.*, 1993; *Bagriantsev et al.*, 1989; *Deacon*, 1979]. WDW is the source of heat and salt for the Weddell Gyre. Its heat enters the winter mixed layer to restrict the seasonal sea ice cover in thickness and duration [*Gordon*, 1981; *Gordon and Huber*, 1984, 1990; *Martinson*, 1990]. Its salt acts to offset the positive freshwater budget with the atmosphere and, in places of limited freshwater input, to destablize the ocean, inducing formation of Antarctic Bottom Water and deep convective cells [*Martinson et al.*, 1981; *Gordon*, 1991].

The horizontal thermohaline pattern of the WDW has structure at a variety of scales, from cells of tens of kilometers in diameter to features of hundreds of kilometers [*Bagriantsev et al.*, 1989]. Cells of relatively warm WDW are associated with local shallowing of the pycnocline [*Gordon et al.*, 1984; *Gordon and Huber*, 1990; *Ou and Gordon*, 1986]. Summer data collected over several years have revealed a warm pool of WDW immediately west of Maud Rise, and it is believed that this may be a quasi-permanent feature resulting from interaction between Maud Rise and the Weddell Gyre circulation [*Bagriantsev et al.*, 1989]. The current measurements reported by *Bersch et al.* [1992] over the flanks of Maud Rise suggest that WDW enters this region along the northern slope of Maud Rise, in agreement with the regional $t$-max distributions [*Bagriantsev et al.*, 1989; *Bersch et al.*, 1992; *Orsi et al.*, 1993]. The detailed $t$-max distribution reported by *Bersch et al.* [1992 Figure 5b] clearly shows the warmest WDW (>1.0°C and in isolated spots above 1.2°C) passing along the northern flank of Maud Rise and forming a pool immediately to the west, as far as 4°W. *Bersch et al.* [1992] show that south of Maud Rise, $t$-max reaches between 0.8° and 1.0°C, cooler than that found to the north but significantly warmer than that observed directly over the Rise ($t$-max < 0.6°C). This indicates that WDW spreading also occurs south of the rise but this may be a weaker advective feature or perhaps a region of stronger heat loss due to mixing.

Warm WDW close to the sea surface enhances the flux of heat from the warmer deep water to the winter mixed layer under the sea ice and hence to the atmosphere. We will follow the nomenclature of *Gordon and Huber* [1990] and refer to this winter heat flux as $Q_f$. The total WDW transfer into the mixed layer averages 45 m/yr for the Weddell Gyre along the Greenwich Meridian, with an associated $Q_f$ of 41 W/m$^2$ [*Gordon and Huber*, 1990]. This flux limits ice thickness to a regional value of about 55 cm, agreeing quite well with observations [*Wadhams et al.*, 1987]. The air temperatures encountered during the 1986 *Polarstern* cruise reported by *Gordon and Huber* [1990] are sufficient to remove the WDW heat input in the presence of observed ice thickness and concentration, suggesting that the sea ice cover and $Q_f$ are in approximate balance by midwinter. *Gordon and Huber* [1990] assert that regions of high $Q_f$ are expected to be regions of early spring sea ice melt, earlier than might be expected solely from atmospheric parameters. The 1989 survey by the Russian ice-breaking research vessel R/V *Akademik Fedorov* of the quasi-stationary pool of relatively warm WDW immediately west of Maud Rise (Figures 1a and 1b) supports this assertion: ice melt is associated with the warmest $t$-max region.



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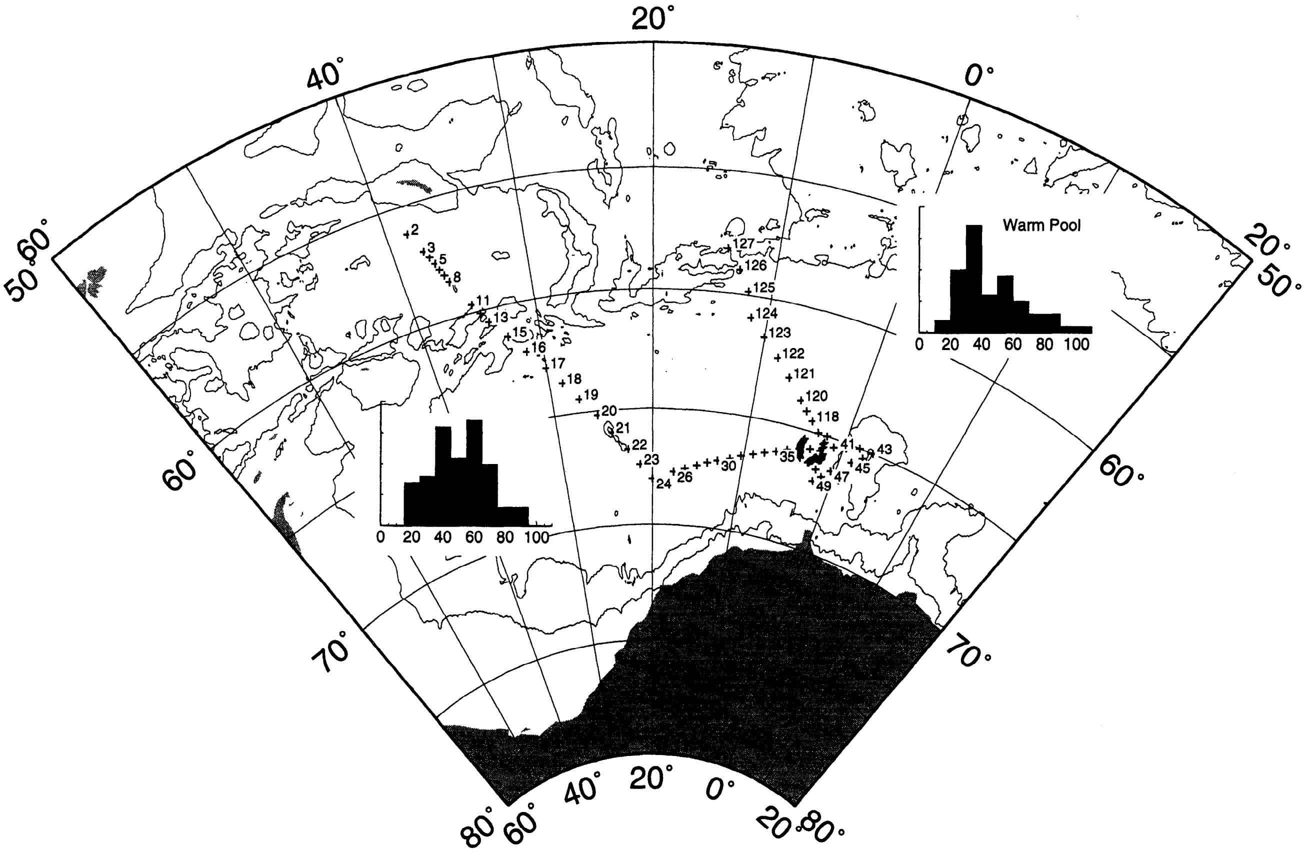


**Figure 1a.** Station positions from 1989 R/V *Akademik Fedorov* cruise. The 2- and 4-km-depth contours are shown. Histograms depict the frequency distribution of minimum observed ice thickness (in centimeters) in the warm pool (right) and for the non–warm pool inbound and outbound sections (left).

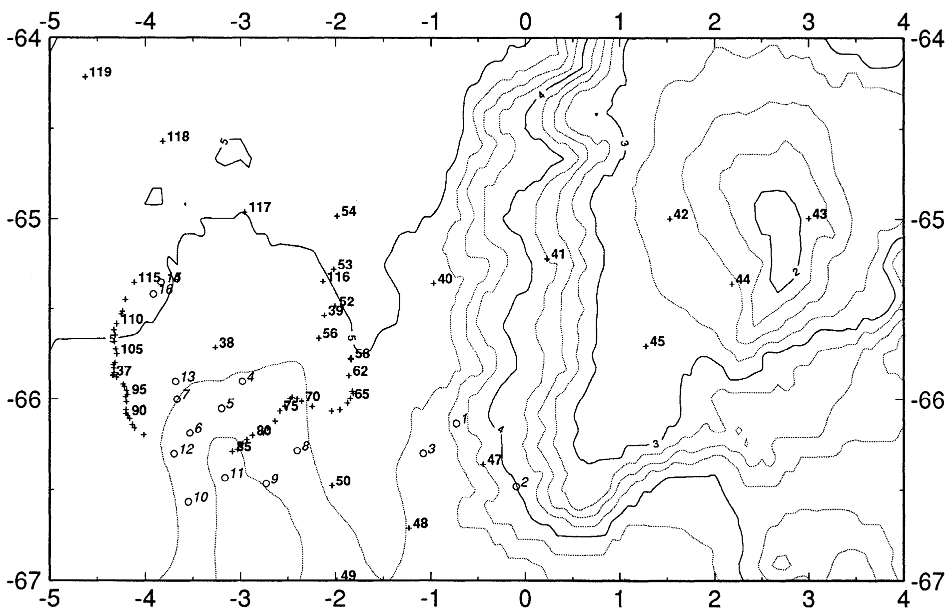


**Figure 1b.** Warm pool survey station grid. The crest of Maud Rise is at 65°S near 3°E. The drift series occurred from October 6 to 18, near 65.5°S and 3°W, just north of a slight ridge in the bottom relief. Helicopter sampling sites are marked with open circles.

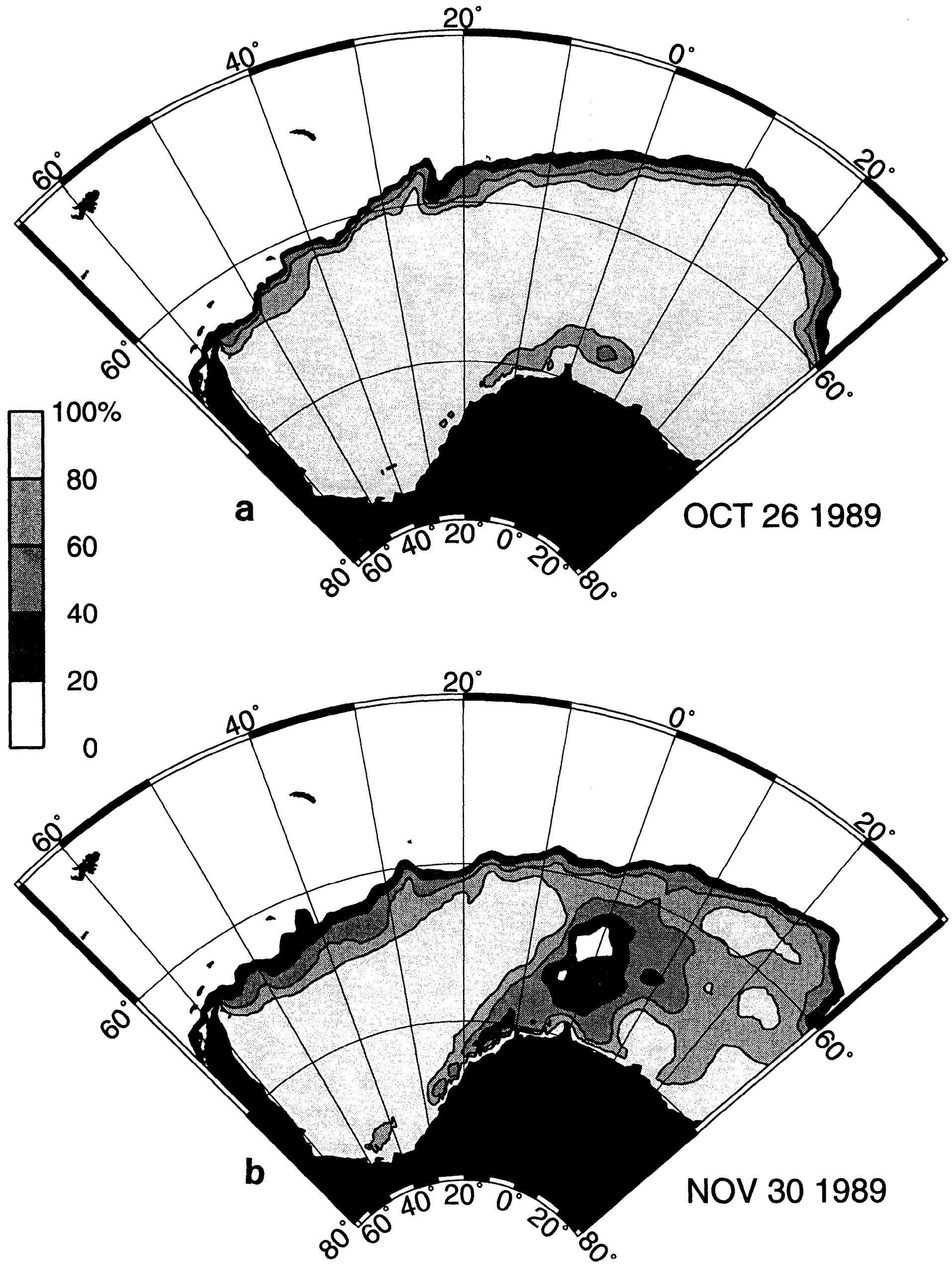


**Figure 2.** (a) Satellite-derived sea ice concentrations on October 26, 1989. The concentrations were computed from special sensor microwave imager data using the Comiso algorithm, as distributed by National Snow and Ice Data Center. (b) Satellite-derived sea ice concentrations for November 30, 1989.

## Winter Weddell Gyre Study 1989

During the austral spring of 1989 a team from U.S. and USSR institutions aboard the Russian ice-breaking *Akademik Fedorov* obtained conductivity-temperature-depth (CTD) profiles in the vicinity of Maud Rise, including a drift station sequence within the warm pool from October 6 to 8 [*Huber et al.*, 1992]. In addition, shallow hydrocasts were obtained at remote sites around the ship. The drift station sequence consisted of a suite of CTD profiles to 500 collected at 4-hour intervals. The drift sequence includes stations 55–115 (Figure 1b), which are divided into two lines: an eastern sequence along 2°–3°W and a western sequence along 4°W. Between stations 85 and 86, high winds forced a 28-hour curtailment of station activities, during which the ship drifted 48 km to the west. Throughout the cruise, sea ice thickness was measured by ice coring [*Meese et al.*, 1991]. The measurements reported by *Meese et al.* [1991] are given as the minimum and maximum thicknesses observed along each measurement transect. The frequency distribution of the minimum observed thickness is shown in Figure 1a for the warm pool region and for the inbound and outbound, non-warm pool region. Minimum thickness in the warm pool has a modal value of 30–40 cm, while outside the warm pool the mode is at higher values, 40–60 cm. The latter is in general agreement with previously reported thickness distributions for the Weddell region [*Wadhams et al.*, 1987]. Sea ice concentrations south and west of Maud Rise were markedly lower than the surrounding area for the period immediately following the warm pool survey. A

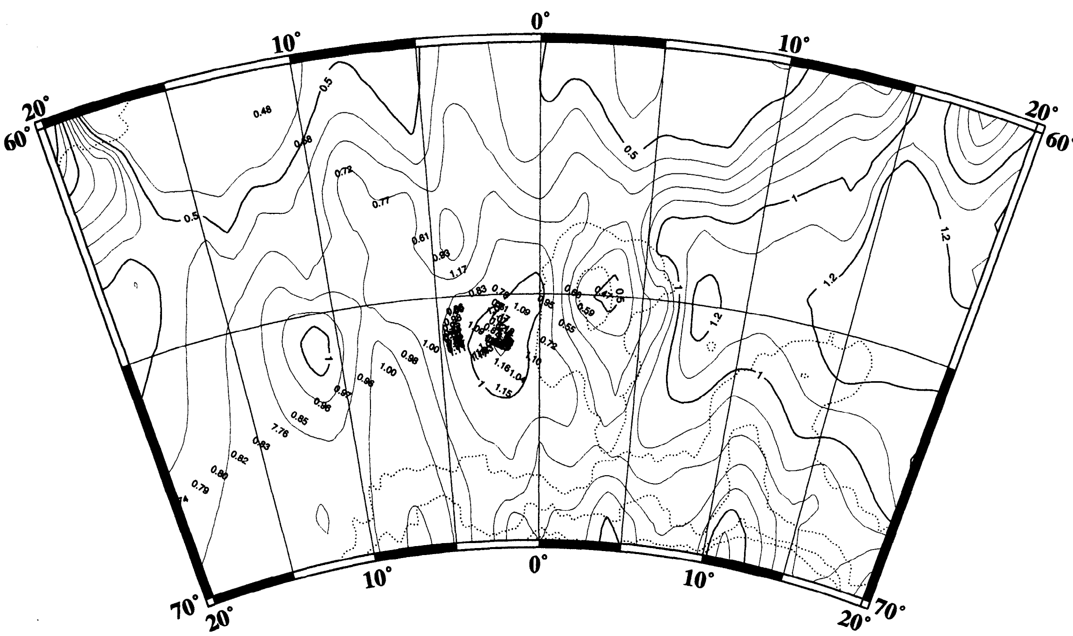


**Figure 3a.** The *Fedorov* $t$-max values superimposed on a temperature maximum core layer map produced from historical data.

special sensor microwave imager satellite image from October 26, 1989 (Figure 2a), shows lower concentrations in the vicinity of the warm pool region, with a more expansive zone of low concentration south of Maud Rise. Concentrations in the Maud Rise region decreased rapidly in the following month, finally resulting in isolated regions of near-zero concentrations by the end of November (Figure 2b). This low ice concentration south of Maud Rise has not been observed by earlier microwave satellite data and suggests that during the 1989 survey the warmest WDW may have been supplied by an advective route along the southern flank of Maud Rise, a possibility supported by the WDW $t$-max core map (Figures 3a and 3b) which shows the greatest expanse of warm WDW southwest of Maud Rise crest.

## Warm Pool Characteristics

$T$-max temperatures (Figures 3a and 3b) of about 1°C define the warm pool. The Weddell Gyre mixed layer is typically thinner over warmer WDW [*Gordon and Huber*, 1984, 1990]. This is true in part for the warm pool, though there is considerable variation in mixed layer depth. The series of potential temperature profiles (Figure 4) indicates that in the eastern part of the drift series (represented by stations 81–85) the mixed layer is shallow, about 50 dbar. At station 69 the mixed layer is very thin, <30 m. From station 86 onward (the western portion of the drift sequence following the storm displacement) the mixed layer deepened to near 100 dbar. The deepening does not appear to be wind-induced. Whether this

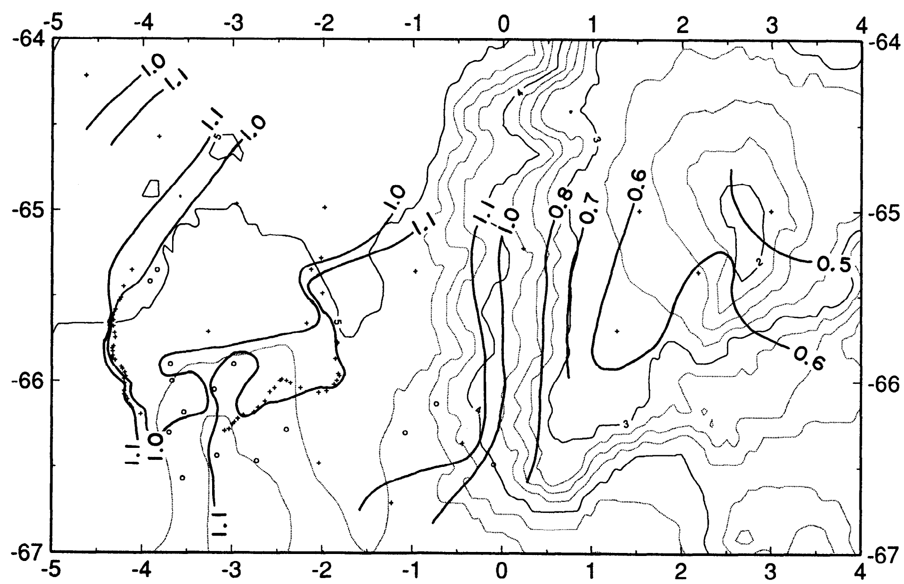


**Figure 3b.** Temperature maximums at the warm pool survey site from *Fedorov* data only.

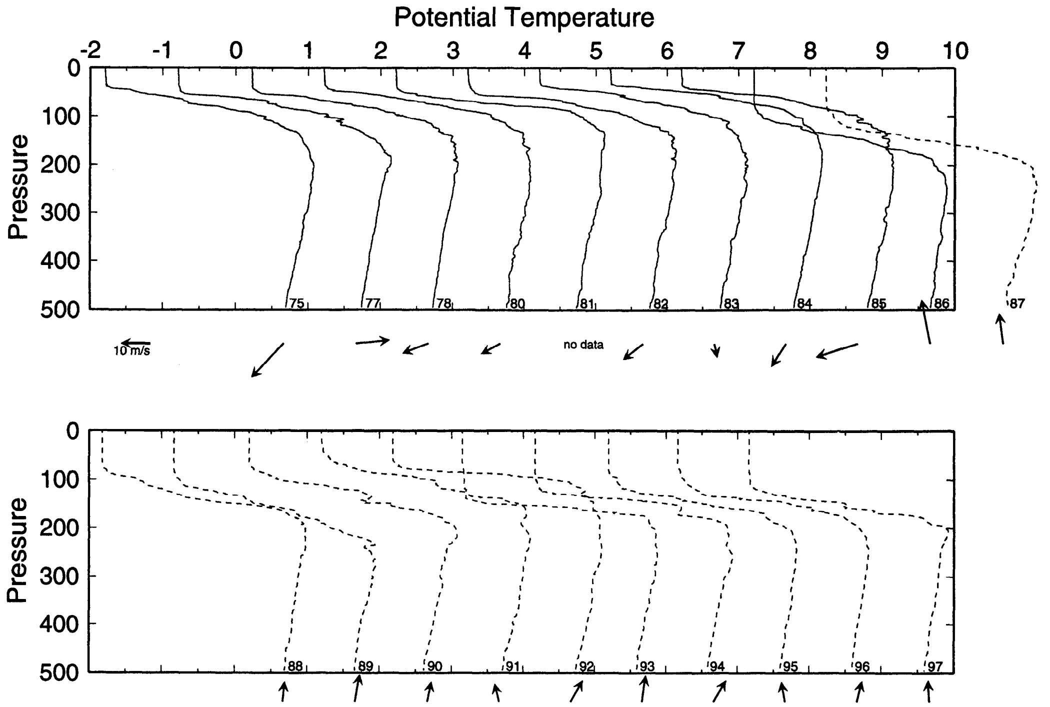


**Figure 4.** Temperature versus pressure plots for selected stations during the drift sequence. Profiles are offset by 1°C for clarity. The wind vector recorded at the beginning of each station is shown at the bottom of the profiles; the scale vector represents 10 m/s.

change represents temporal evolution of the warm pool, spatial variability, or drift from one feature into another cannot be determined with certainty from the data collected. The warmer *t*-max of the eastern segment, however, suggests that they represent different features.

Following the method of *Gordon and Huber* [1984, 1990] the deficit in mixed-layer oxygen relative to the full saturation values is used to determine the amount of WDW entrained into the mixed layer. The regional average $Q_f$ can then be calculated from the onset of the sea ice cover, which is taken as June 1 for the Maud Rise region.

The mixed-layer temperatures are taken at bottle-sampling depths from which oxygen samples were collected. The average depth of the mixed-layer sampling depth is 58 m, with a 24-m standard deviation. The base of the mixed layer is taken to be at the depth of the $-1$°C isotherm. The average mixed-layer depth was 112 m, with a 35-m standard deviation. The mixed-layer temperatures within the warm pool are well above the freezing point, ranging from $-1.85°$ to $-1.65$°C, the latter occurring at station 59, a full 0.27°C above freezing (Figure 5a). The stations with mixed layer temperatures above $-1.75$°C have WDW temperatures which exceed 1.0°C.

The regional averaged mixed-layer depth is used in the calculation of $Q_f$ to remove local divergence effects on the depth of the mixed layer. The average $Q_f$ for the stations shown in Figure 1b is 38 ± 15 W/m$^2$, essentially the same as that derived by *Gordon and Huber* [1990]. Mixed-layer oxygen values below 6.3 mL/L are encountered at stations 72–84, within the southern end of the eastern sequence of drift stations (Figure 5b). The low oxygen within this region indicates a higher percentage of WDW has been incorporated into the mixed layer, forcing a warmer mixed layer and inducing more ice melt for a given regional air temperature. For stations 72–84, $Q_f$ is 58 W/m$^2$, about 50% above the regional average.

The general trend of the mixed layer oxygen-salinity relationship is for decreasing oxygen with increasing salinity, as exhibited by the more extensive *Polarstern* data set (Figure 5c). This is induced by the entrained WDW which is relatively salty and low in oxygen. The *Fedorov* data from the easternmost

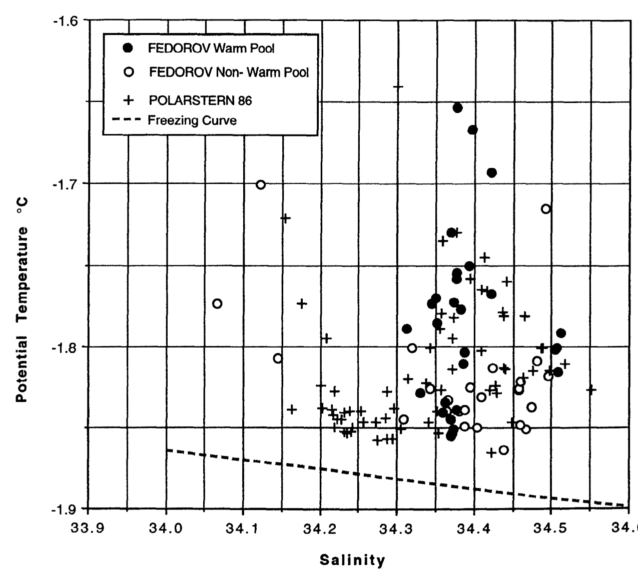


**Figure 5a.** Mixed layer potential temperature versus salinity scatter of *Fedorov* 1989 and *Polarstern* 1986 [*Gordon and Huber*, 1990] data.

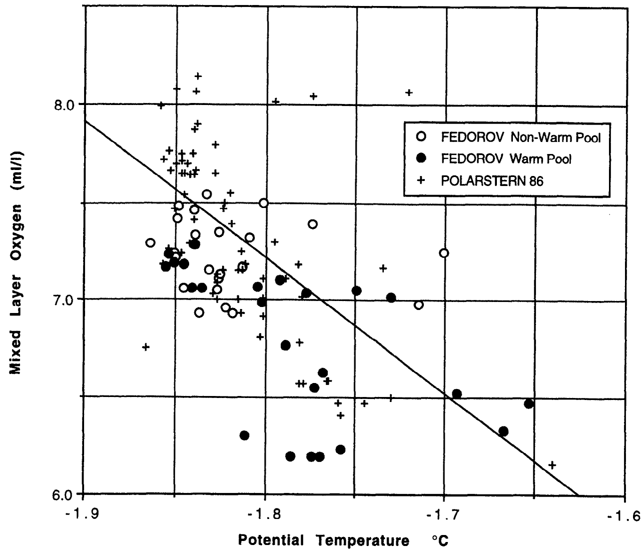


**Figure 5b.** Mixed layer potential temperature versus oxygen scatter of *Fedorov* 1989 and *Polarstern* 1986 [*Gordon and Huber*, 1990] data.

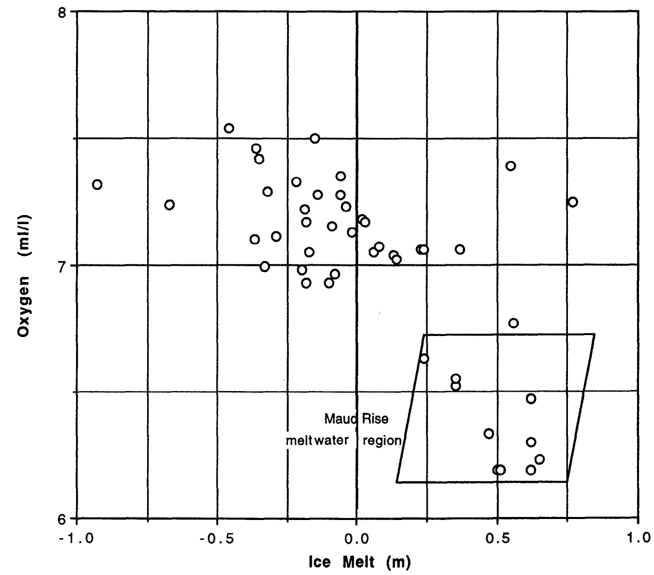


**Figure 6.** Relation of meltwater content of the mixed layer to mixed-layer oxygen.

drift segment do not follow the regional oxygen-salinity trend but are anomalously low in oxygen or, as we prefer, anomalously low in salinity. We propose that low mixed-layer salinity is derived from sea ice melt resulting from the WDW to mixed-layer heat flux. This region (marked as "Maud Rise meltwater region" on Figure 5c) consists of *Fedorov* drift stations 59–84, the southern end of the eastern sequence of drift stations, the area of enhanced vertical heat flux. The *Polarstern* stations falling within this region on Figure 5c are all south of Maud Rise. *Fedorov* stations 11 and 13 (Figure 1a) are within the Weddell-Scotia Confluence, a region of anomalously cool WDW, derived from continental margin water and forming the northern edge of the Weddell Gyre. That the Weddell-Scotia Confluence has anomalously low mixed-layer salinity suggests that it too carries excess meltwater.

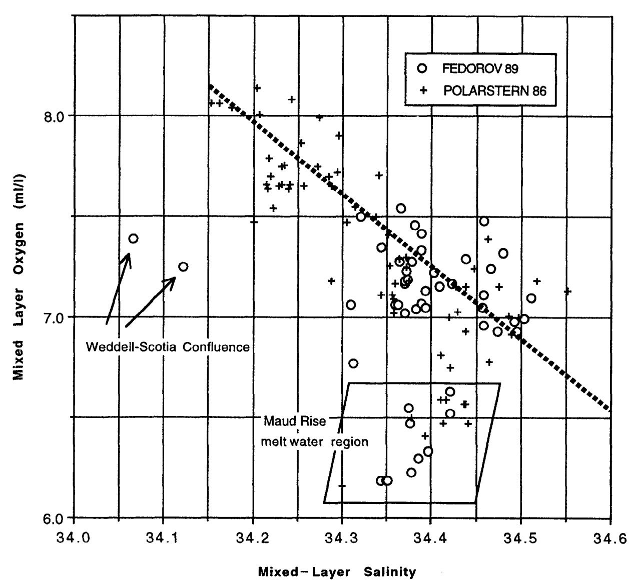


**Figure 5c.** Mixed-layer salinity versus oxygen scatter of *Fedorov* 1989 and *Polarstern* 1986 [*Gordon and Huber*, 1990] data.

It is possible to estimate the amount of meltwater required to account for the anomalously low mixed-layer salinity, relative to the mixed-layer oxygen values in the warm pool. Using the regional trend of mixed-layer oxygen to salinity (Figure 5c), the deficit salinity is determined and converted to the required amount of sea ice melt. The average ice melt for the warm pool area is 0.5 m (Figure 6), confined for the most part, as expected, to the lowest mixed-layer oxygen values. As the difference of the measured ice thickness between the eastern line of drift stations and the region to the north and west is about 0.2–0.3 m, a net convergence of sea ice is required to provide the total amount of meltwater. Ice that is forced by weather patterns into the high ocean heat flux regions would experience excess melting. As 0.5 m of ice melt requires significant heat, a period of the order of 1 month is implied to accomplish the melting from the calculated oceanic heat flux. The limited size of the meltwater region rules out an explicit atmospheric source of heat.

## Conclusion

A pool of relatively warm WDW west of Maud Rise observed in the spring season of 1989 forces localized melting of sea ice in the early spring. Presumably, after enough ice is melted to produce open water, strong short-wave radiation of the spring warms the water to greatly accelerate the ice melt. Were it not for the early spring ocean-induced melting, the higher albedo of the ice cover may delay or even lengthen the ice cover duration resulting in a multiyear ice cover characteristic of the western Weddell Sea.

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