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Note

Decadal change of Antarctic Intermediate Water in the region of Brazil and Malvinas confluence

Xiao-Yi Yang [a,b,*], Zhigang He [b]

[a] State Key Laboratory of Marine Environmental Science, Xiamen University, Xiang an Campus, 361102 Xiamen, Fujian, China
[b] College of Oceanography and Earth Sciences, Xiamen University, Xiang an Campus, 361102 Xiamen, Fujian, China

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ABSTRACT

The Antarctic Intermediate Water (AAIW) exhibits a decadal variability during recent years, i.e., salinification before 1997 and freshening thereafter, with the maximum anomalies locating at the region of Brazil and Malvinas currents confluence. Our study proposed that the local mesoscale eddies may play an important role in triggering this decadal oscillation. The eddy activity intensification (weakening) leads to the increase (decrease) of poleward cross-frontal eddy salinity flux and upward eddy buoyancy flux, which results in the weakening (strengthening) of the subsurface stratification and potential vorticity (PV). The PV anomalies facilitate (block) the poleward transport of warm saline subtropical water, while the stratification weakening favors the further downward transmission of salinity anomalies by processes of eddy flux as well as mean-flow advection (the stratification strengthening inhibits the vertical transport), then initiates the decadal change of the AAIW property. The whole process of the eddy-related propagation of salinity anomalies takes about 4 to 6 years.

1. Introduction

The AAIW has universally been regarded as one of the most important water masses in the world oceans. Originated in the high-latitudes of Southern Hemisphere (SH), AAIW spreads northward all the way to three ocean basins, and exchanges the heat, freshwater and carbon dioxide between them. Particularly in the Atlantic ocean, it can be traced across the equator and extend as far north as 30°N (Talley, 1996).

The controversy about AAIW were never settled down, involving first its origin and then its water mass property change. Some early studies agreed on the circumpolar formation of AAIW by along-isopycnal subduction of Antarctic Surface Water (AASW) (Deacon, 1937; Sverdrup et al., 1942). McCartney (1977) suggested the AAIW is mostly originated from Subantarctic Mode Water (SAMW) due to winter deep convection at the both ends of Drake Passage. Molinelli (1981), in recognizing the non-uniform renewal of AAIW, proposed that the isopycnal mixing of AASW across the Polar Front dominates the AAIW formation. The subsequent observational analyses and numerical simulations support either winter deep convection mechanism (England et al., 1993), or isopycnal processes across PF (Sørensen et al., 2001; Santoso and England, 2004), or their combination (e.g., Piola and Georgi, 1982; Piola and Gordon, 1989; Talley, 1996; Sloyan and Rintoul, 2001; Saenko et al., 2003).

The aggregation of the high-quality repeat hydrographic sections makes it possible to detect the long-term change of AAIW and SAMW property. Some studies reported the warming and/or freshening of the intermediate layers in the SH oceans, including South Pacific (Bindoff and Church, 1992; Johnson and Orsi, 1997; Shaffer et al., 2000), South Atlantic (Arbic and Owens, 2001), South Indian oceans (Wong et al., 1999; Bindoff and McDougall, 2000) and the Southern Ocean as a whole (Gille, 2002). The model simulations further revealed that the changes of AAIW/SAMW property can be mostly traced back to its outcrop region, where the Ekman transport, surface heat and fresh water fluxes vary in response to the anthropogenic forcing (Banks et al., 2000; Banks and Bindoff, 2003; Santoso and England, 2004; Fyfe, 2006). However, Bryden et al. (2003) compared five trans-Indian hydrographic sections ranging from 1936 to 2002 and proposed that SAMW property variability exhibits a decadal oscillation—freshened before 1987 and become saltier hereafter, rather than a linear trend of freshening. The work by Schneider et al. (2005) demonstrated that AAIW turned warmer and saltier in the eastern South Pacific between 1992 and 2003. In the subtropical South Atlantic, the AAIW presents a consistent warming trend since 1950s, but a significant salinification from 1950s to 1990s and a freshening

* Corresponding author at: Xiamen University, State Key Laboratory of Marine Environmental Science, C3-418, Xiping Building, Xiang an Campus, Xiamen 361102, Fujian, China. Tel.: +86 592 218 7671; mob.: +86 158 8027 2957.
E-mail address: xyyang@xmu.edu.cn (X.-Y. Yang).

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after 1990s (McCarthy et al., 2011). The warming and lightening trends of AAIW property persisted into the 2000s, probably reflecting the air-sea turbulent heat flux and sea ice formation trends in its origin regions (Close et al., 2013). In contrast, there is no pronounced long-term AAIW salinity trend, despite a strong variability on decadal time scales (Schmidtko and Jonhson, 2012).

The previous AAIW property change studies are mostly based on the in-situ observations, which, though robust enough, lacks the continuity in both spatial and temporal dimensions. This probably results in the ambiguity involving the decadal variability of AAIW salinity and its mechanisms. Using an assimilated reanalysis dataset, this study proposes a prominent decadal variability of AAIW since 1990s and attributes it to the eddy activity in the southwestern Atlantic.

2. Data and method

The simple ocean data assimilation (SODA) reanalysis dataset is constructed by assimilating all available observational data, including hydrographic profiles, ocean station data, and infrared satellite data, to the Parallel Ocean Program (POP) ocean model output (Carton and Giese, 2008). Here the newly released SODA v2.2.4 is used with the resolution of $0.5^\circ \times 0.5^\circ \times 40$-level spatially and monthly mean ranging from Jan 1871 to Dec 2008 temporally. Compared with the previous versions, this version improves its surface forcing boundary conditions and assimilates more recent observation data, wherefore does a better job on bias suppression (Giese et al., 2011; Giese and Ray, 2011).

To verify the reanalysis data results, the high-resolution conductivity–temperature–depth (CTD) data and profiling float (PFL) data from the World Ocean Database 2009 (WOD09) and the weekly sea surface height anomaly data from AVISO TOPEX/Jason 1 merged satellite product are used in this study. In addition, the other two products of ocean reanalysis data (including NCEP Global Ocean Data Assimilation System (NCEP-GODAS) and the ECMWF system 3 ocean analysis system (ECMWF-ORAs3)) and the GFDL coupled model simulation data are compared with the SODA data results. The NCEP-GODAS data is based on a quasi-global configuration of the GFDL MOMv3, with the resolution of $1^\circ \times 1^\circ$ enhanced to $1/3^\circ$ in the N–S direction within 10° of the equator and vertical 40 levels. GODAS assimilates temperature profiles from XBTs, TAO, TRITON, PIRATA moorings and Argo profiling floats (Behringer et al., 1998). The ECMWF ORAs3 is based on the Hamburg Ocean Primitive Equations (HOPE) ocean model, with the resolution of $1^\circ \times 1^\circ$ and 29 levels in the vertical. In addition to surface and subsurface temperature, this dataset also assimilates altimeter derived sea-level anomalies and salinity data (Balmaseda et al., 2007).

For all the monthly datasets, the high frequency variability is filter out by taking the 13-point running mean, as we focus on the decadal time scale. In addition, for a region with sharply changing isopycnal slope, we interpolate the grid data onto the dynamic height coordinate. The dynamic height is measured in dynamic meters and is defined by

$$D(p_1, p_2) = \int_{p_1}^{p_2} \delta(T, S, p) dp,$$

where p_1 and p_2 are two reference pressure levels, and δ the specific volume anomaly. Dynamic heights are preferred over meridional coordinate because the energy will be conserved along the dynamic height coordinate. Moreover, the dynamic height contours coincide with the geostrophic streamlines, hence the property averaged along the dynamic height coordinate approximates the calculation of a transport-weighted mean. (see Naveira Garabato et al., 2009; Close et al., 2013). The 500 dbar and 1500 dbar are chosen as the reference pressure levels in order to emphasize the dynamics in the intermediate levels.

3. Results

The AAIW is characterized by a salinity minimum layer, with a typical salinity of 34.2–34.4 psu and temperature of 3–5 °C. The density surfaces associated with the core of AAIW fall in the range 1027.1–1027.3 kg/m^3 (Molinelli, 1981; Piola and Georgi, 1982), which is well reproduced in the SODA climatological data (figure not shown). Following the earlier studies (e.g., Santoso and England, 2004), the θ-S properties in the SODA data are interpolated onto the typical potential density surface of AAIW ($\sigma_\theta = 27.2$), and the zonal-mean AAIW salinity variability is shown in Fig. 1a. The prominent change occurs at the time about mid-1990s, with nearly neutral state for the pre-1995 period but large positive anomalies followed by negative anomalies for the

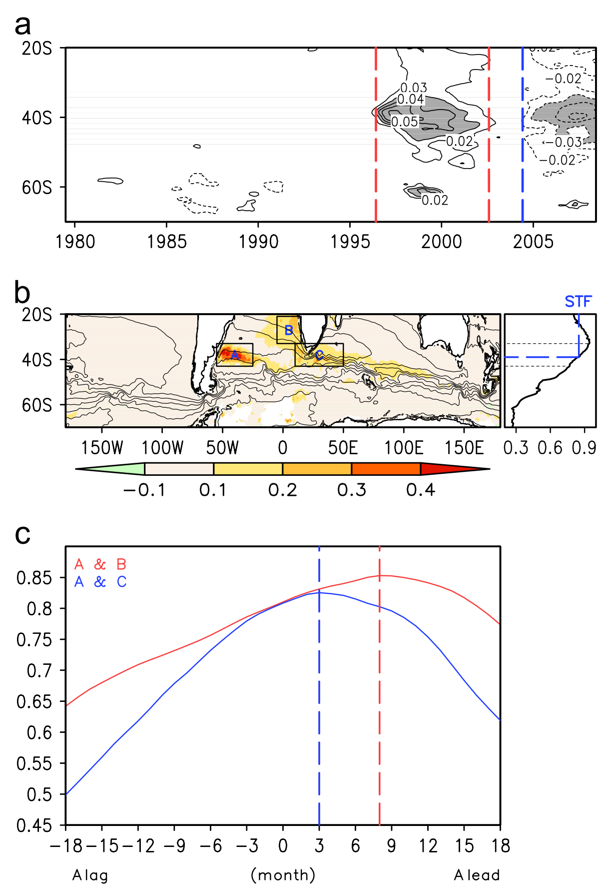

Fig. 1. (a) Zonal mean AAIW ($\sigma = 27.2$) salinity anomalies during 1979–2008 period in the SODA data, with the anomalies exceeding ± 0.03 psu shaded. Dashed lines denote the periods of high salinity (1996.6–2002.8, red) and low salinity (2004.6–2008.12, blue) periods; (b) AAIW salinity composite for high minus low salinity periods (defined by the dashed lines in Fig. 1a, shading) and the 1979.1–2008.12 climatology of 500–1500 dbar dynamic heights with the intervals of 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0 …… (contours, unit: dynamic meter). The rectangles indicate the BMC region (region A, 55–25°W, 43–33°S), the subtropical southeast Atlantic (region B, 5°W–15°E, 33–21°S) and the Agulhas return flow (region C, 10–50°E, 43–33°S), respectively. The BMC zonal-mean 500–1500 dbar dynamic heights are shown in the right panel, with the position of subtropical front indicated by blue dashed lines; (c) the lead-lag correlation coefficients of region A area-mean AAIW salinity with region B area-mean AAIW salinity (red), and of region A area-mean AAIW salinity with region C area-mean AAIW salinity (blue). The horizontal axis is the lead-lag months, with the negative values denoting region A lag region B (region C) by months. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)