Evaluation of the Weddell Sea Time Mean Circulation and Thermohaline Structure using the Ocean Component of the NCAR CCSM3–Coupled Climate Model: Preliminary Results

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Abstract

The Weddell Sea time-mean circulation and thermohaline structure along a transect between the Antarctic Peninsula edge and the Antarctic continent is investigated with the ocean component of the NCAR-CCSM3 coupled climate model (POP3). The model was forced with NCEP winds and corrected sub-ice fluxes. Preliminary results show for the integrated barotropic transport the double-core structure of the Weddell Gyre, but with a much stronger annual mean transport with respect to observations. The annual mean temperature profile along the transect shows a subsurface maximum of 1.1°C at ~800m. Bottom temperature values are warmer than expected (-0.3°C) due to insufficient model resolution to correctly resolve the bottom boundary layer transport of cold water from the continental shelves along the Antarctic Peninsula. The salinity field indicates a down slope transport on the northwestern side of the transect. Relatively fresh waters with salinities less than 34.67 reach down to 3000m.

1. Introduction

The Weddell Sea is considered an important source region for Antarctic Bottom Water (AABW) and thus one of the key regions contributing to the global thermohaline circulation of the world ocean (Mantyla and Reid 1983, Orsi et al. 1999, Hellmer et al. 2005). The characteristics of exported water masses are the result of complex interactions between surface forcing significantly modified by sea ice process, ocean dynamics at the continental shelf break and slope (Muench and Gordon 1995) and sub-ice shelf water mass transformations (Grosfeld et al. 1997).

Beckmann et al. (1999) performed the initial investigations with numerical ocean models, on the Weddell sector of the Southern Ocean. They used the Bremerhaven Regional Ice Ocean Simulations (BRIOS) a stand-alone ocean model, to represent many aspects of the Weddell Sea mean circulation and water mass distributions. Further modeling studies were carried out by Timmermann et al. (2002a,b), Schodlok et al. (2002), and Timmermann and Beckmann (2004). Schodlok et al. (2002) used a modified version of the primitive equation BRIOS, which had enhanced resolution near the sea surface and sea floor to investigate the water mass export from the Weddell Sea. Their results estimate the export rates of the Weddell Sea Deep Water through gaps in the South Scotia Ridge to be 6.4 Sv. In addition, Timmermann et al. (2002a,b) and Timmermann and Beckmann (2004) used the coupled ice-ocean model, BRIOS-2 (derived from BRIOS), based on a hydrostatic regional ocean circulation model and a dynamic-thermodynamic sea ice-model to investigate ice-ocean dynamics of the Weddell Sea.

In this paper, the Weddell Sea structure is investigated with the ocean only component of the NCAR-CCSM3 coupled climate model. The model description is summarized in Section 2. Section 3 contains the preliminary results and discussion. Concluding remarks are presented in Section 4.

2. Model Description

The ocean component of the NCAR-CCSM3 coupled climate model is based upon the POP Version 1.4.3, which was developed at Los Alamos National Laboratory. Gent et al. (2005) provide a detailed description of POP3. The horizontal grid has 320 (zonal) x 384 (meridional) grid points, with uniform (variable) zonal (meridional) resolution. In the southern hemisphere, the meridional resolution is 0.27° at the equator, gradually increasing to 0.54° at 33°S, and is constant towards higher latitudes. There are 40 levels in the vertical, whose thickness increases from 10 m near the surface to 250 m in the deep ocean. The minimum and maximum depths are 30m and 5.5km. The horizontal viscosity is an anisotropic Lapalcian operator (Smith and McWilliams 2003), which uses different coefficients in the east-west and north-south directions. The vertical mixing scheme is the K-profile parameterization (KPP) scheme of Large et al. (1994). Mesoscale eddies are parameterized following Gent and McWilliams (1990). The POP3 integration used here was forced by observed atmospheric fields from 1958-2000 with correct under ice fluxes, that are documented in Large and Yeager (2004). Further details of the CCSM3 ocean component can also be found in Smith and Gent (2004) and Danabasoglu et al. (2005).

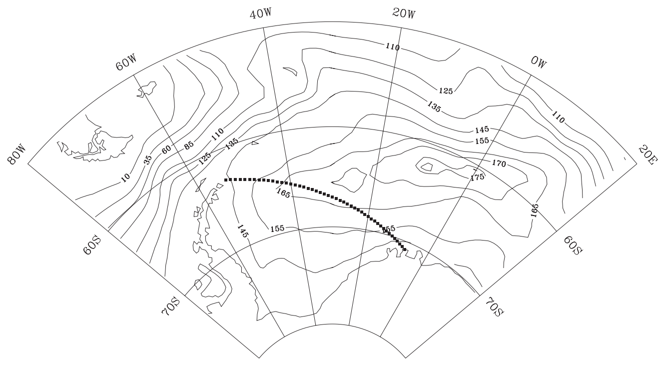

Figure 1 - Annual mean of the integrated barotropic transport from POP3. Contours intervals are from 15-125 (25), 125-165 (10), 165-175 (5) and 175-180 (1) in Sv. The dotted line marks the chosen transect.

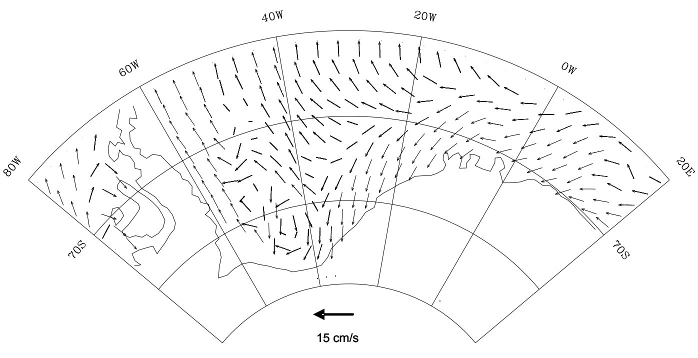

Figure 2 - Coastal-current field at the surface. Velocity unit is cm/s.

3. Results And Discussions

Figure 1 shows for the integrated barotropic transport a double-core structure of the Weddell Gyre, similar to that shown by Beckmann et al. (1999), Timmermann et al. (2002a) and Timmermann and Beckmann (2004), but with a much stronger annual mean transport, about 175 Sv. This is 3-5 times the expected magnitude of the Weddell Gyre transport (Fahrbach et al. 1994), and is most prominent in austral spring. The closed gyre circulation is well captured in the current field analysis (not shown) in the subsurface (500-1000m). The closed circulation associated with the Gyre is not evident at the surface because of the dominant influence of the large scale wind field. The surface coastal-current, with average velocities up to 3cms^{-1}, is shown in figure 2.

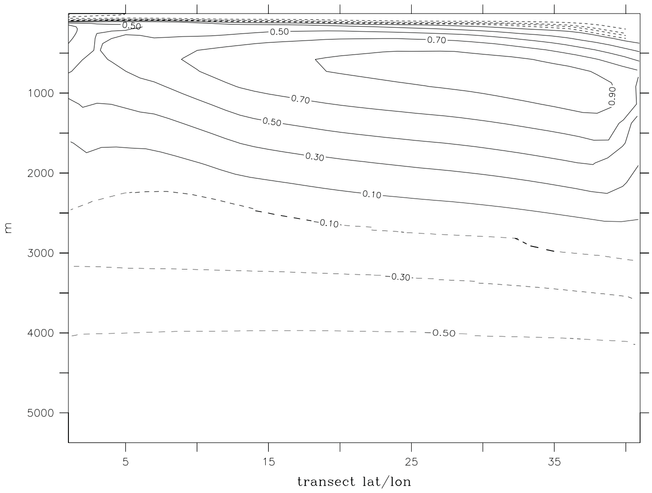

Figure 3 - Simulated annual mean potencial temperature (°C) for the transect. Intervals are 0.1°C

The annual mean temperature profile along the transect shows a subsurface maximum of 1.1°C at ~800m (Figure 3). Bottom temperature values are 0.2°C warmer than expected (Fahrbach et al. 2004). The same analysis using the SODA (Simple Ocean Data Assimilation) data set, for the same transect region, show at the east side temperature values of 0.3–0.4°C at ~1500m. At both sides of the section there is a downward slope of the surface isotherms towards the coast, due to onshore Ekman transport (Fahrbach et al. 1994).

In Figure 4, the salinity field suggests a down slope transport on the peninsula side of the transect. Relatively fresh waters with salinities <34.67 reach down to 3000m, suggesting the model is reproducing reasonably the deep ocean convection associated with the formation of Deep and Bottom water masses in the Weddell Sea.

4. Conclusions

The simulated annual mean vertically integrated transport shows a double-core structure of the Weddell Gyre, similar to that found by previous modeling studies (e.g. Beckmann et al. (1999), Timmermann et al. (2002a) and Timmermann and Beckmann (2004)). The double-core structure simulated for POP3 is displaced 5° to the west compared to Beckmann et al. (1999). Quantitatively, the simulated Weddell Gyre transport is overestimated compared with the calculations by Fahrbach et al. (1994) of 30Sv±10Sv and by Schroder and Fahrbach (1999) of 60Sv±10Sv.

At the surface the model current field distribution shows no recirculation in the northeastern part of the Weddell Sea as observed by Kottmeier and Sellmann (1996) and Beckmann et al. (1999). Below the surface (500-1000m) there is a single core structure with maximum values of 5cms^{-1}.

The simulated westward surface flow at the southern edge of the Weddell Gyre has peak average velocities of up to 3cms^{-1} within the coastal current. This time-mean velocity is close to the Fahrbach et al. (1994) measurements. At this resolution coastal current instabilities can not be resolved. However, the narrowness of the front is well represented and leads us to conclude that this ocean component (POP3) is adequate to simulate the general features of the Weddell Sea. The results described above are just a first step in the investigation of the influence of coupled air-sea-ice interactions in the Weddell Sea.

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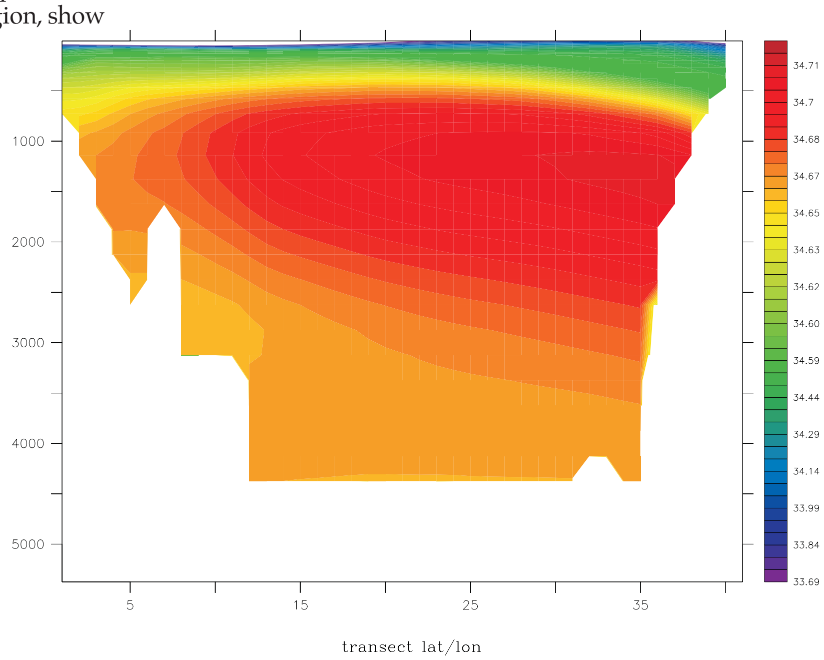

Figure 4 - Simulated annual mean salinity. Intervals are 0.005.

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Deep and bottom water variability in the central basin of Bransfield Strait (Antarctica) over the 1980–2005 period

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Introduction

The Bransfield Strait (BS) is placed between the South Shetland Islands and the tip of the Antarctic Peninsula where several topographic barriers tend to isolate its waters from surrounding seas (fig 1). The strait is separated from the Weddell Sea to the east by a shallow plateau (depth < 750m) and from the southern Drake Passage to the northwest by several topographic barriers. The BS can be subdivided into three basins which are separated from each other by sills shallower than 1000 m. Islands, shallow sills and ridges to the north and west of the Bransfield Strait act as barriers and restrict the inflow of intermediate, deep and bottom waters from the Bellingshausen Sea. Most of the BS water masses therefore originate in the Weddell Sea, especially the deep and bottom waters.

The deep and bottom water properties of the central and eastern basins of the BS have been examined by several authors (Whitworth et al, 1994; Wilson et al, 1999; Gordon et al, 2000). These basins are mainly filled with Modified Warm Deep Water (MWDW, $-1.4 \leq \theta < 0.1$, $34.4 \leq S < 34.6$). Moreover, Gordon et al (2000) point out that bottom waters of the central basin are influenced by both High Salinity Shelf Water (HSSW, $-1.88 \leq \theta < -1.7$, $34.56 \leq S < 34.84$) and Low Salinity Shelf Water (LSSW, $-1.88 \leq \theta < -1.7$, $34.3 \leq S < 34.4$) drawn from the Weddell Sea around the tip of Joinville Island.

In this work we examine the thermohaline properties of cold (θ<-1.4 0C, the lower θ limit for MWDW) and deep (H>1000 m) waters of the Central Basin of the Bransfield Strait (CBBS) over the last 25 years (1980-2005). Interannual variability of the thermohaline properties of theses waters is expected since they are subject to temporal variations of source waters.

Data and Methods

Much of the data for the period (from 1980 to 1996) originated from the National Oceanic Data Centre (NDOC). In addition three oceanographic cruises conducted in 2003, 2004 and 2005 under the umbrella of the Brazilian Antarctic Program were also included. The Brazilian cruises were carried out on board the Brazilian Navy R/V Ary Rongel in January 2003, 2004 and 2005 when the BS waters were sampled for temperature, salinity, oxygen, nutrients, bio-optical properties, phytoplankton and zooplankton. The temperature and salinity data were collected using a Seabird CTD 911+ mounted on a 12 bottles (5 litres) carousel. Accuracies for temperature and salinity were about 0.002 ^{0}C and 0.003, respectively, for all Brazilian cruises. Only CTD thermohaline data from the deepest waters (H>1000m and $\theta \leq$ -1.40C) of the CBBS are considered in this work. The dataset comprise observations from the following periods: Dec 1980, Nov 1983, Dec 1984, Jan 1985, Nov 1987, Nov 1990, Dec 1996, Jan 2002, Jan 2003 and Jan 2005.

Results

Figure 2 shows the θ-S diagram for CBBS waters deeper than 1000m and colder than -1.4°C, which comprises the deepest waters in the BS. The main characteristic of these profiles is the

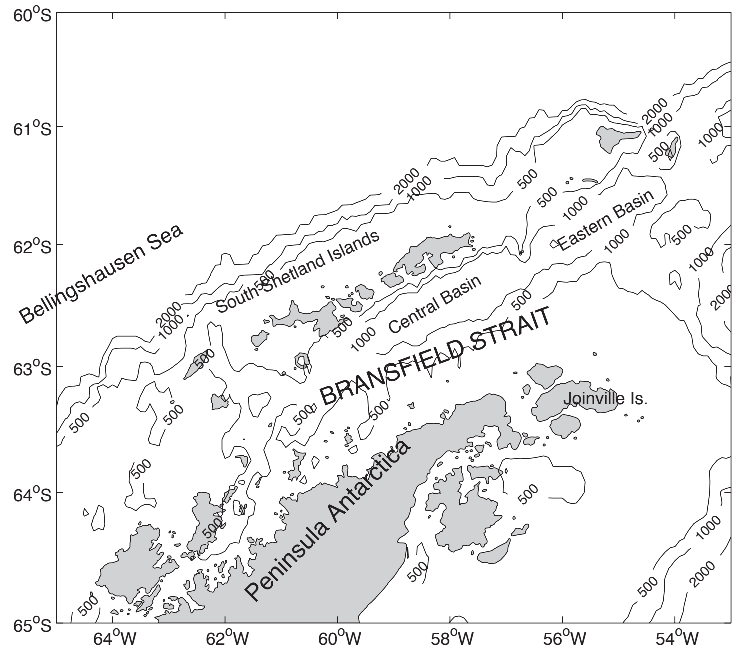


Figure 1. The Bransfield Strait and the surroundings seas. The Central Basin of the Bransfield Strait (CBBS) is highlighted for clarity.

significant influence of the High Salinity Shelf Water (HSSW), a major player in the formation of Weddell Sea Bottom Water. The minimum potential temperature was -1.767 0C in Jan 2005. The noise level present in the θ-S pairs differs from one year to another, however it is clear that lower noise levels are present in data gathered in recent years. The θ-S profiles during Jan 2003, Jan 2004 and Jan 2005 (Brazilian cruises) are shown in blue, green and red, respectively, to differentiate them from the NODC data.

We calculated the mean potential temperature ($\bar{\theta}$) and the mean salinity ($\bar{S}$) for the deep waters during the 25 years period. Figure 3 shows the property time series for both (a) potential temperature and (b) salinity. The $\bar{\theta}$ range was about 0.226 ^{0}C while the $\bar{S}$range was 0.061. Care should be taken when analysing Dec 1984 and Jan 1985 years because they originate from the same austral summer. The $\bar{\theta}$ and $\bar{S}$ time-series also show high variability for the 2003-2005 period during the Brazilian cruises. The warming 1990-1996 period in the Warm Deep Water (WDW) and Weddell Sea Bottom Water (WSBW), observed by Fahrbach et at (2004, see fig 5 in their paper), also occurred in the deep waters of the Bransfield Strait (warming of 0.044 ^{0}C, fig 3a). During the 25 years, there is a marked decrease in salinity of about 0.0362 in CBBS (fig 3b) and an increase in potential temperature. A linear fitting shows salinity (r=-0.74, N= 10) and potential temperature (r=0.35, N= 10) gradients of -0.0014/year and 0.0027 ^{0}C/year, respectively. The above results are evidence that the observed change in salinity is more pronounced - and statistically more significant - than in temperature because the characteristics of the water sources of deep and bottom CBBS have changed over the years.

The θ-S diagram of the $\bar{\theta}$-$\bar{S}$ pairs summarizes the results of the analysis performed here (fig 4). Over the 25 years period, there was a decrease in salinity but no significant trend was observed in potential temperature. According to Gordon et al (2000), the recipe for deep and bottom waters in the CBBS consists of about 60% of HSSW, 30% of LSSW and 10% of WDW (or MWDW). Near the freezing point, the potential sources are the LSSW and HSSW, which do not differ in temperature but do so significantly in salinity. The observed trend in salinity is likely to be associated with changes in the relative contribution of these shelf waters to the mixing or with a general freshening of the HSSW characteristics during the years considered. Conversely, the evidence of warming in the CBBS can also be due to modifications in the MWDW (or WDW), which is strongly influenced by remote as well as local conditions in the Weddell Sea which, for instance, presented a marked warming trend during the 1990s (Fahrbach et al, 2004). The changes in salinity are strong enough to decrease the density of the deep and bottom waters of the Bransfield Strait over the 25-years period (fig 4).

Conclusions

Thermohaline properties of the deep and bottom waters (H>1000m and θ≤-1.4°C) of the Central Basin of the Bransfield Strait have been used to examine their variability over the 1980-2005 period. A general trend of decreasing salinity of about 0.0362 is observed over the entire period. The analysis of the potential temperature reveals a warming trend during the same period, but less pronounced than the salinity change. Our results further suggest that the recipe of CBBS deep and water change during the years and that a general freshening of the HSSW flowing around the tip of Joinville island is also occurring. Another possible scenario is that these waters are becoming more influenced by the inflow of LSSW.

High interannual variability is observed in the 2003-2005 period during the Brazilian cruises. The warming of deep waters in the Weddell Sea during the early 90s is also observed in the deepest waters of the Central Basin of the Bransfield Strait. The overall result shows that the deep and bottom CBBS waters have become less dense over the 25 years period.

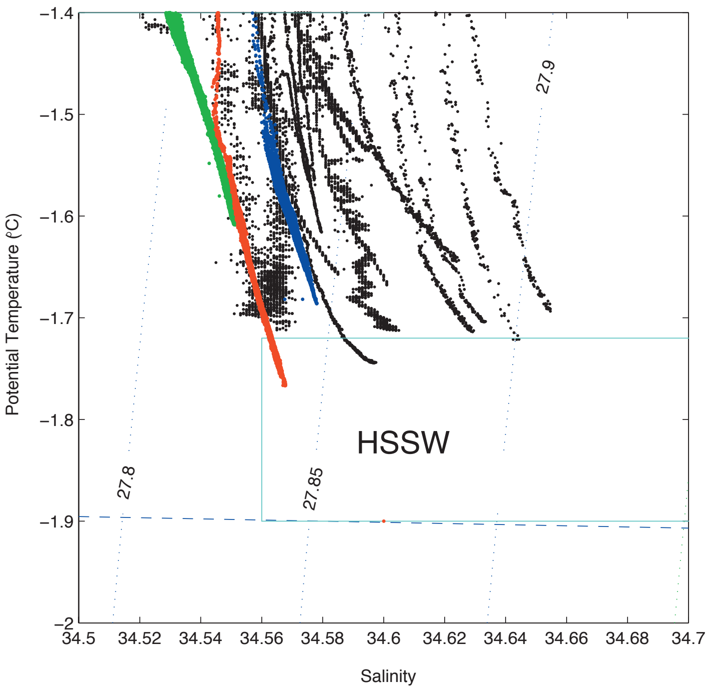
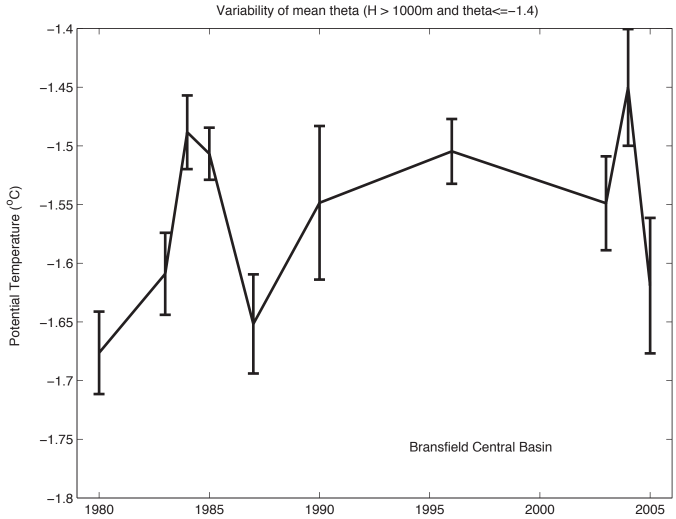


Figure 2. θ-S diagram for all profiles. NODC data are in black while Brazilian cruises are in blue (Jan 2003), green (Jan 2004) and red (Jan 2005). The High Salinity Shelf Water (HSSW) thermohaline indices are also shown for clarity.



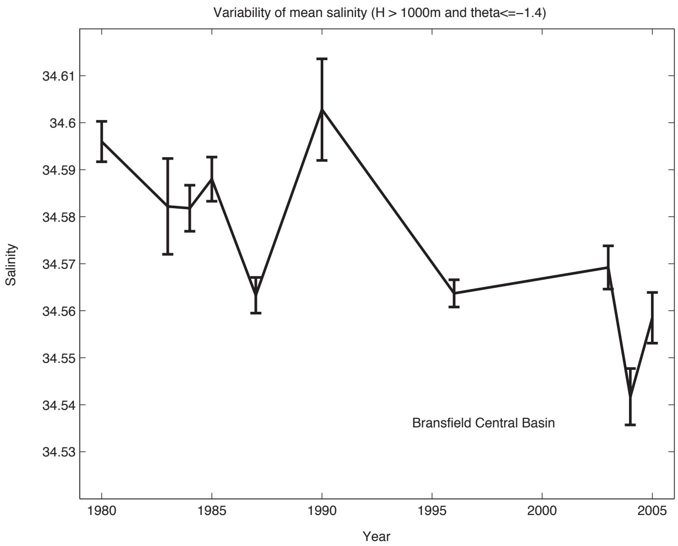


Figure 3. Time series of mean CBBS potential temperature and mean salinity over the 25 years. Data were taken only from waters deeper than 1000 m and colder than -1.4 ^{0}C.

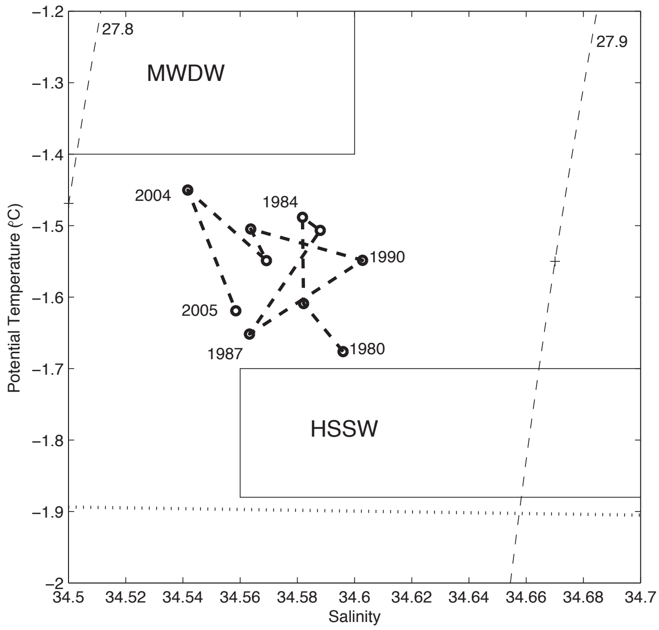


Figure 4. θ*-S diagram for mean potential temperature and mean salinity over the last 25 years. The limits of TS indices for the High Salinity Shelf Water (HSSW) and Modified Warm Deep Water are shown. Dotted line is the seawater freezing point. Isopycnal (dashed lines) are drawn relative to sea surface.*

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