Available online at www.sciencedirect.com
ScienceDirect
Deep-Sea Research I 54 (2007) 1390–1401
DEEP-SEA RESEARCH PART I
www.elsevier.com/locate/dsri

Instruments and Methods

Meridional heat transport determined with expendable bathythermographs—Part I: Error estimates from model and hydrographic data

Molly O. Baringer*, Silvia L. Garzoli

NOAA Atlantic Oceanographic and Meteorological Laboratory, Miami, FL 33149, USA

Received 1 November 2006; received in revised form 20 March 2007; accepted 26 March 2007
Available online 13 April 2007

Abstract

Heat transports estimated CTD data collected during the World Ocean Circulation Experiment (WOCE) along the January 1993 30°S hydrographic transect (A10) and the output from a numerical model show a mean heat transport of 0.40 and 0.55 ± 0.24 PW (standard deviation), respectively. The model shows a large annual cycle in heat transport (more than 30% of the variance) with a maximum (minimum) heat transport in July (February) of 0.68 (0.41) PW. Using these data, a method is proposed and evaluated to calculate the heat transport from temperature data obtained from a trans-basin section of expendable bathythermographs (XBTs) profiles. In this method, salinity is estimated from Argo profiles and CTD casts for each XBT temperature observation using statistical relationships between temperature, latitude, longitude and salinity computed along constant-depth surfaces. Full-depth temperature/salinity profiles are obtained by extending the profiles to the bottom of the ocean using deep climatological data. The meridional transport is then determined by using the standard geostrophic method, applying NCEP-derived Ekman transports, and requiring that the salt flux through the Bering Straits be conserved. The results indicate that the methods described here can provide heat transport estimates with a maximum uncertainty of ± 0.18 PW ($1\,\mathrm{PW} = 10^{15}\,\mathrm{W}$). Most of this uncertainty is due to the climatology used to estimate the deep structure and issues related to not knowing the absolute velocity field and most especially characterizing barotropic motions. Nevertheless, when the methodology is applied to temperatures collected along 30°S (A10) and direct model integrations, the results are very promising. Results from the numerical model suggest that ageostrophic non-Ekman motions can contribute less than 0.05 PW to heat transport estimates in the South Atlantic.
Published by Elsevier Ltd.

1. Introduction

One of the goals in the global ocean observing system is to accurately describe the strength of the meridional overturning circulation (MOC), the vigorous circulation that redistributes heat, nutrients, carbon and fresh water globally. In the South Atlantic, the MOC is composed of northward transport of warm surface and intermediate layer waters in the upper 1200 m, southward transport of North Atlantic Deep Water (NADW) between approximately 1200 and 4000 m, and northward flowing Antarctic Bottom Water (AABW) below 4000 m. Within the subtropical region, in the

*Corresponding author. Tel.: +1 305 361 4338; fax: +1 305 361 4392.
E-mail addresses: Molly.Baringer@noaa.gov (M.O. Baringer), Silvia.garzoli@noaa.gov (S.L. Garzoli).

0967-0637/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.dsr.2007.03.011

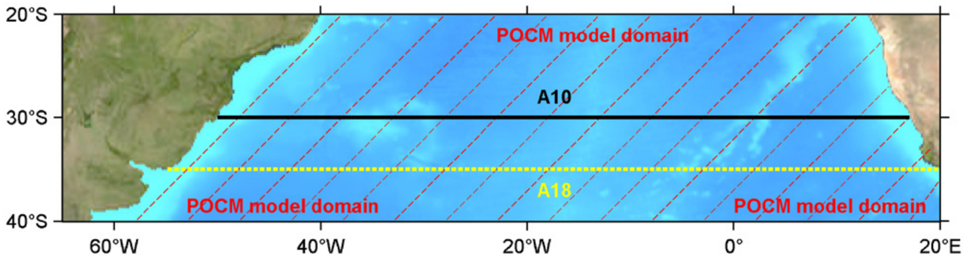

Fig. 1. Map of A10 location, XBT locations, POCM area with the main circulation elements schematically drawn (see text).

30–35°S band, historical heat transport estimates range from small southward values (e.g., −0.23 PW, de las Heras and Schlitzer, 1999) to close to 1 PW northward (0.88 PW, inverse model, Fu, 1981). To see the large range in various estimates of South Atlantic heat transport see Fig. 13. in Garzoli and Baringer (2007). Note that large heat transport variability may be a real feature of the South Atlantic circulation because both margins are highly energetic and the winds are variable.

The 'best-practices' method for estimating the net meridional transports typically includes the costly and time-consuming full-water-column, cross-basin hydrographic section. Such full-depth sections have been used with the geostrophic method to estimate the strength of the meridional heat transport at many locations. Direct estimates of the meridional heat transport in the South Atlantic have include Holfort and Siedler (2001), Saunders and King (1995) and Talley (2003). More involved estimation methods have included using more than one section and using observed velocities to constrain the circulation (e.g., Macdonald et al., 2001; Ganachaud and Wunsch, 2003).

Partly because of the expense of these 'best-practices' sections, other observations systems were envisioned to measure parts of the MOC in hopes of capturing some aspects of its variability. In particular, expendable bathythermographs (XBTs) deployed in cross-basin (full-width), relatively closely spaced (high-density) sections were conceived to measure the mesoscale variability at higher frequencies than one can afford to occupy full basin sections and thus the XBT sections can help assess whether unusual circulation features are present that could bias estimates based on a single full-depth section (Smith et al., 1999). Roemmich et al. (2001) demonstrated that XBTs could also successfully be used to estimate the meridional transport in the North Pacific. They estimated the net heat transport by specifically prescribing the transport below the deepest level of the XBT observations. In this paper, we will develop a methodology to calculate directly the deep transports using climatological data. In particular, the high-density XBT line called AX18 is used as an example XBT section where this method could be applied. The AX18 line, between Cape Town, South Africa, and Buenos Aires, was designed to monitor the upper-layer mass budget in the South Atlantic and to estimate the variability of the upper limb of the MOC transport. We evaluate the method against the full-depth, complete hydrographic section taken during the World Ocean Circulation Experiment (WOCE), the 30°S A10 section, in the same region. Errors are also estimated by analyzing the output of a numerical model simulation of the South Atlantic taken from the Princeton Ocean Circulation Model (Tokmakian and Challenor, 1999). The locations of the sections used in this paper are shown in Fig. 1.

2. Data and methodology

Direct estimates of meridional volume (V) mass (M) and heat (H) transport require the knowledge of the potential temperature (T), salinity (S) and meridional velocity (v) fields:

$$V = \int\int v\,dx\,dz \quad [Sv = 10^6\,m^3\,s^{-1}],$$

$$M = \int\int \rho v\,dx\,dz \quad [kg/s],$$

$$H = \int\int \rho c_p T v\,dx\,dz \quad [PW = 10^{15}\,W],$$

where ρ is the density of the water and c_p the specific heat capacity.

The total meridional velocity (v) can be decomposed into three components:

$$v = v_g + v_{ag} + v_b,$$