that warm events play some role in melting the ice.

Concluding remarks

We have found strong indications that variation of the main southern limb flow of the Weddell Gyre, which winds around the northern reaches of Maud Rise in a relatively narrow jet, induces warm events at its lower flank. We conjecture that the generating of warm events in the oceanic surface layer plays an important role in removing the ice-pack and forming ice-free regions. It should be realised that the relatively warm intermediate water from the main flow around Maud Rise occurs at shallow depths, typically <100 m. What makes the warm events meaningful is that this already shallow warm water is further uplifted through circulation-topography interactions at the flanks of the Rise. If the warm events occur in winter, they have the potential to melt the pack ice and generate polynyas or, in early spring, open the pack.

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Circulation of Subantarctic Mode Water in the Indian Southern Ocean from ARGO and ALACE floats

K Speer[1], N. Wienders[1], J.-B. Sallee[2], R. Morrow[2]
[1]Department of Oceanography, OSB 435, Florida State University, Tallahassee FL 32306-4320, USA
[2]LEGOS-UMR5566, 18 av Edouard Belin, 31401 Toulouse cedex 9, France
Corresponding author: kspeer@ocean.fsu.edu

Abstract

Subantarctic Mode Water is the name given to the relatively deep surface mixed layers found directly north of the Subantarctic Front in the Southern Ocean, and their extension into the thermocline as weakly stratified or low potential vorticity water masses.

ARGO profiling floats provide estimates of temperature and salinity typically in the upper 2000 metres, and the horizontal velocity at various parking depths. Mode water circulation is determined with ARGO data, earlier ALACE float data, and climatological hydrography.

Introduction

Mode water is the name given to an ocean layer with physical properties (temperature, salinity) that are nearly homogeneous vertically and horizontally, covering an extended area in a given basin (a recent review is provided by Hanawa and Talley, 2001) and thus occupying a relatively large volume compared to other water types. They are one of the primary results of air-sea interaction (Speer et al., 1995), and serve to ventilate the interior of the upper ocean as they spread within gyres and boundary currents (McCartney, 1982; Hanawa and Talley, 2001).

In the Southern Ocean, the Subantarctic Mode Water (SAMW) forms in the deep winter mixed layers in the Subantarctic Zone (SAZ), north of the Subantarctic Front (SAF) and south of the Subtropical Front (STF).

Talley's (1999) map of mixed layer oxygen saturation shows an onset of higher oxygen in the southern Indian Ocean, at about 70°E, which supports the idea that the southeast Indian Ocean is a dominant source region of mode water; McCarthy and Talley (1999; see also Keffer, 1985) show a low potential vorticity (PV) pool near 26.8 sigma-theta centered near 90°W, 40°S which is generated by relatively deep winter mixed layers, spreads into the subtropical Indian Ocean. The low PV pool also extends in a narrow tongue eastward south of Australia, a pattern that becomes more pronounced at slightly greater density.

Data

The ARGO float program has seeded the World Ocean for several years, and in particular, the Southern Ocean, which historically is poorly sampled. Good data coverage in the southern Indian Ocean started in late 2002, and this study focuses on the years 2003 and 2004. These data were collected and made freely available by the International Argo Project and the national programs that contribute to it. PALACE data (Davis, 2005) were combined with ARGO floats to compute the mean flow in the Southern Indian Ocean.

We obtained 8849 velocity components from the ARGO database and 11667 from the ALACE/PALACE database. The velocities were averaged into 2 degrees of longitude by 1 degree of latitude bins. We then mapped the velocity field and a stream function from the ARGO data in the Southern Indian Ocean using an objective analysis following Gille (2003). The mean 10-day current velocities estimated from ARGO data at the parking depth contain errors, mainly due to the float drift at the surface. Furthermore, the float drift during the descent and ascent phase is also unknown. A study on the error in the drifting velocity at the float parking depth by Ichikawa et al. (2002) estimates this error to be between 10 to 25 percent.

Our averaged, interpolated velocity field has substantial errors, formally of magnitude 50% or so, worse around the boundaries of the domain. However, other sources of error from sampling bias and unresolved flow probably dwarf this error locally.

Circulation of the southern Indian Ocean

Figure 1 shows a climatological average of velocities at 400 metre depth deduced from an objective analysis of ARGO and PALACE floats in the Southern Indian Ocean. We see a rich array of gyres embedded within the general flow of the ACC

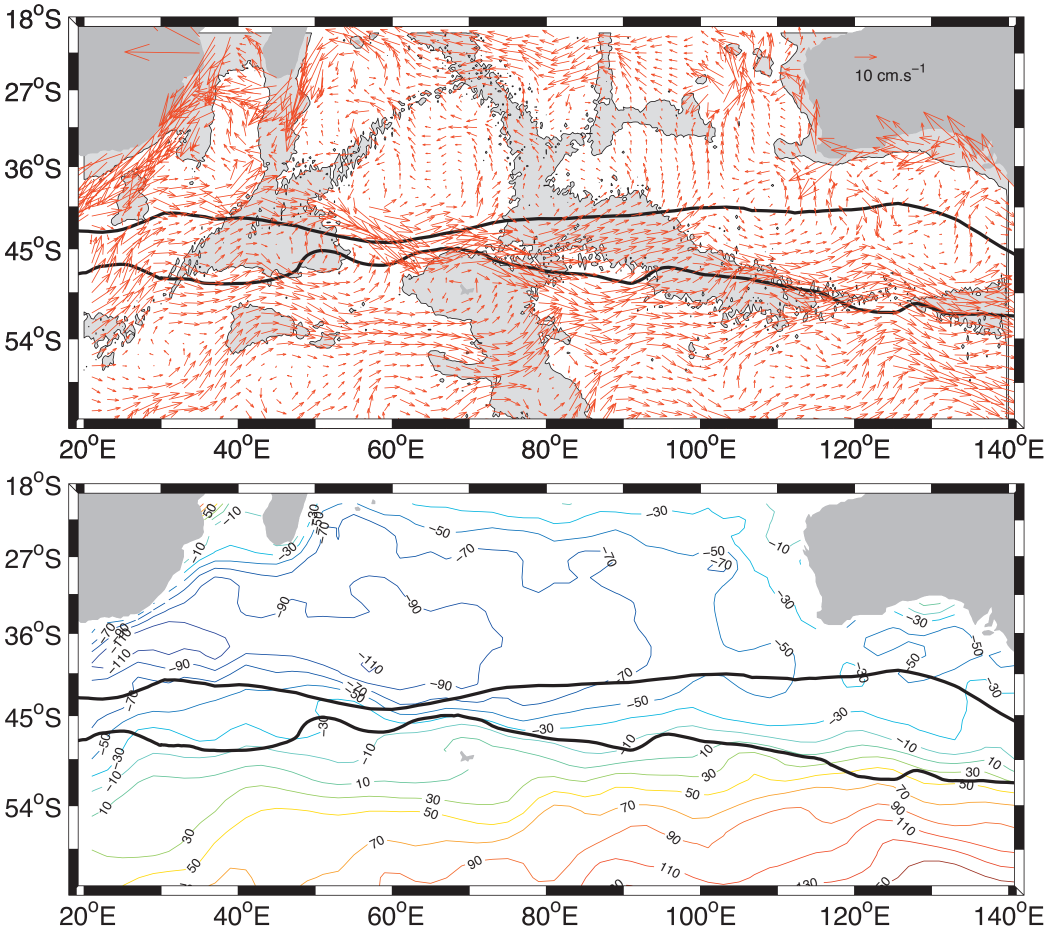

Figure 1: Averaged velocities at 400 metre depth deduced from an objective analysis of ARGO and PALACE floats in the southern Indian Ocean (upper). Bathymetry less than 3500 metres depth is shaded gray. Solid lines indicate the STF (north) and the SAF (south) from Orsi et al. (1995). A geostrophic streamfunction constructed from the same flow field is displayed for a smoother view of the circulation (lower).

and subtropical gyre. A geostrophic streamfunction view of the same flow field smoothes over some features but suggests a gyre south of Australia and others nested within the general subtropical gyre circulation.

The meandering Agulhas Retroflection is centered on about 40°S with velocities greater than 40 cm/s at 400 m depth. In this analysis, the Antarctic Circumpolar Current (ACC) bifurcates upstream of the Crozet Plateau at 40 S, the northern branch merging with the Agulhas Retroflection, and the southern branch continuing eastward. Further downstream, this eastward branch bifurcates again around the Kerguelen Plateau. A main southerly branch continues eastward across the plateau, merging with flow downstream of the plateau. The merging of ACC and Agulhas waters upstream of the two plateaus gives rise to strong lateral mixing.

Downstream of the Kerguelen Plateau near 80°E, the main fronts diverge; the STF moves northward, whereas the main branch of the SAF follows the northern flank of the Southeast Indian Ridge (Sandwell and Zhang, 1989). This is the region of deepest winter mixed layers described by Talley (1999), McCarthy and Talley (1999).

The northward spreading of mode water into the subtropical gyre is presumably due primarily to northward advection, itself a result of wind stress forcing and the fluxes that create mode water. Stramma (1992) showed that southeast of Africa the Subtropical Front (STF) is associated with a geostrophic transport of some 60 Sv (1 Sv = 106 m3/s) and that this transport is reduced to less than 10 Sv as Australia is approached. South of Australia the strength of the STF decreases further, reaching negligible magnitude near 130 E (Schodlock et al., 1997). The surface water between the STF and SAF becomes progressively cooler and denser as it moves east; this allows the development of northward thermal wind, thus gradually carrying away water from the northern side of the ACC and into the subtropical gyre.

Fine (1993) divided Indian Ocean SAMW into three density ranges: 26.65-26.7 sigma, which dominates in the southwestern region, 26.7-26.8 sigma, which dominates in the central region, and 26.8-26.85 sigma, which dominates in the south-eastern region. These divisions are presumably related to the large-scale wind-driven circulation, bathymetry, and the dynamics of mode water itself.

The mean wind stress curl (not shown) from QuikScat shows a complex spatial structure related to wind systems and flow over land, and also to SST; this tends to drive gyres at sub-basin scales.

Bathymetry clearly has a direct impact on the circulation in this region, creating large permanent meanders of the Agulhas Retroflection and the ACC, and limiting the latitudinal excursions of the hydrological fronts. North of the ACC distinct interior recirculation regimes exist apparently related to bathymetry that may set the primary mode water divisions.

Finally, strong eddy activity is associated with instabilities of the main currents and other dynamical fronts. The Agulhas Current System has the highest eddy kinetic energy (EKE) of the global ocean, and EKE maximums are located along the main axes of the meandering Agulhas Retroflection and the ACC (Le Traon and Morrow, 2001). Eddy mixing can be important in the diffusion of tracers, and in the transport of properties across the SAF.

In a separate study we investigate the primary sources of heat to mode water and the importance of eddies to the heat balance of mode water (Sallee et al. 2005).

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The Carbon Cycle In Mode Waters Of The Southern Indian Ocean: Anthropogenic Vs. Natural Changes

C. Lo Monaco and N. Metzl
Laboratoire d'Océanographie et du Climat: (LOCEAN/ IPSL CNRS) Université P. et M. Curie, France
Corresponding author: lomonaco@ccr.jussieu.fr

Introduction

The ocean carbon cycle is closely linked to climate. The ocean's uptake of anthropogenic CO_2 regulates the increase of this greenhouse gas in the atmosphere and thus global warming. In turn, the rate of the ocean's uptake of CO_2 is affected by climate-induced changes in biogeochemical and physical ocean processes. Global models have shown that the Southern Ocean is of particular interest here both because it is where most anthropogenic CO_2 enters the ocean and because it will be particularly sensitive to future climate change. However, the Southern Ocean is also the region where the highest disagreements exist among different ocean carbon models (Orr et al., 2001) and between models coupling the global carbon cycle with climate change (Friedlingstein et al., 2003). In that context, long-term observations of carbon dioxide in the Southern Ocean and data-based studies of the carbon uptake and its variability represent important steps to validate current ocean carbon models and to reduce uncertainties attached to climate change predictions. As part of the long-term observational OISO project, started in 1998 onboard the R.S.S. Marion-Dufresne (IPEV), several hydrographic stations were conducted in the Southern Indian ocean and corresponding Antarctic sector (figure 1). One aim of the project was to complement WOCE stations occupied in 1995 in this area, to reoccupy historical stations (GEOCECS, INDIGO) and investigate the seasonality of the oceanic carbon properties (summer and winter data). In this note, we focus on recent results obtained in mode waters in this region. Both the spatial and temporal evolution of anthropogenic carbon accumulated by the ocean are analyzed.

A large-scale view of anthropogenic carbon in mode waters

Subantarctic Mode Water (SAMW) is formed during the deep winter mixing that occurs north of the Subantarctic Front (45-50°S) and sinks at intermediate depth (500-800m) towards low latitudes, thus providing a privileged path for the penetration of anthropogenic CO_2 into the ocean interior. Current observation-based methods for estimating the ocean's uptake of anthropogenic carbon (C^{ant}) agree on a large accumulation of C^{ant} in SAMW, both for cumulated uptake since the pre-industrial period (20-40 μmol/kg, Sabine et al., 2004; Lo Monaco et al.,