On the Seasonal Variability of the Southern Ocean Meridional Overturning

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Introduction

Recent numerical model results focussed on the Southern Ocean meridional overturning [*Hellmer and Beckmann,* 2001] support the observationally derived formation rate of dense Antarctic Bottom Water (AABW) of the order of 10 Sv, mainly confined to the Atlantic sector of the Southern Ocean [*Orsi et al.,* 1999]. The numerically derived rate doubles if a slightly lighter component of the Indian-Pacific (IP) sector is included, supporting the hypothesis that the sources in the southern and northern hemisphere contribute equally to the ventilation of the world ocean abyss [*Broecker et al.,* 1998]. Most of the estimates based on observations, however, repesent long-term means which do not reflect the seasonal and interannual variability inherent to the bottom water formation process (e.g., *Fahrbach et al.* [2001]).

In the framework of BRIOS (Bremerhaven Regional Ice Ocean Simulations) we run a model with a horizontal resolution of 20-100 km in the Weddell Sea sector, embedded in a coarser circumpolar Southern Ocean, and a vertical resolution of 24 terrain-following levels [*Beckmann et al.,* 1999]. The model domain extends from 82°S, including the major ice shelf cavities, to 50°S where temperature and salinity fields are strongly restored to the climatology of *Olbers et al.* [1992]. BRIOS is forced with averaged monthly mean surface fluxes of momentum and freshwater, all resulting from a stand-alone sea ice model (after *Lemke et al.* [1990]), which is driven with 6-hourly ECMWF reanalysis data of the period 1985-93.

Our analysis concentrates on the zonally integrated overturning transport streamfunction plotted as a function of latitude and density (σ_2). This presentation is preferred to latitude and depth, because most of the water masses are modified at the same latitude and within the same depth range as they move with the southern branches of the subpolar gyres. The density was chosen relative to 2000 meters to present an isopycnal range which coincides with *Orsi et al.'s* [1999] density based definition of AABW formed south of the Antarctic Circumpolar Current (ACC), $\sigma_2 \geq 37.16$ kg m^{-3}. In the following, we focus on the seasonal variability of the meridional overturing.

Results and Discussion

Spatial and temporal separation of the Southern Ocean meridional overturning into Atlantic and Indian-Pacific sectors south of 66°S and into summer (DJF) and winter (JAS) months, respectively, shows that the densest water is found year-round on the the Ross Sea continental shelf (Fig. 1). However, this dense water does not reach the deep basins as the admixture of lighter bottom water between 72°S and 68°S seems to erase the high-density signal of the Ross Sea outflow. Instead, the densest water crossing 66°S year-round is formed at the southern Weddell Sea continental slope in winter propagating northward as the year progresses. Dense water formation occurs close to the edges of Filchner-Ronne (Atlantic) [*Timmermann et al.,* 2001]

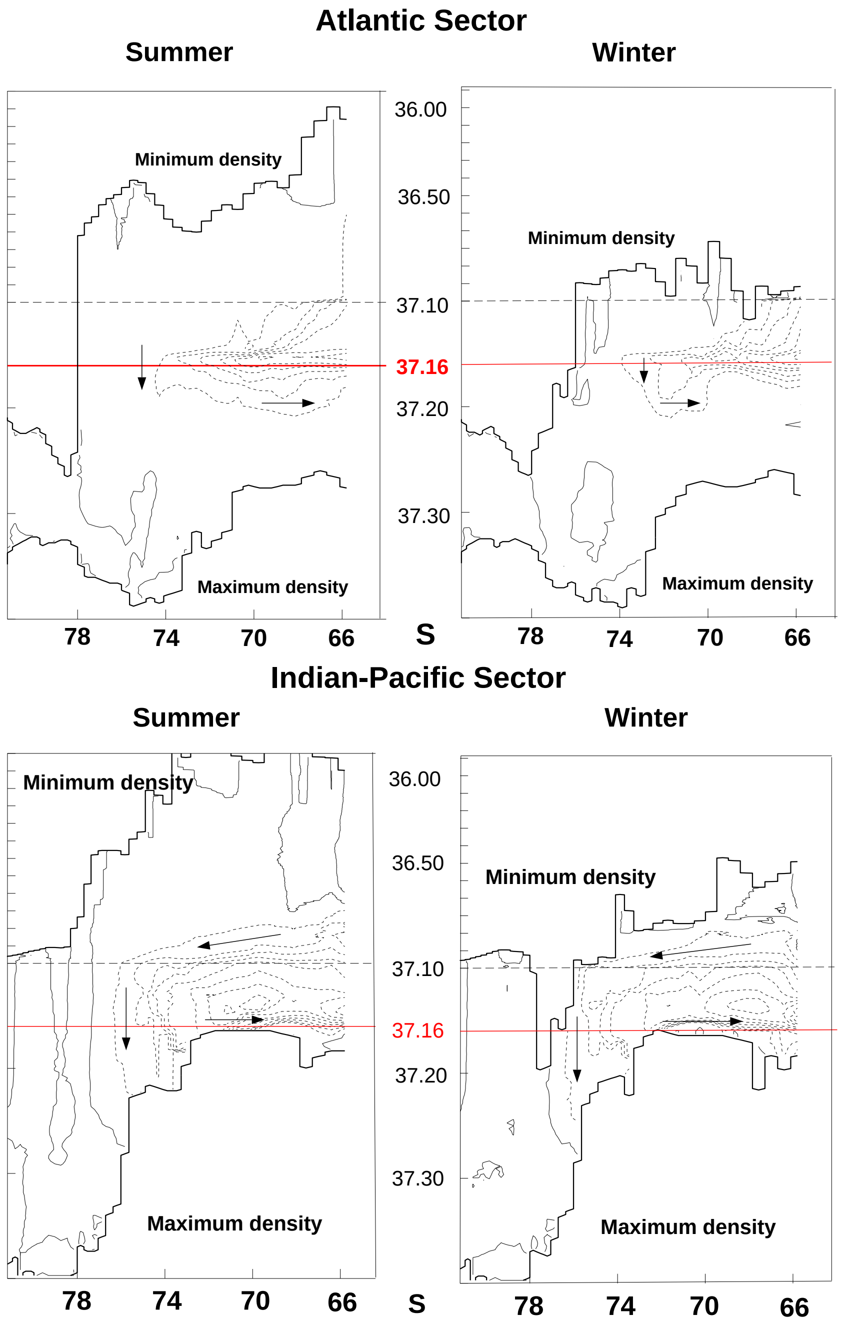

Figure 1: Summer (left) and winter (right) overturning transport streamfunction for the Atlantic (upper) and Indian-Pacific (lower) sectors of the Southern Ocean south of 65°S as a function of latitude and density (σ_2). Since a sensible transport streamfunction calculation requires a coast-to-coast integration, the Atlantic sector extends from Enderby Land (50°E) to Antarctic Peninsula (60°W) while the Indian-Pacific sector encompasses the remaining Southern Ocean. This results in an Indian-Pacific coastline two-times longer than the Atlantic coast. For densities $\sigma_2 \geq 37.1$ kg m^{-3} (dashed line), the vertical scale is stretched to better present the narrow dense water transports. The gray line marks the density $\sigma_2 = 37.16$ kg m^{-3} defined as upper bound for dense AABW formed south of the ACC [*Orsi et al.*, 1999]. Dashed contours indicate counter-clockwise, solid contours clockwise circulations (see arrows). Bold solid lines represent the minimum (upper) and maximum (lower) density value for each latitudinal band. Contour spacing is 2×10^6 m^{3}s^{-1} starting from $\pm1 \times 10^6$ m^{3}s^{-1}.

and Ross (IP) ice shelves [*Jacobs and Giulivi,* 1998], and is related to ocean surface processes as indicated by the steep increase of minimum (surface) densities north of ~ 78°S (Fig. 1). The lack of a seasonal signal in the distribution of maximum (bottom) densities indicates that the reservoirs of dense shelf water are not drained totally before the onset of new brine release during sea ice formation.

Dense AABW ($\sigma_2 \geq 37.16$ kg m^{-3}) is formed mainly in the Atlantic sector at an annual mean rate of ~ 10 Sv [*Hellmer and Beckmann,* 2001]. This is twice the rate of dense bottom water formation in the IP sector which occurs north of 68°S (Fig. 1) and corresponds to the continental slopes off Adélie Land [*Rintoul,* 1998] and Prydz Bay [*Jacobs and Georgi,* 1977, *Schodlok et al.,* 2001]. A slightly lighter AABW ($\sigma_2 \geq 37.15$ kg m^{-3}) is mainly formed in the IP sector also at an annual mean rate of ~ 10 Sv [*Hellmer and Beckmann,* 2001].

In contrast to the formation of light AABW, the dense AABW formation is subject to seasonal variability which ranges from 7 Sv (3 Sv) in summer to 11 Sv (5 Sv) in winter for the Atlantic (IP) sectors. This is more than inferred from the circumpolar tracer budget [*Orsi et al.,* 1999]. However, the IP sector produces ~ 30% of the Southern Ocean's dense AABW in both seasons which agrees well with the 72% estimated for the Weddell Sea/Atlantic sector [*Carmack,* 1977]. In addition, lighter bottom water might form at the southern Weddell Sea continental shelf since the mid-80's due to the disturbance of the shelf regime by stranded icebergs [*Grosfeld et al.,* 2001] which is not covered by this model. In summary, we emphasize that our model provides the transport of bottom waters without considering their degree of ventilation which could post the modeled ranges as an upper estimate.

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