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Key Points:

- A strong, negative wind stress curl generates the Weddell Polynya via upwelling
- A high heat content of deep water is a necessary condition for Weddell Polynya
- The next Weddell Polynya may occur when the SAM shift to an upward trend

Correspondence to:
W. G. Cheon,
cwg@add.re.kr

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Replicating the 1970s' Weddell Polynya using a coupled ocean-sea ice model with reanalysis surface flux fields

Woo Geun Cheon[1], Sang-Ki Lee[2,3], Arnold L. Gordon[4], Yanyun Liu[2,3], Chang-Bong Cho[1], and Jong Jin Park[5]

[1]The 6th R&D Institute-1, Agency for Defense Development, Changwon, Republic of Korea, [2]Cooperative Institute for Marine and Atmospheric Studies, University of Miami, Miami, Florida, USA, [3]Atlantic Oceanographic and Meteorological Laboratory, NOAA, Miami, Florida, USA, [4]Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York, USA, [5]School of Earth System Sciences, Kyungpook National University, Daegu, Republic of Korea

Abstract The 1970s' Weddell Polynya is simulated in the framework of a coupled ocean-sea ice model forced by reanalysis surface flux fields. A rapid emergence of strongly negative wind stress curl over the Weddell Sea intensifies the cyclonic Weddell gyre and thus causes the relatively warm and salty Weddell Deep Water (WDW) to upwell, generating an open-ocean polynya by melting sea ice or hindering its formation. Once the polynya occurs in the austral winter, the underlying water column is destabilized due to the combined effect of the high-salinity WDW, a massive cooling at the air-sea interface, and the ensuing brine rejection from newly forming ice, thus inducing open-ocean deep convection. Further analysis shows that the buildup of a large heat reservoir at depth by the mid-1970s was a necessary condition to establish the Weddell Polynya of the 1970s.

1. Introduction

Soon after the Antarctic sea ice concentration was first estimated by the Electrically Scanning Microwave Radiometer carried on the Nimbus 5 satellite launched at December 1972, the large-scale (about 2–3 $\times$ 10^5 km^2), open-ocean (sensible heat) polynya was observed in the Weddell Sea during three consecutive winters from 1974 to 1976 [*Carsey*, 1980]. The so-called "Weddell Polynya" was thus at first considered a normal phenomenon occurring in the Southern Ocean (SO) but in reality has never been observed since then, though short-term, small-scale polynyas have been intermittently observed [*Comiso and Gordon*, 1987; *Gordon and Huber*, 1995]. Comparing hydrographic station data estimated in the Weddell Sea in 1973 with those from 1976 to 1978, *Gordon* [1982] identified a linkage between this special phenomenon and open-ocean deep convection on the basis of the deep water being colder and fresher within a region of about the same size and position of the Weddell Polynya.

Several studies using observations and models have investigated the processes leading to the Weddell Polynya and open-ocean deep convection [e.g., *Goosse and Fichefet*, 2001; *Gordon et al.*, 2007; *Marsland and Wolf*, 2001; *Hirabara et al.*, 2012; *Cheon et al.*, 2014; *de Lavergne et al.*, 2014; *Stössel et al.*, 2015]. These studies have collectively suggested that for the occurrence of a Weddell Polynya the relatively warm Weddell Deep Water (WDW) must rise to the surface, melting sea ice or preventing its formation. According to *Gordon et al.* [2007], an increase in sea surface salinity weakens the pycnocline and thus increases the WDW flux into the surface layer. They further hypothesized that a prolonged negative phase of the Southern Annular Mode (SAM) and a strong La Niña event could produce drier-than-normal air condition and larger-than-normal brine rejection due to new sea ice formation in the Weddell Sea, both of which could contribute to an increase in the sea surface salinity. Relatively warm and salty WDW eddies, spawn from the eastern limb of the Weddell gyre, are also expected to play a role through dynamic interactions with the Maud Rise, the so-called "Maud Rise effect" [*Gordon*, 1978; *Ou and Gordon*, 1986; *Alverson and Owens*, 1996]. Recently, *Cheon et al.* [2014] proposed that a strongly negative wind stress curl following a recovery from the prolonged negative phase of SAM could strengthen the cyclonic Weddell gyre, enhancing WDW upwelling and thus leading to polynya conditions in the Weddell Sea. Combined with the aforementioned processes generating a precondition, this would be very effective in triggering the formation of Weddell Polynya.

In summary, three factors have been identified as the potential causes for the Weddell Polynya of the 1970s: (1) an increase in the sea surface salinity weakens the pycnocline and thus increases the WDW flux into the surface layer; (2) a strongly negative wind stress curl over the Weddell Sea enhances the cyclonic Weddell gyre and thus causes the WDW to upwell; and (3) relatively warm and salty WDW eddies, spawn from the eastern limb of the Weddell gyre, can play a role through dynamic interactions with the Maud Rise. It is possible that these three factors operated in sequence to produce the Weddell Polynya in the 1970s. However, since in situ observations in the Weddell Sea were very poor in the 1970s, the complete processes from the preconditioning to the open-ocean deep convection has not been fully comprehended nor why this phenomenon has not occurred since then. Here we present a surface-forced global ocean-sea ice coupled model simulation that successfully reproduces the Weddell Polynya and associated open-ocean deep convection in the 1970s, similar to observations. In this study, the Maud Rise effect is not simulated since the coupled model does not resolve mesoscale eddies. Although the reanalysis near-surface humidity enters the latent heat flux calculation thus affecting the sea surface salinity through evaporation, the application of climatological precipitation cycle (see section 2 for more detail) limits our investigation on the role of drier-than-normal air conditions over the Weddell Sea proposed by *Gordon et al.* [2007]. Therefore, among the aforementioned factors to raise the warm WDW to the surface, only the role of cyclonic winds over the Weddell Sea is faithfully explored in this experimental framework.

The main objectives of this study are to investigate the dynamic atmosphere-ocean interaction associated with the Weddell Polynya and to explore differences between the Weddell Polynya in the 1970s and small-scale polynyas in the late 1980s. In the following sections, we describe the model, atmospheric forcing data, and modeling methodology (section 2) and then analyze the real-time model simulation focusing on the basic mechanisms for generating the open-ocean polynya and the key factors that separate the 1970s' Weddell Polynya from small-scale polynyas in the late 1980s (section 3). Finally, we present a summary of our findings and a discussion (section 4).

2. Model Setup

The primary tool for this study is the coupled ocean-sea ice model of the Geophysical Fluid Dynamics Laboratory (GFDL) Modular Ocean Model version 4.1 (MOM4p1). The ocean model domain covers the global ocean with a grid size of 360×200 on a tripolar grid with a longitudinal resolution of about 1.0° and a variable latitudinal resolution from approximately 0.3° near the equator to 1.0°. The ocean model is divided into 50 vertical z coordinate levels: 22 upper levels with 10 m thickness and 28 lower levels of increasing thickness to about 400 m. The ocean model is coupled to the GFDL Sea Ice Simulator (SIS) [*Winton*, 2000], which is a dynamcal ice model with its thermodynamics treated with two ice layers and one snow layer similar to *Semtner* [1976]. For a more detailed description of MOM4p1 readers are referred to *Griffies et al.* [2004] and *Gnanadesikan et al.* [2006].

The global ocean-sea ice model is forced by the 6-hourly surface wind vectors, air temperature, and specific humidity, the daily shortwave and downward longwave radiative heat fluxes, and the monthly precipitation derived from the Coordinated Ocean-ice Reference Experiments data set version 2 (CORE2) [*Large and Yeager*, 2009]. The upward longwave radiative heat flux and turbulent surface fluxes are imposed interactively by the 6-hourly surface wind speed, air temperature, and specific humidity along with the model-produced SST. The surface flux variables of CORE2 are based on the National Centers Environmental Prediction reanalysis, with its known biases [*Smith et al.,* 2001] adjusted by using available observations, such as wind vectors estimated from QuikSCAT, surface humidity from the National Oceanography Centre ship data, and radiation from the International Satellite Cloud Climatology Project.

To spin up the model, the temperature and salinity fields are initialized by using the hydrographic climatological fields obtained from the World Ocean Atlas 2001 [*Conkright et al.,* 2002]. The model is integrated for 600 years. During the spin-up the surface forcing fields in each model year are randomly selected from the period between 1948 and 1977 to incorporate the impact of atmospheric variability and weather noise on the ocean mean state [*Kirtman et al.,* 2012], following the spin-up methodology used in *Lee et al.* [2011]. The heat content of the SO circumpolar deep water shows no drift during the last 100 years of the spin-up run, which implies that the model is fully spun-up after around 500 years of the model integration. After the spin-up, the model is integrated for 1948–2009 using the CORE2 surface flux

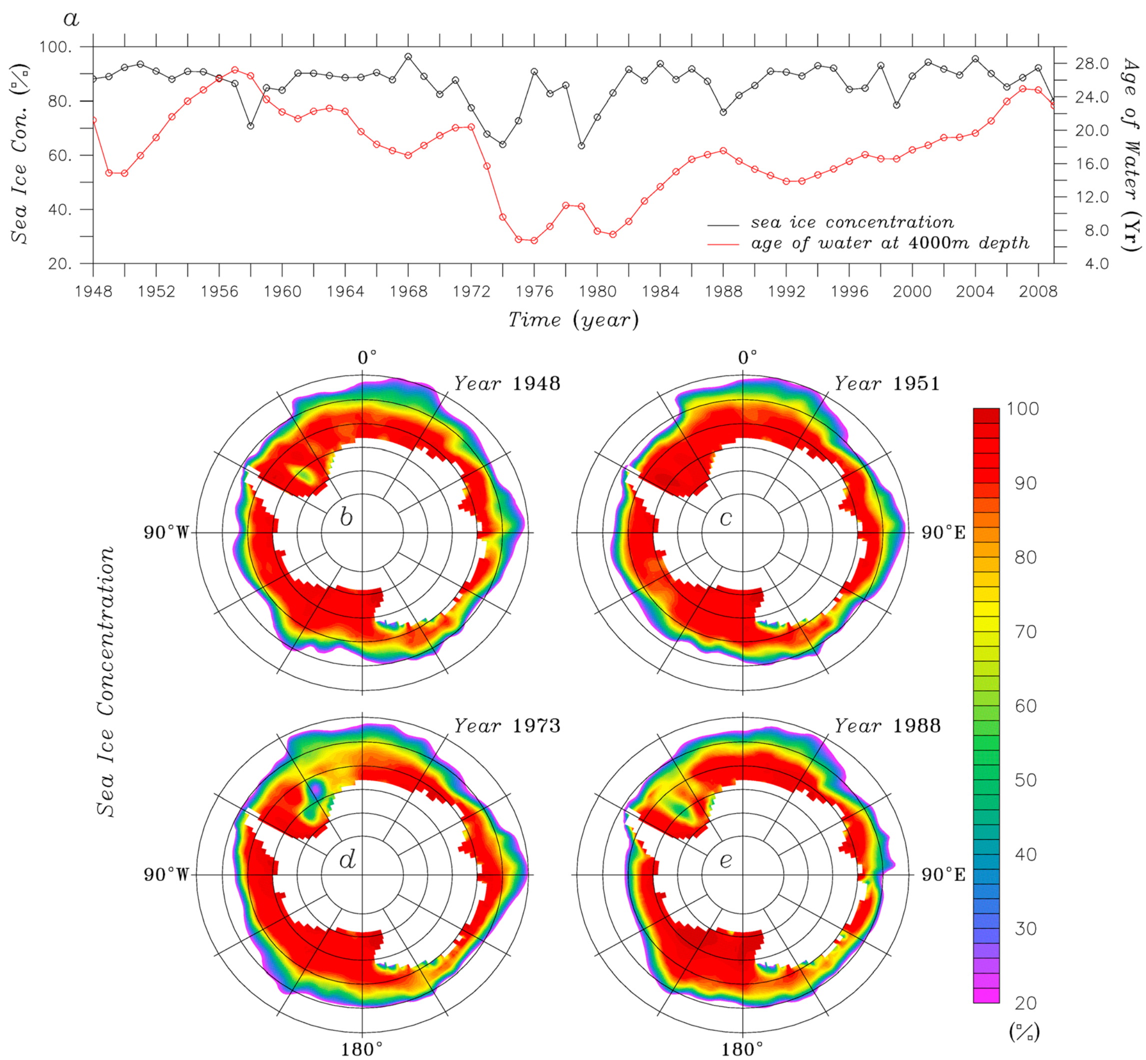

Figure 1. Time series of (a) sea ice concentration (black line with circles) and age of water at 4000 m depth (red line with circles) averaged over the region where open-ocean polynyas occur (45°W to 25°W and 72°S and 65°S) and (b–e) distributions of sea ice concentration in 1948, 1951, 1973, and 1988.

fields. Since radiative fluxes before 1984 and precipitation before 1979 are given only as climatological mean annual cycles in CORE2, both are kept as climatological throughout the entire modeling period for consistency. Additional experiments with the original CORE2 surface flux fields show that the climatological radiative fluxes and precipitation employed in our model simulations do not have a significant effect on the model fields of our interest. It should be noted that in this model any change in the ocean-sea ice system does not affect the atmosphere, such as the surface air temperature and pressure fields, which implies that massive ocean-to-air heat flux through the Weddell Polynya does not change the atmosphere.

3. Results

Figure 1 shows the time series of the austral winter mean (June, July, and August) sea ice concentration and age of water (AOW) at 4000 m depth in the central Weddell Sea for the entire modeling period and horizontal distributions of sea ice concentration in 1951 when there is no polynya event and in 1948, 1973, and 1988 when open-ocean polynyas occur. The AOW indicates how old the water mass is after sinking from the ocean surface. Therefore, relatively young water masses at 4000 m depth imply the occurrence of open-ocean deep convection. Although not shown in the time series (Figure 1a), small-scale open-ocean polynya is observed in 1948 (Figure 1b), which is the first year of the real-time simulation, presumably

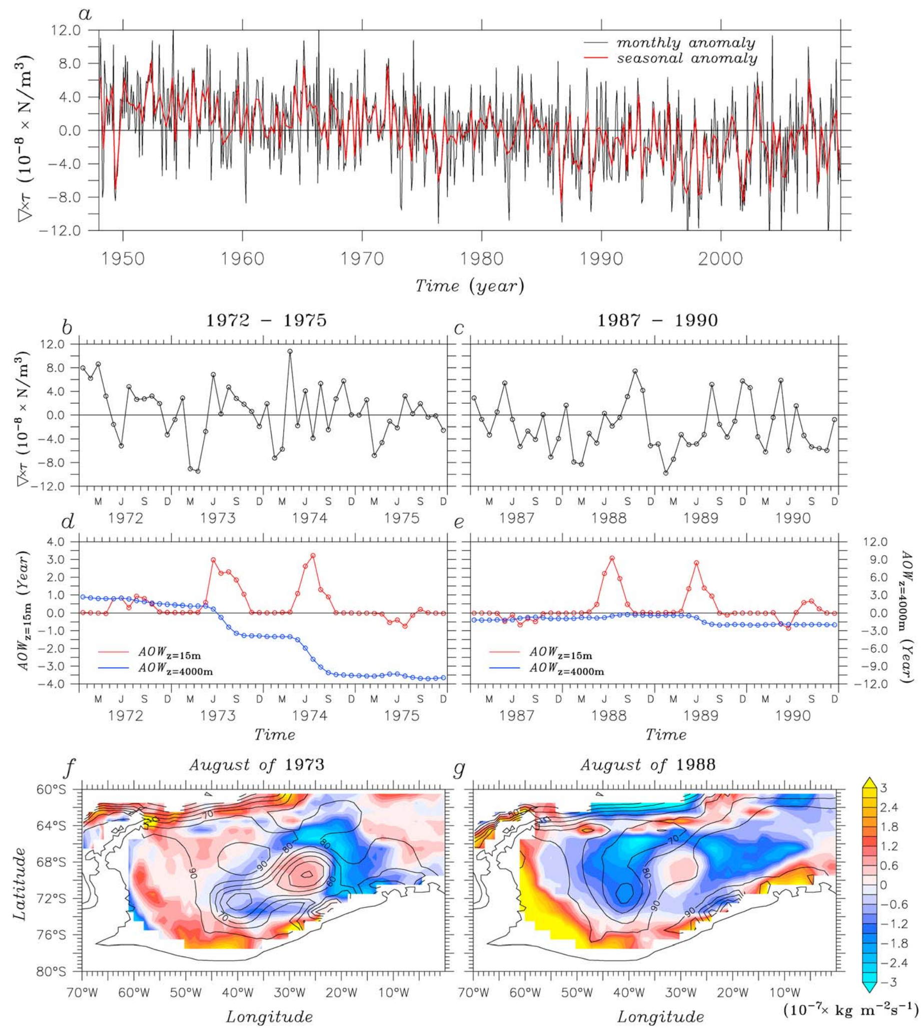

Figure 2. (a) Time series of monthly (black line) and seasonal (red line) anomalies of wind stress curl over the Weddell Sea, averaged from 60°W to 20°E and from 80°S to 60°S. (b–e) Time series of monthly anomalies of wind stress curl and age of water (AOW) at 15 m and 4000 m depths for periods (left) between 1972 and 1975 and (right) between 1987 and 1990. Horizontal distributions of sea ice concentration (contour) and anomalous ice-to-ocean salt flux (color shading) for August (f) 1973 and (g) 1988. The AOWs are averaged below the region where open-ocean polynyas occur (45°W to 25°W and 72°S and 65°S).

associated with strong, negative wind stress curl anomaly over the Weddell Sea (Figure 2a) and a transition period between the spin-up run and the real-time simulation, and quickly disappears in a few years (Figure 1c). The deep convection in 1948 affects the AOW at 4000 m depth in 1949, gradually recovering by 1957. Small-scale polynya events still occur after 1957, affecting the AOW at 4000 m depth. However, no apparent long-lived large-scale open-ocean polynya occurs until the early 1970s.

Sea ice concentration decreases markedly twice in the 1970s. Slight decreases are also observed several times mainly since the 1980s. When the actual Weddell Polynya was observed west of the Greenwich meridian, its sea ice concentration decreased below 20%, and its area reached about $2–3 \times 10^5$ km^2 throughout three winters from 1974 to 1976 [*Carsey*, 1980]. The Weddell Polynya simulated in this study, however, occurs farther west with smaller scale than the observations, and its sea ice concentration reaches down to about 20% only in 1973. Nevertheless, it occurs at about the same time as observed and immediately leads to open-ocean deep convection, causing the young water masses including the surface water to be found at 4000 m depth within a year. This bottom-reaching convective event occurring during such a short time is consistent with the observations [*Gordon*, 1982]. The polynya simulated in the late 1970s is smaller than the previous, and its minimum sea ice concentration does not reach 20%. However, the ensuing convection decreases the AOW at 4000 m depth as before. The sea ice decrease in late 1970s and 1989 is temporally in line with small-scale polynya events of 1980 [*Comiso and Gordon*, 1987] and 1989 [*Gordon and Huber*, 1995].

3.1. Role of Wind Stress Curl in the Formation of Open-Ocean Polynya

Figure 2a shows the time series of monthly and seasonal anomalies of wind stress curl over the Weddell Sea, directly calculated from the CORE2 forcing. Its climatology spans from -14.5×10^{-8} N/m^3 in April to -5.0×10^{-8} N/m^3 in December, which controls and sustains the cyclonic Weddell gyre [*Wadhams*, 2000]. While the positive anomalies, which weaken the gyre, are predominant before the early 1970s, the period of no polynya, the negative anomalies, which intensify the gyre, are predominant after the mid-1980s, the period of frequent occurrence of small-scale polynyas.

From early to mid-1970s, the wind stress curl anomalies shift drastically from a positive to a negative phase, strengthening the gyre instantaneously, thus causing the Weddell Polynya to form. In order to investigate the detailed processes involving the Weddell Polynya formation as well as the difference between the Weddell Polynya and small-scale polynyas, two periods are selected: one is between 1972 and 1975 and the other is between 1987 and 1990. Figures 2b–2e show monthly anomalies of the wind stress curl and the AOWs at 15 m and 4000 m depths for the respective periods. The AOW at 15 m depth (= the second layer of model) indicates upwelling of the old (deep) water, whereas that at 4000 m depth indicates the deep convective event, as previously discussed. While a weak negative anomaly is observed in June 1972, the negative wind stress curl is significantly intensified in March and April 1973 by about -10×10^{-8} N/m^3, which is larger than the amplitude of seasonal variability (-14.5×10^{-8} to -5.0×10^{-8} N/m^3). This strongly negative wind stress curl induces the cyclonic Weddell gyre to spin up. Thus, the relatively warm and saline WDW rises to the surface within 1–2 months, generating the Weddell Polynya by melting the sea ice or preventing it from forming. In austral winter, throughout the ice-free area surrounded by sea ice, the relatively warm water is brought in direct contact with the extremely cold surface air and is thus transformed to sea ice. As shown in Figure 2f, new sea ice formation in the ice-free area (where the Weddell Polynya occur) leads to brine rejection, which in combination with the relatively high salinity of the upwelled WDW further weakens the stratification of the underlying water column, thus giving rise to open-ocean deep convection. These are monthly averaged features, whereas in a shorter time scale the ocean undergoes oscillation between stabilization and destabilization. That is, this convective event brings a large amount of WDW toward the surface, inducing massive ice melting due to a strong ocean-to-ice heat flux, thus leading to restratification of the water column. The relatively warm WDW, being again in contact with the cold surface air, induces a strong ocean-to-air heat flux and thus new sea ice formation with a weakening of ice melting, finally leading to redestabilization of the water column and the convective event. These processes are repeated during the winter [*Goosse and Fichefet*, 2001]. The strongly negative wind stress curl leads to upwelling again in 1974, enhancing the oceanic convection, but not in 1975, because from this year open-ocean deep convection becomes prevalent and thus acts to suppress the upwelling driven by spin-up of the Weddell gyre. Due to mass balance, the deep water rise to the surface farther south than the simulated Weddell Polynya (not shown here).

This dynamic process is in the same way applicable to the small-scale polynyas occurring in the late 1980s (Figures 2c and 2e). The strongly negative wind stress curl gives rise to distinct upwelling consecutively in the austral winters of 1988 and 1989. In contrast to the 1973's Weddell Polynya whose sea ice concentration diminishes to about 20%, the sea ice concentration of the open-ocean polynya occurring in 1988 reaches only about 50% (Figures 2f and 2g). Although being located in the east of the region with the minimum sea ice concentration, the positive anomaly of ice-to-ocean salt flux due to the small-scale open-ocean polynya is observed. Since this positive anomaly is relatively small, the oceanic convection in 1989 is much weaker than that in 1974 (see Figure 1a). A large ice-to-ocean salt flux is observed along the coastline in 1973 and particularly in 1988 and is associated with coastal (latent heat) polynyas, which induce near-boundary (slope) convection and thus controls the formation of Antarctic Bottom Water. This is a very important feature in the Weddell Sea and the global thermohaline circulation but is beyond the scope of this study. To sum up, in the late 1980s, the similar dynamic process to the early 1970s,

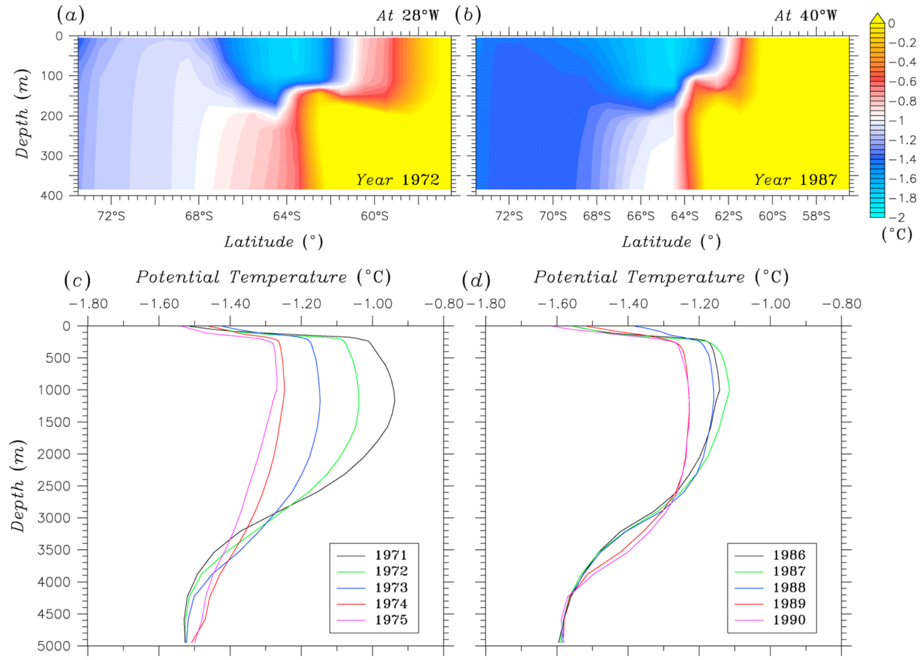

Figure 3. The austral winter mean potential temperature at (a) 28°W in 1972 and (b) 40°W in 1987, and vertical profiles of potential temperature averaged over the region where open-ocean polynyas occur (45°W to 25°W and 72°S and 65°S) for periods (c) between 1971 and 1975 and (d) between 1986 and 1990.

i.e., the strongly negative wind stress curl and the ensuing upwelling of WDW, leads only to shortly lived, small-scale open-ocean polynyas. We explore in the next section why the polynyas in the late 1980s are small scale and shortly lived.

3.2. A Necessity of Deep Ocean Heat Content in the Formation of Weddell Polynya

Within the experimental framework used in this study, the formation process of the open-ocean polynya in the Weddell Sea is explained by the strongly negative wind stress curl causing the relatively warm and saline WDW to rise to the surface. An obvious question is, why such a process does not lead to a long-lived and large-scale Weddell Polynya in the late 1980s? *De Lavergne et al.* [2014] suggested that the increasing presence of a fresh surface layer due to the increased greenhouse gases has prevented the recurrence of the Weddell Polynya. While we acknowledge the effect of surface freshening in suppressing open-ocean polynyas in the Weddell Sea, we here propose another factor, namely the heat content of the WDW. Figure 3 shows latitude depth cross sections of the winter mean potential temperature at 28°W in 1972 and at 40°W in 1987, and vertical profiles of the winter mean potential temperature averaged over the region where the open-ocean polynya occurs for the respective periods (1971–1975 and 1986–1990). Years 1972 and 1987 are selected to show the oceanic state before deep convection occurs, and the meridional sections of temperature at 28°W and 40°W cross centers of polynyas occurring in the early 1970s and the late 1980s, respectively. It is clear that the deep water below ~100 m is much warmer in 1972 than in 1987 suggesting that a trace of oceanic convection in 1980 still lingers in 1987 (see Figure 1a). This suggests that the upwelled WDW in 1973 is sufficiently warm to melt sea ice or prevent it from forming, which enables a persistent, large-scale Weddell Polynya to form and leads to the bottom-reaching open-ocean convection. Due to this massive convection event, the heat content of WDW is severely depleted and does not fully recover by 1987 just before upwelling occurs in 1988 and 1989 (see Figure 2e). Therefore, the upwelled WDW is not warm enough to generate a large-scale open-ocean polynya in the late 1980s.

This depletion of WDW heat content induced by the 1970s' Weddell Polynya reaches to 4000 m depth or even deeper (Figure 3c). In the entire Weddell Sea, the deep ocean heat content drastically drops by 4.35×10^{21} J in 3 years from 1973 to 1975 and then slowly recovers until 1987, though there is another drop associated with the 1979's polynya (see Figures 1a and 1d). However, even in 1987 the deep ocean heat content is still

2.80×10^{21} J short of that in 1972 just before the Weddell Polynya occurs. Regarding the 1988's polynya, from 1987 to 1990 the deep ocean heat content decreases by 3.17×10^{21} J, about 73% of the Weddell Polynya event. This depletion/recovery of WDW heat content due to the polynya events is confirmed by observations [*Robertson et al.,* 2002; *Smedsrud*, 2005]. *Hirabara et al.* [2012] and *Martin et al.* [2013] also proposed an important role of the heat reservoir at depth in controlling vertical instability and thus open-ocean deep convection.

4. Summary and Discussion

A coupled ocean-sea ice model forced by reanalysis surface flux fields is used to investigate the dynamic atmosphere-ocean interaction processes responsible for the 1970s' Weddell Polynya and the short-lived small-scale polynyas in the late 1980s. The persistent and large-scale Weddell Polynya leading to open-ocean deep convection in the early 1970s is successfully reproduced, albeit slightly earlier (1973–1975) and farther west (40° to 28°W) than observed (1974–1976; 20°W to 0°). The rapid development of strongly negative wind stress curl spins up the cyclonic Weddell gyre and gives rise to upwelling of the relatively warm and saline WDW, which plays a direct role in the formation of the Weddell Polynya by melting the sea ice or preventing it from forming. The increased ice-to-ocean salt flux (i.e., brine injection) in combination with the relatively high salinity of WDW and surface cooling further destabilizes the underlying water column, thus leading to open-ocean deep convection. A sufficient heat content of WDW appears to be an important precondition for a long-lived, large-scale open-ocean polynya and deep convection to occur.

Even after the 1980s, very short lived, small-scale open-ocean polynyas were simulated (see Figure 1a) and appeared to be generated by the same dynamic atmosphere-ocean interaction but with lower heat content of WDW (not shown here). This suggests that small-scale polynyas and the ensuing small-scale convective events act to hinder accumulation of deep ocean heat transported by the eastern limb of the Weddell gyre. According to the historical data analysis of *Smedsrud* [2005], very short lived, small-scale polynyas occasionally occurred in the 1990s and 2000s, and there was a period of depletion of WDW heat content, the so-called "Maud Polynya Cooling." However, it is unclear whether the WDW heat content had already recovered to its original state before the 1970s' Weddell Polynya or was still under the process of recovery from the massive loss, since the observational data that can assess the WDW heat content before the 1970s are very scarce. Although the deep water in the inflow/outflow regions of the Weddell Sea appears to have recovered to its original state in the late 1990s [*Robertson et al.,* 2002], the analyzed regions are far from the region where the Weddell Polynya occurred.

On the basis of our modeling study and previously proposed hypotheses, the next Weddell Polynya is expected to occur when the SAM, which is currently in the declining positive phase, enters a prolonged negative phase, reaches its minimum, and then shifts to an upward trend. That is, under the favorable precondition of a high-salinity upper ocean and sufficiently warm WDW that are expected to develop during a prolonged negative phase of the SAM, the Weddell Polynya may reoccur when the Southern Hemispheric westerly winds intensify and moves poleward in association with an upward trend of the SAM. Previous studies have attributed the positive trend of the SAM during the twentieth century to the combined anthropogenic effects of increased greenhouse gases and decreased stratospheric ozone [e.g., *Gillett and Thompson*, 2003; *Shindell and Schmidt*, 2004; *Arblaster and Meehl*, 2006]. According to *Son et al.* [2008] analyzing the climate models including a fully interactive stratospheric chemistry, the recovery of the ozone hole, expected to occur in the first half of the 21st century, induces a deceleration of the SH westerly winds in the austral summer even under a global warming scenario (A1B), which is in line with *Perlwitz et al.* [2008]. If their prediction based upon the modeling study is realized, the Weddell Sea will undergo a prolonged negative SAM and have a sufficient time for the favorable precondition to develop by the mid-21st century. However, the contrasting impacts of the increasing greenhouse gases and the recovering ozone hole on the SAM need to be investigated further.

It should be noted that the warm and salty WDW eddies can also generate short-lived, small-scale polynyas under a positive phase of SAM in association with the dynamic interaction between the inflowing Weddell gyre and Maud Rise [*Gordon*, 1978; *Ou and Gordon*, 1986; *Alverson and Owens*, 1996]. This Maud Rise effect and the impact of drier-than-normal air condition proposed by *Gordon et al.* [2007] are beyond the limit of the experimental framework used in this study and, more importantly, may be the causes for the simulated Weddell polynya being located farther west and smaller than the observation. Therefore, further study employing an eddy-resolving ocean-sea ice coupled model and new atmospheric forcing fields including at least daily varying precipitation is necessary for a more comprehensive investigation and future prediction of a Weddell Polynya occurrence.

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