# Observations of Brazil Current baroclinic transport near 22°S: variability from the AX97 XBT transect

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## 1. Introduction

The Brazil Current (BC) is the Western Boundary Current (WBC) associated to the wind-driven circulation of the South Atlantic. This current can be identified furthest north where the southern branch of the westward flowing South Equatorial Current (SEC) bifurcates close to the South American coast near 15°S [e.g. Stramma and Schott, 1999]. As much as 15 to 22 Sv of the volume transport of the SEC flows northward as part of the inter-hemispheric flow of the North Brazil Current/Undercurrent [Silveira et al., 1994], leaving a relatively weak BC to close the subtropical wind-driven circulation in the western boundary at these latitudes. As the BC flows southwards to higher latitudes its depth and associated transport are increased, reaching 7.7 Sv in the upper 750 m to the south of the Vitoria-Trindade Ridge (Figure 1) [e.g. Campos et al., 1995]. Further south, the BC intensifies with the volume transport reaching values as high as 22 Sv near the Brazil-Malvinas Confluence at about 38°S [e.g. Peterson and Stramma, 1991]. Nevertheless, the BC is still classified as relatively weak when compared to its northern hemisphere counterparts, such as the Gulf Stream and the Kuroshio Current. Despite the recognized importance of the WBCs to the oceanic and climate systems from regional to basin-wide scales, the BC remains one of the least studied and understood of all WBCs, especially in terms of its variability or its relationship to the larger-scale subtropical gyre variations.

Recent progress in understanding the BC mean flow and associated features has been achieved [e.g. Stramma and England, 1999; Oliveira et al., 2009], however several aspects of BC low-latitude variability remain unexplained mostly due to the lack of observations. For example, south of 18°S, the BC poleward flow is normally thought to be largely composed of eddies, which leads to an ill-defined mean current with strong temporal and spatial fluctuations [e.g. Campos et al., 1995; Campos, 2006]. In order to increase the number of observations of the BC in this area, Brazilian institutions and NOAA have partnered to implement a long-term high-density XBT (eXpendable-BathyThermograph) transect in the southwestern Atlantic. This project has been named MOVAR (Monitoring the upper ocean transport variability in the western South Atlantic) and the XBT transect has been designated as AX97 running between Rio de Janeiro and Trindade Island (30°W, 20°S). One of the main objectives of this transect is to build a long-term time series of the BC baroclinic transports (and associated features) in order to improve understanding of the mean and temporal variations of the BC in this infrequently-sampled area of the South Atlantic Ocean. In addition, these observations contribute to the South Atlantic Meridional Overturning Circulation (SAMOC) initiative. Therefore, using a combination of the XBT data and satellite altimetry observations, this study analyzes the BC observed variability near 20°S and examines its possible causes.

## 2. Data Sources and Methods

The MOVAR project collects XBT data from Brazilian Navy supply ships, which sail from Rio de Janeiro to Trindade Island up to five times per year. A total of 29 complete realizations of the AX97 transect have been carried out between August 2004 to December 2011. The typical XBT deployment spacing is ~27 km along the transect and ~18 km near the boundaries. Most of the XBT probes were used to measure temperature up to 760 m (Sippican Deep Blue®), but several deep probes were also used (Sippican T-5® up to 1830m). Following the approach by Hansen and Thacker [1999], the salinity is estimated for each XBT profile based on an empirical relationship between historical salinity and temperature data collected in the region (Figure 1) from CTD (conductivity-temperature-depth) profiles, which are available in both US and Brazilian National Oceanographic Data Centers [van Caspel et al., 2010]. The dynamic method was then used to compute the baroclinic component of the geostrophic flow for each pair of stations along AX97 referenced to 400 dbar, level accepted as the typical interface between the southward flowing BC and the northward flow of its associated undercurrent in the region [Silveira et al., 2008]. To allow for direct comparisons between the repeat realizations, the velocity field was objectively mapped onto a regular longitude vs. depth grid of 0.25° by 10m and the transports were estimated by vertically integrating the gridded fields.

To gain further insight on the large-scale nature of the variability observed along AX97, we use the regional surface geostrophic circulation fields derived from the Maps of Absolute Dynamic Topography (MADT) dataset, which were objectively derived and distributed by AVISO Project. The MADT dataset uses data from all available satellite altimeters (up to four) added to a mean sea level [Rio and Hernandez, 2004; AVISO, 2011]. These maps are provided with a resolution of 1/3° x 1/3° every seven days.

## 3. Baroclinic current field and transports from XBT data

The mean AX97 baroclinic velocity field, as derived from XBT observations, indicates the presence of the main BC clearly confined to the west of 39°W with its mean core position located at about 200 km from the coast, at a local water depth of about 2200 m (Figure 2, upper panel). The maximum mean baroclinic velocity exhibits values of up to 0.2 m $s^{-1}$ in the core of the BC. The standard deviation of the BC is of comparable magnitude to the mean (0.2 m $s^{-1}$) in the BC core (Figure 2, middle panel), highlighting the importance of the spatial and temporal variability in the BC regime at 20°S. In addition, relatively large coherent mesoscale structures along the entire AX97 transect are evident in the mean and in the standard deviation sections, which suggests that a longer time series than what is used here may be needed to determine the mean dynamic structure in the region.

The zonally integrated transports across all AX97 realizations reveal that the variability observed in the velocity sections is translated into net baroclinic transport estimates, which are only weakly different from zero (Figure 2, bottom panel). The transport increases until reaching its maximum value of about 2.3 Sv near 39°W, a value that is roughly kept constant until the end of the section. The high variability in the transports across this section can be identified as three different 'typical' situations found during our AX97 cruises (Figure 3). The first case shows the baroclinic velocity field from the April 2007 realization (Figure 3, upper panel), which reveals a very strong BC with speeds up to 0.7 m $s^{-1}$ and a net southward transport of up to 6 Sv. The current main core was positioned to the west of 40°W, close to the shelf break. The zonally integrated transport increases up to 8 Sv near 37°W. In the second case, exemplified by the February 2006 realization (Figure 3, middle panel), the flow right next to the coast is moving towards the equator. This suggests a change of configuration of the BC main axis (or even a current reversal near the shelf break). Indeed, the baroclinic velocity field shows that the BC jet is now positioned further offshore (to the east of 40°W), with surface velocities reaching up to 0.6 m $s^{-1}$ and an associated transport of 5 Sv. Inshore of the southward moving BC (west of 40°W), the northward flowing current contains surface speeds reaching up to 0.2 m $s^{-1}$ and associated transports of ~1.5 Sv. In a third configuration, here exemplified in the August 2004 realization (Figure 3, bottom panel), there seems to be no evidence of a strong BC baroclinic jet anywhere along the AX97 transect. During this time, the zonally integrated transports have no clear direction, fluctuating around zero.

These three different regimes of the BC jet examined here also help to explain the high levels of baroclinic velocity variability west of 38°W (Figure 2). These results support the hypothesis that the observed variability is associated with the spatial fluctuations of the BC core, which can exceed 150 km in the region. Furthermore, when the BC jet moves offshore to the east of 40°W, the onset of a northward circulation inshore of the main jet next to the continental slope is observed. Finally, the third case (Figure 3, bottom) suggests that the BC is not always present as a poleward jet across AX97, which helps to explain why the variability levels are greater than the mean in this region.

## 4. Regional circulation and variability

The altimetry from the MADT dataset confirms the dominance of the three regimes (dates) examined in the previous section. During April 2007, the MADT pattern and corresponding circulation (Figure 4, upper panel) suggests the presence of a strong southward flowing BC that is broadly fed by flow to the west of 37°W. In particular, the high-sea level is centred along the AX97 line near 37.5°W and 22°S. This high-sea level "cell" is part of a double-cell structure at the western end of the South Atlantic subtropical gyre, first proposed by Tsuchiya [1985]. The centre of the second cell is located near 32°S just off the western boundary (not shown). In a more recent study, Mattos [2006] uses in situ data from the Brazilian Navy database to confirm the presence of the northernmost cell and uses a quasi-geostrophic model to conclude that the high-sea level cell is a ubiquitous large-scale feature of the southwestern Atlantic. This feature is also well depicted and consistent in the mean surface circulation as obtained from the GRACE satellite gravimetry mission [Vianna et al., 2007] and from multi-mission satellite altimetry [Vianna and Menezes, 2011]. In addition, the field from April 2007 reveals a very strong state of the northern high-sea level cell with its "crest" clearly crossing the AX97 transects. In the corresponding velocity fields, the BC appears as a swift jet next to the western boundary confined mostly to the west of 40°W. During this time, the BC jet is also well observed to the north of AX97. Furthermore, the corresponding mean surface geostrophic circulation shows a complex pattern, where the BC jet is fed by two main inflows, at ~22°S and further north at ~18°S.

The regional surface circulation field during the February 2006 realization is different from the April 2007 case. During this time the northern high cell seems somewhat less defined and the BC jet is meandering offshore just south of 22°S to cross the AX97 section to the east of 40°W (Figure 4, middle panel). The high-sea level cell is closer to the coast almost reaching the continental boundary near 24°S. Further to the north from AX97, the BC jet seems to be present right next to the slope but not as clearly as in the April 2007 time frame. Between 22°S and 23°S, the MADT field contains a low-sea level feature suggesting the presence of cyclonic circulation right next to the coast. The presence of this cyclonic cell is consistent with the recurrent unstable quasi-stationary BC frontal meander named the Cape São Tomé eddy [Silveira et al., 2008; Calado et al., 2010]. This cyclonic cell produces northward flow inshore from the BC main jet observed during some of the AX97 realizations (Figure 3, middle panel).

The regional circulation during August 2004 (Figure 4, bottom panel), which corresponds to the third regime, indicates that the crest of the northern high cell was even further to the south, almost not crossing AX97 at all. The main finding here is that that the BC is weaker and most of the velocity vectors appear parallel to the section, hence explaining the absence of the BC main jet from the in situ observations (Figure 3, bottom panel). In this case, the BC seems to intensify further to the south of the AX97 transect.

## 5. Summary

The variability of the baroclinic velocity associated with the BC along the AX97 XBT transect is related to both the migration of the South Atlantic gyre northern high-sea level cell and, closer to the continental boundary, to the development of a cyclonic vortex off Cape São Tomé. As the BC mean flow is relatively weak, these features can impose strong spatial and temporal variability to the associated transports leading to weak mean baroclinic transports. Ongoing research using AX97 observations will be able to document this observed variability and link the BC transport changes to other sources of variability in the area, such as the rough topography of the Vitoria-Trindade submarine ridge, a major topographic feature just to the north of this XBT transect.


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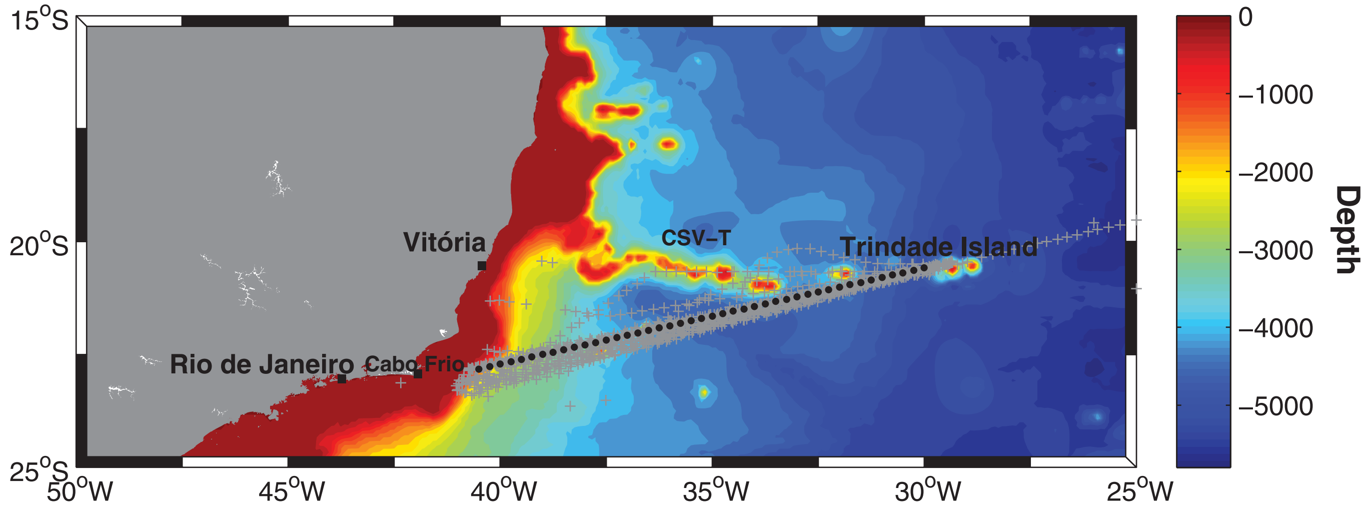


Fig 1: The AX97 transect with deployment positions (grey) and the reference transect (black dots). The main ship route goes from Cabo Frio City to Trindade Island. The regional bathymetry is shown in the background (units in metres). The position of the Vitoria-Trindade Submarine Ridge is indicated (CSV-T).

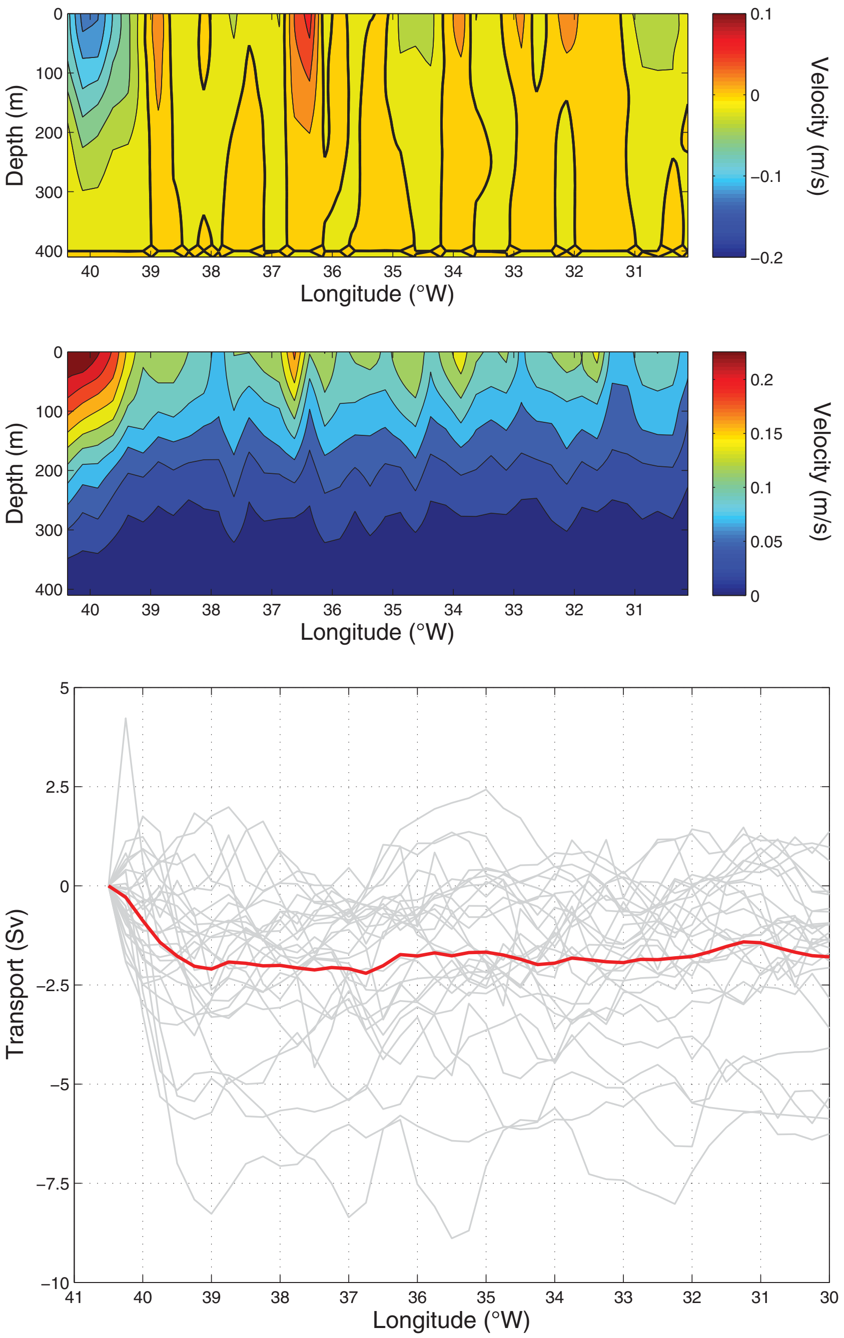


Fig 2: (top) The average baroclinic velocity field along the AX97 transect (referenced to 400 dbar) and (middle) the corresponding standard deviation. Negative values indicate southward flows and the zero velocity line is marked in bold. (bottom) Zonally integrated baroclinic transports (in Sv, referenced to 400 dbar) for the 29 available AX97 realizations (grey) and the corresponding average (red).

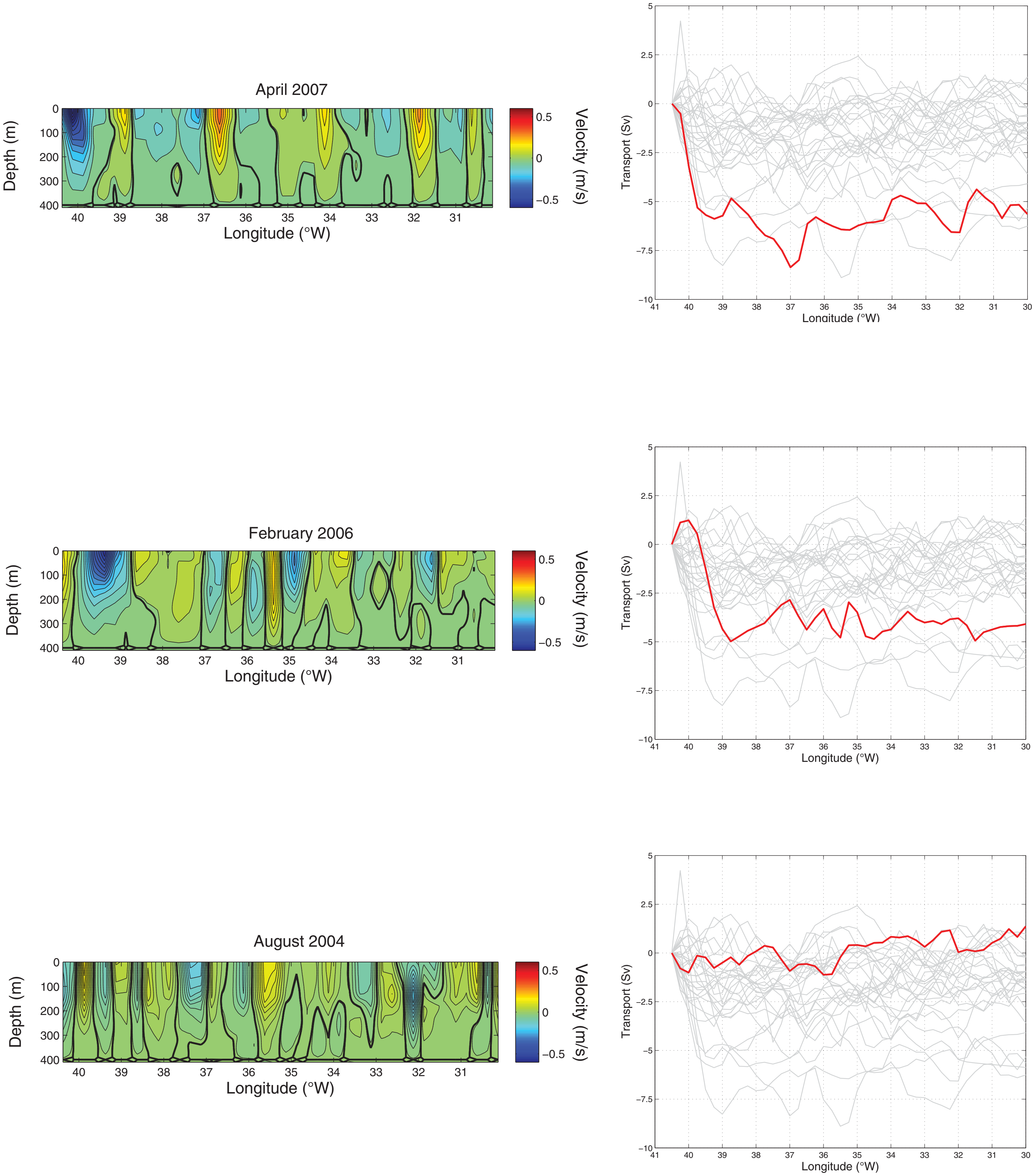


Fig 3: The baroclinic velocity field along the AX97 transect referenced to 400 dbar (left) and the corresponding zonally integrated transports (right) for the following cruises: (top) April 2007, (middle) February 2006 and (bottom) August 2004. The units are m.s-1 and Sv for the velocity field and transports, respectively. Negative values indicate southward flow and the zero velocity line is marked in bold.

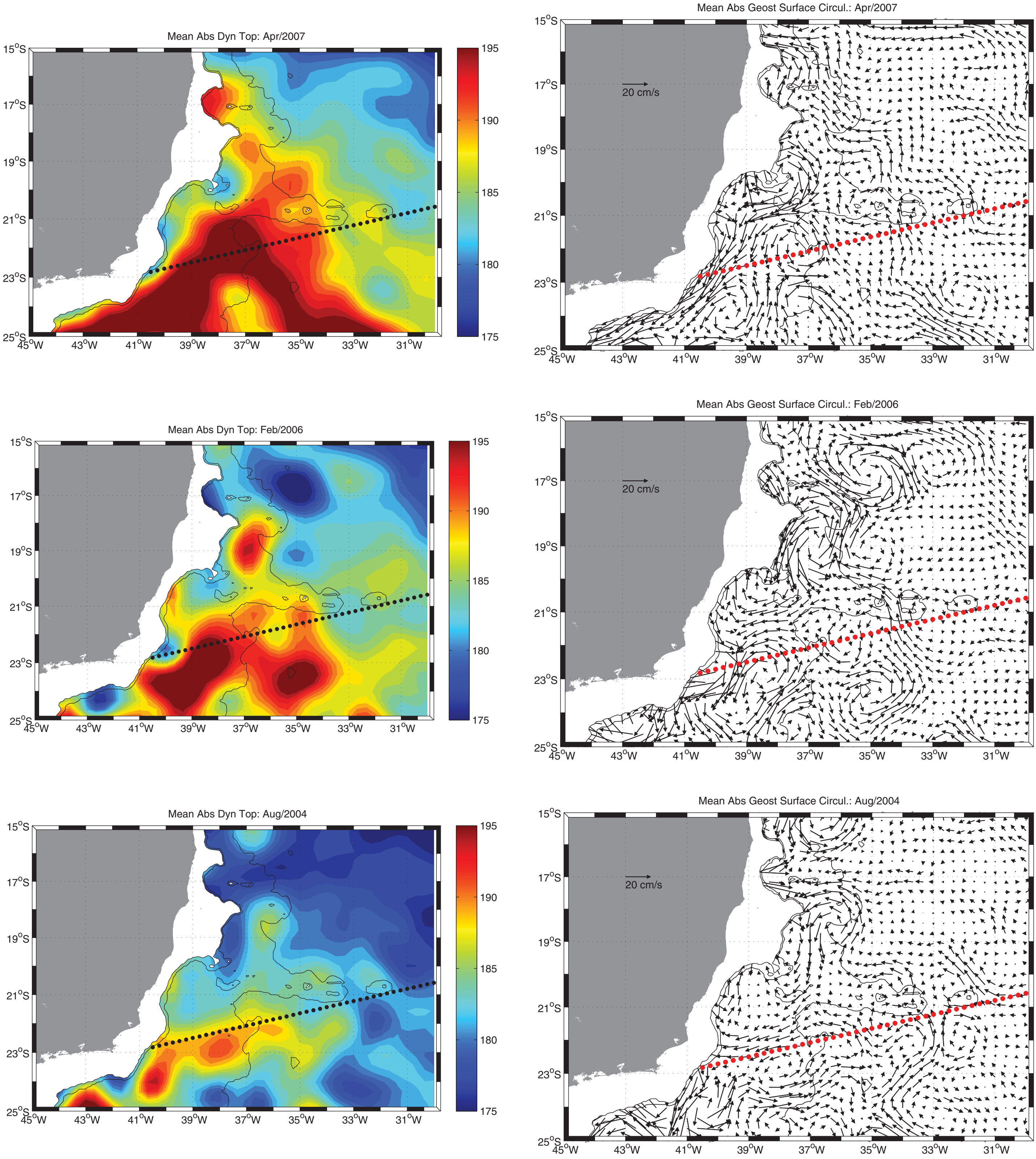


Fig 4: The regional Absolute Dynamical Topography field (left) and the corresponding surface geostrophic circulation (right) for the following cruises: (top) April 2007, (middle) February 2006 and (bottom) August 2004. The units are dyn.cm and cm.s-1 for the dynamical topography and surface geostrophic currents, respectively. The dots indicate the AX97 reference line.