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High-resolution regional ocean dynamics simulation in the southwestern tropical Atlantic

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ABSTRACT

The southwestern tropical Atlantic (05°S–25°S/20°W–47°W), where part of the South Equatorial Current (SEC) enters at its eastern border, is of particular interest as it is fed by many western boundary currents along the eastern Brazilian continental shelf. However, the long-term variability of the dynamics in this region, which are also important as they contribute to the climate over northeastern Brazil, is largely unknown. We use the Regional Ocean Model System (ROMS) here for the first time in this area to simulate the ocean circulation with an isotropic horizontal grid resolution of 1/12° and 40 terrain-following layers. As a primary evaluation of the ROMS configuration, we explore surface and vertical thermal structures, the surface mixed layer, and mass transports within the upper levels. Interannual variability results are compared with the first two-year series of observed thermal profiles derived from the three PIRATA-SWE moorings. The simulated thermal structure in the upper ocean layers agrees well with *in-situ* data. ROMS simulations point out a broad and relatively weak SEC flow composed of a sequence of more or less defined near-surface cores. The westward SEC transport for the upper 400 m along the PIRATA-SWE section, calculated from the ROMS simulation for 2005–2007, shows an average volume transport of 14.9 Sv, with a maximum observed in JFM (15.7 Sv), and a minimum during MJJ (13.8 Sv). ROMS results indicate that the 2005–2007 seasonal near-surface westward SEC transport is modulated by the zonal wind variability. Three zonal sections extending from the American continent to the PIRATA buoy sites confirm that stronger northward NBUC transport and decreasing BC transport were achieved during May 2006 and May 2007, *i.e.* at the time the sSEC bifurcation reaches its southernmost position. On the other hand, the maximum southward BC flow was verified during January 2006, January 2007 and March 2007, with a minimum northward NBUC flow in December 2005 and October/December 2006, corresponding to the period when the sSEC bifurcation reaches its lowest latitude (OND). Sea Surface Height (SSH) and the surface Eddy Kinetic Energy (EKE) derived from simulations and AVISO Rio05 product point out the highest surface meso-scale activity (EKE $\geqslant 50\ cm^2\ s^{-2}$) along the cSEC and NBUC/BC patches. Preliminary results provide additional ingredients in the complexity of the SEC divergence region and encourage us to conduct a more detailed exploration of the dynamics of this region using the ROMS. This also shows the need to continue, extend, and vertically upgrade the observational PIRATA-SWE array system, especially with more levels of salinity measurements and the installation of current measurements.

1. Introduction

Surface cold water formation in the North Atlantic and its subsequent plunging to feed the Northern Atlantic Deep Water (NADW), which runs out towards the South Atlantic, are relatively well known (Arhan et al., 1998; Stramma et al., 2005). Paradoxically, the warm counterpart, *i.e.* the subduction formation in the southern hemisphere of shallow warm water and its northward transfer across the equator, is less well understood. The South Atlantic Ocean is of prime importance in global climate change because there are a number of key zones where ocean signals on various timescales (from intraseasonal to decadal) must pass. In the southern subtropical Atlantic basin, which is subjected to both cyclonic and anticyclonic gyres strongly controlled by the surface wind (Stramma and Schott, 1999; Lumpkin and Garzoli, 2005), one can distinguish the following key zones, from South Africa to South America successively:

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(i) The Agulhas Current off South Africa, coming up from the Indian Ocean and propagating northwards while skirting the African coast;
(ii) the Benguela Current system, including the continuation towards the north of the previous current, and the regional cyclonic circulation within the Angola Dome region;
(iii) the subtropical Atlantic eastward circulation (15°S–20°S, 40°W–20°W), corresponding to an important area of warm and salty water formation by subduction that feeds the South Equatorial Current (SEC), itself formed by at least four easterly branches (the northern branch, nSEC; the equatorial branch, eSEC; the central branch, cSEC; and the southern branch, sSEC) separated by narrow regions of less obvious counter-currents (Stramma, 1991; Stramma and Schott, 1999); and
(iv) more westwards, the zone of divergence of the southern branch (sSEC) of the SEC as it approaches the Brazilian edge.

This latter region is partially responsible for feeding numerous current systems that border the Brazilian coast, towards either the north or the south. Towards the north, the cSEC and sSEC terminations form the North Brazil Undercurrent–North Brazil Current (NBUC–NBC) system, which is one of the most powerful western boundary currents in the world. This system participates in feeding a few other currents (Schott et al., 1995; Bourlès et al., 1999a,b; Stramma et al., 2005); among them, the northward Guyana Current, as well as the eastward North Equatorial Countercurrent and its associated complex retroflection system (Goes et al., 2005), and finally the eastward Equatorial Undercurrent (EUC). Stramma (1991) and Stramma and England (1999) showed that the NBC accounts for approximately one-third of the net warm-water transported across the equatorial tropical gyre boundary into the North Atlantic, compensating for the southward export of NADW. After the bifurcation close to the Brazilian shelf, the sSEC also feeds the Brazil Current (BC), propagating southward along the coast of Brazil (Stramma, 1991; Peterson and Stramma, 1991; Stramma et al., 1995) and meeting the Malvinas Current at about 35°S (Gordon and Greengrove, 1986; Olson et al., 1988; Garzoli and Garrafo, 1989), which itself is fed in part by cold water coming from the Pacific Ocean via Drake's passage.

The latitude where the sSEC bifurcation occurs is not well known, although it has been demonstrated from observation and model results (Silveira et al., 1994; Stramma et al., 1995; Rodrigues et al., 2007) that the North Brazil Undercurrent (NBUC) originates south of 10°S.

The SEC as a whole, where the present study is focused (Fig. 1), has a potential climatic influence in several remote regions: (i) mainly in the northward direction through its participation in the NBC–NBUC system and its derived complex system (Talley, 2003; Ganachaud, 2003; Lumpkin and Speer, 2003) and (ii) also in the southward direction through its effect on the Brazil–Malvinas Current confluence and the return of the South Atlantic gyre (Stramma and Peterson, 1990; Peterson and Stramma, 1991). Furthermore, as it is in the region of the southeast trade winds and the South Atlantic Convergence Zone (SACZ), interactions between sea surface temperature (SST) and the easterly atmospheric circulation may play a significant role in local climate fluctuations of northeastern Brazil, a region affected by intermittent severe droughts and floods (Moura and Shukla, 1981; Rao et al., 1993).

We are mainly interested here in analyzing the accuracy of a versatile new generation state-of-the-art Regional Ocean Modeling System (ROMS) as it reproduces some aspects of intraseasonal to interannual ocean dynamics in the region of the southernmost extent of the westward SEC. Thanks to its refined spatial resolution (1/12° = 9.25 km in latitude and longitude; 40 vertical levels, of which 20 are from surface to 500 m depth) one should expect that

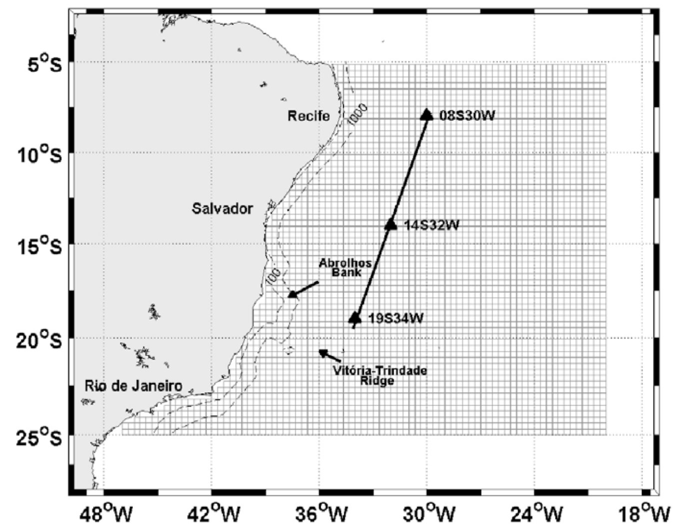

Fig. 1. Model domain (grid) and PIRATA-SWE buoy locations (triangles) along the western boundary. The 100 and 1000 m isobaths are represented by the two dashed lines. Section across PIRATA-SWE buoys (solid black line).

ROMS resolves the thermohaline properties and meso-scale dynamics in the study region that cannot be resolved when using OGCMs with lower resolutions.

We first compare the model results with both instantaneous and rare available long-term observations. Continuous subsurface observations in this study region were non-existent until the recently deployed ATLAS buoys in August 2005 as part of the South West Extension of the Pilot Moored Research Array in the Tropical Atlantic (PIRATA-SWE) (Servain et al., 1998; Bourlès et al., 2008; Nobre et al., 2005), which runs along the edge of Brazil's coastline south of the equator (Fig. 1). Therefore, this work intends also to refine the arguments for a continuation, and even extension, of the oceanic observing system in this region.

The main characteristics of ROMS and conditions of the interannual simulation are presented in the next section, while Section 3 gives some details of the PIRATA-SWE observation dataset. The ROMS evaluation is performed in Section 4 by comparing outputs of the model to high-frequency observed SST fields estimated by satellite, thermal structures and mixed layer depths provided by the PIRATA-SWE dataset. As a first dynamical application of ROMS, Section 5 shows examples of the simulated variation of mass transports across three zonal transects, and the section along the PIRATA-SWE sites. The last section presents a conclusion and perspectives.

2. The model simulation

ROMS is an ocean model (Shchepetkin and McWilliams, 2005) previously adapted to different regions of the world ocean (Haidvogel et al., 2000; Malanotte-Rizzoli et al., 2000; She and Klinck, 2000; Penven et al., 2000, 2001a,b; McCready and Geyer, 2001; Lutjeharms et al., 2003). The model solves the free surface primitive equations in an Earth-centered rotating environment based on the classical Boussinesq approximation and hydrostatic vertical momentum balance. ROMS is discretized in terrain-following vertical coordinates. The model grid, forcing, initial and boundary conditions were built using the ROMSTOOLS package developed by the Institut de Recherche pour le Développement (IRD) (Penven et al., 2008). Upstream advection is treated with a third-order scheme that enhances the solution by generating steep gradients as a function of a given grid size (Shchepetkin and McWilliams, 1998).