



South Atlantic meridional fluxes

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ABSTRACT

The properties of the meridional overturning circulation (MOC) and associated meridional heat transport (MHT) and salt fluxes are analyzed in the South Atlantic. The oceanographic data used for the study consist of Expendable bathythermograph (XBT) data collected along 27 sections at nominally 35°S for the period of time 2002–2011, and Argo profile data collected in the region. Previous estimates obtained with a shorter record are improved and extended, using new oceanographic sections and wind fields. Different wind products are analyzed to determine the uncertainty in the Ekman component of the MHT derived from their use. Results of the analysis provide a 9-year time series of MHT, and volume transport in the upper layer of the MOC. Salt fluxes at 35°S are estimated using a parameter introduced by numerical studies, the M_{ov} that represents the salt flux and helps determine the basin scale salt feedback associated with the MOC. Volume and heat transport by the western and eastern boundary currents are estimated, and their covariability is examined. Analysis of the data shows that the South Atlantic is responsible for a northward MHT with a mean value of 0.54 ± 0.14 PW. The MHT exhibits no significant trend from 2002 to 2011. The MOC varies from 14.4 to 22.7 Sv with a mean value of 18.1 ± 2.3 Sv and the maximum overturning transport is found at a mean depth of 1250 m. Statistical analysis suggests that an increase of 1 Sv in the MOC leads to an increase of the MHT of 0.04 ± 0.02 PW. Estimates of the M_{ov} from data collected from three different kinds of observations, contrary to those obtained from models, feature a positive salt advection feedback ($M_{ov} < 0$) suggesting that freshwater perturbations will be amplified and that the MOC is bistable. In other words, the MOC might collapse with a large enough freshwater perturbation. Observations indicate that the mean value of the Brazil Current is -8.6 ± 4.1 Sv at 24°S and -19.4 ± 4.3 Sv at 35°S, increasing towards the south. East of 3°E, the northward flowing Benguela Current and Agulhas rings have a net northward transport of 22.5 ± 4.7 Sv. No significant correlation is observed between the MOC and the Brazil Current transport, and most of the compensation derives from the eastern boundary and interior transports. Products from the Ocean general circulation model For the Earth Simulator (OFES) are used to validate methodology used to extend the XBT record, and to aid in the interpretation of the observed findings.

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1. Introduction

The mechanisms and pathways of mass and heat transport in the global ocean are due in large part to the wind-driven and buoyancy-driven components of the meridional overturning circulation (MOC). Associated with the strong thermohaline (buoyancy-driven) circulation in the Atlantic Ocean heat and salt are exchanged between the hemispheres. The South Atlantic Ocean plays a unique role in the global energy balance, transporting heat from the poles to the equator (e.g., Talley, 2003) as upper layer water spreads northward to compensate for the southward export of colder North Atlantic Deep Water. The northward flow

is a complex mixture of waters originating from the Indian and Pacific oceans, blended together in the South Atlantic and overlain by large-scale gyre circulations. The ability to understand and quantify this northward flow is crucial to properly model and forecast weather and climate. Maximum northward heat transport is observed in the subtropical North Atlantic, 1.3 PW ($1 \text{ PW} = 10^{15} \text{ W}$) accounting for 25% of the global combined atmosphere–ocean heat flux (e.g., Hall and Bryden, 1982; Lavin et al., 1998; Ganachaud and Wunsch, 2003; Lumpkin and Speer, 2007; Johns et al., 2011). Observed and simulated estimates of the meridional heat transport (MHT) in the South Atlantic range from negative values (-0.23 PW, de las Heras and Schlitzer, 1999) to almost 1 PW (0.94 PW, direct method, Saunders and King, 1995; 0.88 PW, inverse model, Fu, 1981). The main reason for the large range in estimated MHT values for the South Atlantic is the limited amount of data available in the region at the time.

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The South Atlantic has been historically one of the least sampled basins, and as an expected consequence, model estimates in this region have been poorly constrained. In the past decade, however, the situation has been improved by the initiation of repeated high-density expendable bathythermograph (XBT) lines (AX18 crossing the South Atlantic from South America to South Africa, AX22 across Drake Passage, and AX25 across the Agulhas retro-flection), as well as the broad scale temperature and salinity profiles collected throughout the region by the Argo program (Roemmich and Owens, 2000) and the quasi-decadal occupation of several trans-basin hydrographic lines (e.g., Saunders and King, 1995; McDonagh and King, 2005; Bryden et al., 2011).

Due to the above-described increase in data coverage in the South Atlantic, observed and simulated estimates of mean MHT and the MOC in the region have become more consistent. Baringer and Garzoli (2007) developed a methodology to obtain the heat transport from XBT data collected nominally along the latitude 35°S (XBT line AX18). Using this methodology, Garzoli and Baringer (2007) estimate the mean MHT from 14 AX18 sections, collected between July 2002 and May 2006, as 0.54 PW with a standard deviation of 0.11 PW. Using an extended version of the AX18 data set (17 sections collected between July 2002 and March 2007), Dong et al. (2009) estimate the mean strength of the meridional overturning circulation (MOC), defined as the maximum volume transport stream function (equivalent to the total northward transport in the upper water column), and the MHT. The obtained time-mean MOC is 17.9 ± 2.2 Sv and MHT is $0.55 \text{ PW} \pm 0.14 \text{ PW}$. They show that MHT variability is significantly correlated with the MOC variability, where a 1 Sv increase in the strength of MOC would yield a 0.05 ± 0.01 PW increase in the MHT. Dong et al. (2009) also partition the MOC and MHT into contributions from the western and eastern boundaries and the interior, and demonstrated that the variability of the contributions from boundary currents and interior are comparable.

Observations indicate that the annual cycle of the Ekman component of the flux is out of phase and of the same order of magnitude as the geostrophic component (Garzoli and Baringer, 2007; Dong et al., 2009). As a consequence, the observed annual cycles of the total (Ekman plus geostrophic) MHT and the MOC are almost non-existent. Models, in contrast, show a strong annual cycle for the total MHT, as well as for the MOC, in the South Atlantic that depends very little on the geostrophic component of the fluxes (Jayne and Marotzke, 2001; Baringer and Garzoli, 2007; Dong et al., 2011; Perez et al., 2011). Therefore, the dominant variability arises from the Ekman component of the fluxes that has a marked seasonal cycle.

Another important concept for which observations and models are in disagreement is the direction of the salt flux within the Atlantic sector, which is an indicator for the stability of the overturning circulation (Dijkstra, 2007; Huisman et al., 2010; Bryden et al., 2011). The stability and variability of the Atlantic MOC has been the object of numerous model studies (e.g., Weijer et al., 2003; Weijer and Dijkstra, 2003). de Vries and Weber (2005) showed from modeling studies that the instability of the MOC results from salt feedback in the ocean. When the MOC transports salt to the North Atlantic, a decrease in the MOC due to a freshwater anomaly in the convection sites will amplify the freshwater anomaly further by freshening the Atlantic basin. In contrast, when the MOC transports freshwater to the north, a decrease in the MOC due to a freshwater anomaly in the convection sites will damp the freshwater anomaly by the salinification of the Atlantic basin. Drijfhout et al. (2011) reinforced this concept that the basin-scale MOC-salt feedback determines whether the thermohaline circulation is monostable or bistable and that a more robust estimate of the MOC-trend and its variability can be made by combining sections in the North and

South Atlantic. The basin-scale MOC-salt feedback is associated with the sign of the overturning component of the freshwater flux, defined as the M_{ov} . According to Drijfhout et al. (2011) the sign of M_{ov} at the latitude 35°S in particular can be used to determine the stability of the MOC. In other words, when the M_{ov} in the South Atlantic is positive (negative salt advection feedback), salt is transmitted to the south and the MOC is monostable; when the M_{ov} is negative (positive salt advection feedback), salt is transmitted to the north and the MOC is bistable; it might collapse with a large enough freshwater perturbation.

The objectives of this paper are: to present new estimates of the MHT and MOC obtained by using a higher resolution wind field and the XBT data collected up to present (from July 2002 to February 2011); to provide an estimate of the M_{ov} from different kind of observations; and, to analyze the time series of volume transport to obtain estimates of the flows at the boundaries and the component of the MHT associated with them. Results are compared with estimates from a high-resolution eddy-resolving model, the Ocean general circulation model For the Earth Simulator (OFES) run by Japan Agency for Marine-Earth Science and Technology (JAMSTEC).

2. Methodology

The methodology used in this paper to obtain the MHT and MOC has been previously described in Baringer and Garzoli (2007) and Dong et al. (2009). Baringer and Garzoli (2007) tested the methodology with previous full depth CTD data and model products, and concluded that it can provide heat transport estimates with a maximum uncertainty of ± 0.18 PW. The methodology can be summarized as follows: Salinity (S) is estimated for each XBT profile by using empirical relationships developed for the South Atlantic by Thacker (2008) from available Argo profiler and CTD data in the region to provide an estimate of S as a function of Temperature (T), T^2 , pressure (p), latitude, and longitude. Where insufficient CTD and Argo data are available to define a statistically robust empirical estimate for S , the World Ocean Atlas 2001 (WOA01) gridded annual climatology (Stephens et al., 2002) is used. XBT profiles provide data only up to about 850 m, and the data are extended to the bottom using the WOA01 gridded 0.25° climatology interpolated to the location of each XBT profile to generate an annual mean climatology for the deep ocean. The bottom is determined to be the depth at the location of the XBT profile from the Smith and Sandwell (1997) two-minute database of bathymetry. Note, although an updated version of the World Ocean Atlas was generated in 2009 (WOA09), the coarse resolution used for WOA09 (1°) does not resolve oceanic features at the eastern boundaries as well as WOA01. Hence, WOA01 is used in this study.

Ekman volume and heat transports are determined using a daily NCEP reanalysis (Kalnay et al., 1996) winds interpolated to the location of the XBT observations. Observed temperatures from the XBT lines are used to determine the mixed layer depth and temperatures to compute the Ekman heat transport (Baringer and Garzoli, 2007). The net meridional volume and heat transport are then given by the sum of the geostrophic (described below) and Ekman components of the volume and heat transport.

Geostrophic velocities are determined from the T and S fields generated from XBT, CTD and Argo observations using the dynamic height method where an initial level of no motion is chosen at $\sigma_2 = 37.09 \text{ kg m}^{-3}$ (σ_2 defined as potential density relative to 2000 dbar). These geostrophic velocities are then zonally and vertically integrated to obtain the geostrophic volume transport. Note, the initial level of no motion velocity field is uniformly adjusted so that the net salt transport across the

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