On the origin of the deep CFC maximum in the eastern
Weddell Sea – numerical model results

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Abstract. CFC tracer observations indicate that Prydz Bay in the Indian sector of the Southern Ocean is a region of deep and bottom water formation. Results of a circumpolar ocean circulation model which includes CFC, an age tracer, and numerical floats indicate Prydz Bay as being a convection site which contributes to the reservoir of freshly ventilated waters in the Weddell Sea. In contrast to the newly formed Weddell Sea Bottom Water, captured near bottom, water masses of Prydz Bay origin spread on horizons which pass the ridges confining the Weddell Sea, therefore, contributing directly to the ventilation of the global abyss.

Introduction

The Weddell Sea is traditionally regarded as one of the main locations for deep and bottom water formation around Antarctica [Gill, 1973]. Weddell Sea Deep Water (WSDW), a mixture of Warm Deep Water (WDW) and Weddell Sea Bottom Water (WSBW), spreads from the Weddell Sea into the world ocean where it is known as Antarctic Bottom Water (AABW).

The dominant dynamical feature of the Weddell Sea is the cyclonic circulation of the Weddell Gyre consisting of two subgyres [Beckmann et al., 1999]. Waters ventilated in the Weddell Sea spread towards the north with the deep western boundary current of the Weddell Gyre hugging the eastern continental slope of the Antarctic Peninsula. The South Scotia Ridge effectively blocks its advance farther north; only small volumes of some WSDW escape into the Scotia Sea through deep (~ 3000 m) passages [Locarnini et al., 1993]. Thus the remaining newly formed water flows to the east with the northern branch of the Weddell Gyre.

Transient tracers are a suitable method of detecting recently ventilated water masses [Bullister and Weiss, 1988] which carry high chlorofluorocarbon (CFC) concentrations. The injection of CFCs into deeper layers occurs vertically by convection and subduction followed by a lateral redistribution through advection and mixing.

Tracer observations at the Greenwich Meridian ex-
hbit two deep cores of CFC maximum. The northern maximum located at the southern flank of the Mid Atlantic Ridge [Haine et al., 1998] is usually associated with deep/bottom water formed in the Weddell Sea spreading eastward with a bottom intensified current. The origin of the southern maximum located at the Antarctic continental slope is subject to speculation. Dickson [1994] suggested a recirculation of deep and bottom water to the west of the Kerguelen Plateau, hence this could be regarded as a contributing source for the southern core at the Prime Meridian [Archambaud et al., 1998]. However, the southern core being similar in CFC concentration [Klatt et al., 2001] cannot be replenished entirely by recirculating Weddell Gyre waters.

Since other locations along the Antarctic periphery have been identified as additional deep and bottom water sources [Jacobs and Georgi, 1977], we attempt to answer in this study the following questions:

i) Where is the origin of the southern CFC maximum core at the Greenwich Meridian?

ii) What are the pathways and travel times of its source waters?

iii) How much water does enter the Weddell Sea within this core and contributes to the renewal of Weddell Sea Deep Water (WSDW)?

The Ocean Model

The ocean model used belongs to a family of hydrostatic primitive equation ocean circulation models in the framework of BRIOS (Bremerhaven Regional Ice Ocean Simulations) [Beckmann et al., 1999]. The configuration of the model consists of a circumpolar model domain extending from 82°S to 50°S including shallow shelf areas as well as sub-ice shelf cavities. The horizontal grid focuses on the Weddell Sea sector, where the resolution is 1.5° in zonal and 1.5°cosφ in meridional direction. Outside the Weddell sector, zonal grid spacing increases gradually to 6.75°.

A detailed description of the BRIOS model configuration and main model results has been provided by Beckmann et al. [1999].

Tracer and float experiments

To highlight the origin and spreading of dense Antarctic water masses we used several strategies: direct simulation of anthropogenic tracers (CFCs), the combined use of age and dye tracer simulation and the computation of Lagrangian float trajectories.
The CFC tracer runs were driven with a CFC climatology [Walker et al., 2000]. We used techniques for tracer input as described by England et al. [1994], e.g., boundary flux conditions and gas exchange dependency on sea ice and wind speed. For the CFC study, the model integration started in 1920 and was integrated for 77 years to reveal CFC characteristics in 1997.

Transports and transit times were determined with age tracers and numerical floats released off Amery Ice Shelf (see Figure 1). The age of a water parcel is defined as the time elapsed since the parcel under consideration left the region where its age is prescribed to be zero. In our case, for every grid box outside Prydz Bay the ageing with temporal evolution is calculated. Mixing processes are implemented in the same way as for temperature and salinity. With increasing time, values converge towards the mean spreading age as being a stable mixture between advected old water and local increase of age. In order to obtain the portion of the ventilated water mass, a dye tracer experiment was performed, i.e., every grid box was set to zero at the time of initialization except the area off Amery Ice Shelf, where the dye is prescribed as one.

Results

Figure 1 shows the simulated circumpolar CFC-11 concentration distribution in summer 1997 in the bottom layer of the model domain. Due to the temporal evolution of the input function, high concentrations depict recently ventilated water. There are several areas along Antarctica’s periphery that reveal sites of high CFC concentration. The shelf areas off Filchner–Ronne and Ross Ice Shelves, known to contribute to the deep and bottom water formation, contain the highest concentrations (maximum adjacent to Berkner Island). These areas are mainly broad continental shelves bounded by land which allow shelf water to gain salt from brine rejection during sea ice formation [Gill, 1973]. Water parcels containing high CFC-11 values thus mix into waters of the coastal current and follow the general gyre circulation.

A feature well-known from observations and reproduced by the model is a c-shaped region in the western Weddell Sea associated with the lowest concentrations of the entire model domain. This documents the model’s ability to keep newly formed bottom water close to the continental slope without much lateral mixing with the interior of the basin and is consistent with the observations by, e.g., Fahrbach et al. [1995].

Newly ventilated water from the Ross Sea shelf interacts with the coastal current and also fills the Amund-
sen abyssal plain via the Ross Gyre. In addition, to
the west of the Ross Sea confined areas off Adélie and
Wilkes Lands, and Prydz Bay contain newly formed wa-
ter masses. This is consistent with the picture derived
from recent observations [Rintoul, 1998]. Whilst high
CFC contents at the sea floor (Figure 1) depict Prydz
Bay as a ventilation site, this is also documented by a
vertical temperature section of the upper 2000 m (Fig-
ure 2) showing a lens of low temperatures (< -0.2°C)
surrounded by warmer water. Winter Water is present
in the upper 60 m of the water column below which
isotherms rise towards the coast due to Circumpolar
Deep Water (CDW) upwelling [Smith et al., Wong
et al., 1998].

Another means of showing ventilation and spreading
is the use of particles released off Amery Ice Shelf within
the mixed layer (Figure 3), resulting in a cloud of parti-
dles spread over the entire water column. The ventilated
water is advected with the coastal current towards the
west where it becomes part of the southern branch of
the Weddell Gyre. Travel times depend on the location
within in the water column. Floats ventilated down to
the depth of the CFC maximum core (lower than 3000
m) need 5.7±0.7 years to reach the Greenwich Merid-
ian. Floats higher in the water column, i.e., within the
coastal current’s high velocity core (depth range 2000
to 3000 m) are faster by about a year.

The steady state dye tracer distribution near Green-
wich Meridian (Figure 4) reveals the observed core
structure across this transect. The highest concentra-
tions are attached to the continental slope at a depth
of about 3000 m corresponding to the deep core flow-
ing westward into the Weddell Sea.

Mean transit times (MTT) of Prydz Bay Water (PBW)
to the Prime Meridian are calculated using known PBW
fraction and local ages Figure 5. MTT’s for the south-
ern core were calculated from year 15 to 25 of integra-
tion as the ratio of PBW to local water had reached an
asymptotic value for these years.

The core has its highest fraction of PBW in 3250 m
depth (dashed line). It takes about 5.9 years to reach
the Greenwich Meridian. The velocity maximum at the
continental slope is considerably higher in the water col-
umn revealing a lower travel time of 4.4 years at 2500 m.
PBW is concentrated in the core at the continental slope
decreasing rapidly northward. In the model 2.5 Sv (the
upper limit) with 0.2 Sv seasonal variability is trans-
ported across the Greenwich Meridian. This agrees well
with observations Hoppema et al. [2000]. Transport
values in summer are lowest increasing steadily towards
winter.
Discussion and Conclusions

Observations focused on deep and bottom water formation in the Indian sector of the Southern Ocean are sparse [Rintoul, 1998; Jacobs and Georgi, 1977; Wong et al., 1998]. Although coarse in resolution, our model results present a coherent picture of water masses being formed in and convected to great depth near Prydz Bay, finally advected along the continental slope towards the Weddell Sea as suggested by Meredith et al. [2000]. These findings are based on CFC model data, and age tracer and numerical float experiments.

The results do not reveal the deep double-core structure known from tracer sampling along the Greenwich Meridian (Fig. 4a), indicating that the observed core near the Mid-Atlantic Ridge has its origin in the southern Weddell Sea. This implies that the core near the continental slope, entering the Weddell Sea from the Prydz Bay area at a rate of 2.5 Sv, additionally contributes to the reservoir of newly ventilated waters in the Weddell Sea. About 20% of the PBW leaves the Weddell Sea eastward across the Prime Meridian while roughly 2 Sv escape through the gaps contributing to the ventilation of the World Ocean (Figure 3).

Hence, our results suggest that the southern core is not replenished by a recirculating northern core within the Weddell Gyre, but an independent feature from a ventilation site outside the Weddell Sea. This reduces the relative importance of the Weddell Sea as source for AABW.

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References


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**Figure 1.** CFC distribution in the bottom layer of the BRIOS model domain after 77 years (Summer 1997). Bottom topography is contoured at 500 m intervals. The red box indicates the Prydz Bay area where floats and age tracers were released, the dashed line the section shown in Figure 4.

**Figure 2.** Mid-winter (beginning of September) temperature section of the upper 2000 m along 72°E of model year 20.

**Figure 3.** Modelled trajectories of particles released in the surface layer off Amery Ice Shelf. Particles were released in September at the time of deep convection. Travel times are symbolized. Islands are indicated by initials: SG – South Georgia, SSI – South Sandwich Islands, SOI – South Orkney Islands and BI – Berkner Island. Major Ice Shelves are shaded.

**Figure 4.** Comparison of CFC-11 concentration in pmol/kg, from Polarstern cruise ANT XV/4 along Prime Meridian in 1998 (left) with modelled dye tracer distribution along 0°E, showing the water mass fraction originating in Prydz Bay after 30 years of integration (right). EIS – Ekstrøm Ice Shelf; MAR – Mid-Atlantic Ridge.

**Figure 5.** For selected depth intervals (circle: 2500 m, diamond: 2750 m, upward triangle: 3000 m, downward triangle: 3250 m and square: 3500 m), left: percentage of Prydz Bay Water in the southern core at Greenwich Meridian, right: transit time of water at Greenwich Meridian released at Prydz Bay. Legend depicts depth.
Figure 2

Temperature [°C]

Depth [m]
Figure 5