The Atlantic Equatorial Undercurrent: PIRATA observations and simulations with GFDL Modular Ocean Model at CPTEC

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[1] This paper shows the Atlantic Equatorial Undercurrent (EUC) revealed by a PIRATA ADCP during 2002 at 0°N, 23°W and simulated by an eddy-resolving ocean general circulation model (MOM) forced by NCEP/NCAR reanalysis wind stresses. The PIRATA data revealed the shallowing of the EUC between January and May, concurrently with the reversal of the easterly trades to westerly, and the deepening of the EUC from May to December. Empiric Orthogonal Function (EOF) analysis shows two main components; the first mode, explaining 63.7% of the total variance, represents the main seasonal variation of the undercurrent during 2002, while the second mode, explaining 19.9% of the variance, represents higher frequency variability occurring in the EUC core, from 60 to 80 m. All model experiments were able to reproduce this variability, and the best one was chosen objectively using EOF and joint EOF analysis techniques. **Citation:** Giarolla, E., P. Nobre, M. Malagutti, and L. P. Pezzi (2005), The Atlantic Equatorial Undercurrent: PIRATA observations and simulations with GFDL Modular Ocean Model at CPTEC, *Geophys. Res. Lett.*, *32*, L10617, doi:10.1029/2004GL022206.

1. Introduction

[2] The Atlantic and Pacific tropical oceans have been the focus of many studies due to their importance to regional and global climate variability. Intense oceanic zonal currents are observed in these regions. On the surface, the current structure consists of an eastward flowing North Equatorial Countercurrent bounded by the westward flows of the South Equatorial Current (SEC) and the North Equatorial Current (NEC) [*Weisberg and Weingartner*, 1988]. The strongest current, the Equatorial Undercurrent (EUC), is an eastward equatorial subsurface ocean current, which flows in the opposite direction of the trade winds at the surface, playing a crucial role on the dynamics of both oceans. For example, the well-known tropical instability waves, which act mixing and regulating some physical and biological properties of the equatorial oceans, have as one of their sources the barotropic instability energy from the EUC, NEC and SEC current shear.

[3] To better understand the dynamics and thermodynamics involved in the complex equatorial current system, observed data and numerical results are needed in order to learn about its processes and structure with certain accuracy. Many equatorial studies have been done so far. Some of them employ numerical models [e.g., *Wacongne*, 1990; *McPhaden*, 1993]. Also, model parameterizations have been tested and tuned on the equatorial current system [e.g., *Maes et al.*, 1997; *Pezzi and Richards*, 2003]. They have investigated the impact of the form of lateral mixing of momentum and tracers on the state of an equatorial ocean. A decrease in these coefficients increases the strength of the EUC.

[4] The Atlantic EUC has also been studied with the aid of observational data, from programs such as FOCAL/SEQUAL ("Programme Francais Ocean et Climat Dans l'Atlantique Equatorial/Seasonal Response of the Atlantic Ocean Experiment" [e.g., *Hisard and Hénin*, 1987]), and ECLAT ("Etudes climatiques dans l'Atlantique Tropical" [e.g., *Bourlès et al.*, 2002]). More recently, the "Pilot Research moored Array in the Tropical Atlantic" (PIRATA) project [*Servain et al.*, 1998] has generated temperature-salinity vertical profiles, current profiles, and surface meteorological data sets over the tropical Atlantic.

[5] The PIRATA program has ten ATLAS buoys moored in the tropical Atlantic and, in special, an ADCP (Acoustic Doppler Current Profiler) was added to the buoy site at 0°N, 23°W, and operated during the year of 2002.

[6] This paper analyzes the temporal variability of the EUC as revealed by the PIRATA ADCP during 2002. It will be shown that the "Modular Ocean Model", using a global tropical domain (40°S–40°N) and an eddy-resolving grid in the deep tropics, is able to reproduce the seasonal cycle of the Atlantic EUC at 0°N, 23°W.

2. PIRATA Data and Model Description

[7] The PIRATA ADCP daily data at 0°N 23°W, covering the year 2002, was smoothed with a 10 day running mean average to filter out high frequency variability. The current profile reaches a depth of approximately 140 m. The original vertical grid is 4 m spaced, and it was averaged to match the model grid.

[8] The model used for this work is the "Modular Ocean Model" (MOM) version 3 from the Geophysical Fluid Dynamics Laboratory (GFDL) and installed at CPTEC (Brazilian center for weather forecasts and climate studies). Global tropical oceans were considered, with the ocean basins limited at 40°N and 40°S. For the vertical resolution, 20 levels were adopted, 7 of them in the first 100 m, spaced by 15 m. The vertical mixing scheme chosen was based on *Pacanowski and Philander* [1981]. An eddy-resolving grid was set for the Tropical Atlantic, with 1/4 degree for latitudinal and longitudinal resolution between 10°N, 10°S and 60°W, 12°E, decreasing uniformly to about 3 degrees out of this area. The model was integrated for 30 years from Levitus climatology, forced with climatological wind stress

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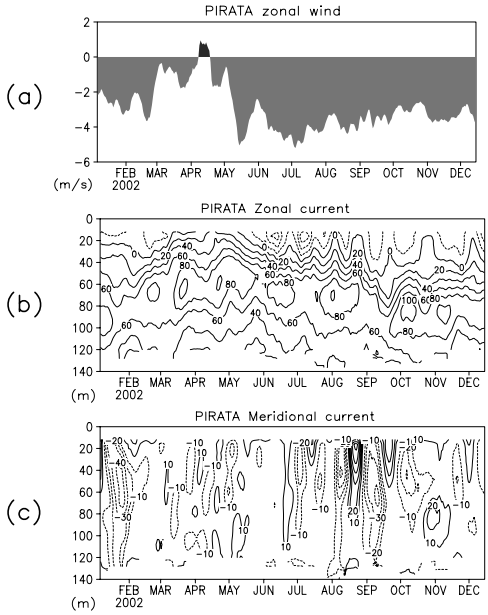

Figure 1. 10-day averaged PIRATA (a) surface zonal wind (m/s), and vertical current profiles of the (b) zonal and (c) meridional velocities (cm/s) at 0°N, 23°W from 6 January to 20 December 2002.

from the ECMWF analysis [*Trenberth et al.*, 1989], climatological solar radiation from *Oberhuber* [1988], and surface heat flux parameterized according to *Rosati and Miyakoda* [1988] bulk formulas. After the period of spin–up, the model was forced by monthly means of wind stress from the NCEP/NCAR reanalysis [*Kalnay et al.*, 1996] for the period January 1971 to December 2000. Finally, from January 2001 to December 2002, daily NCEP/NCAR reanalysis wind stress data was used to force the model. Daily model outputs for 2002 were then subjected to a 10 day running mean average.

3. Observed Undercurrent Variability

[9] Figure 1 shows the vertical profile of currents (Figures 1b and 1c) along the year, and the zonal wind (Figure 1a) measured by the ATLAS buoy at 0°N, 23°W. In the zonal component (Figure 1b), the surface current flowing westward (negative values) near the surface as well as the EUC flowing eastward (positive values) in greater depths can be observed. Between January and May, the easterly wind decreases, reducing the ocean surface westward flow, and the undercurrent moves upward, reaching the surface and reverting the surface flow. The core of the EUC moves then from 90 to 60 m depth. Conversely, from May to December, the EUC gradually moves downward. The maximum current speed is over 100 cm/s and is reached during October–November at the depth of 80 m. Besides this seasonal variability, there are other fluctuations in shorter time scales, which can be seen as an abrupt weakening of the zonal flow (e.g. events in September and October). The meridional component (Figure 1c), in turn, presents variability mainly in higher frequencies, with events where southward flows become northward flows in periods of 15 days (e.g. September and October). Note that these events are correlated to the mentioned abrupt weakening of the zonal component of the current shown in Figure 1b, thus representing variations in the undercurrent direction. The variations shown by the meridional component of the EUC are possibly related to the presence of tropical instability waves during that period [see, e.g., *Masina et al.*, 1999; *Pezzi and Richards*, 2003].

[10] Figure 2 shows results of an Empirical Orthogonal Functions (EOF) analysis of the PIRATA zonal current, using the correlation matrix EOF method (original data centered, and reduced to unit standard deviation). The first component, which explains 63.7% of the total variance, represents the main seasonal variation of the undercurrent during 2002. The eigenvector pattern shown in Figure 2 presents negative values in the upper ocean, a sign change around 75 m (the approximate mean depth of the EUC core during this period), and positive values at greater depths. The negative values of the time series between March and June correspond to the period when the surface current reverses, as a consequence of the EUC shallowing (Figure 1b). The second component, explaining 19.9% of the variance, represents the variability occurring in the EUC core. Sign changes occurring in its coefficient time series in periods of about a month (e.g. September–October) suggest that this EOF component includes those events of abrupt weakening of the EUC zonal flow.

4. Model Results

[11] A set of six numerical simulations was performed varying the lateral viscosity and diffusion coefficients (from 2×10^6 to 2×10^5 cm^2 s) and vertical viscosity and diffusion coefficients (from 1×10^5 to 1×10^3 cm^2 s) to adjust the model to the chosen grid resolution. In all experiments, the seasonal variability of the EUC – the main objective of this research — was reproduced. This fact is confirmed when individual EOF analyses of these experiments (figures not shown) are compared to the PIRATA data EOF analysis shown in the last section. For the first

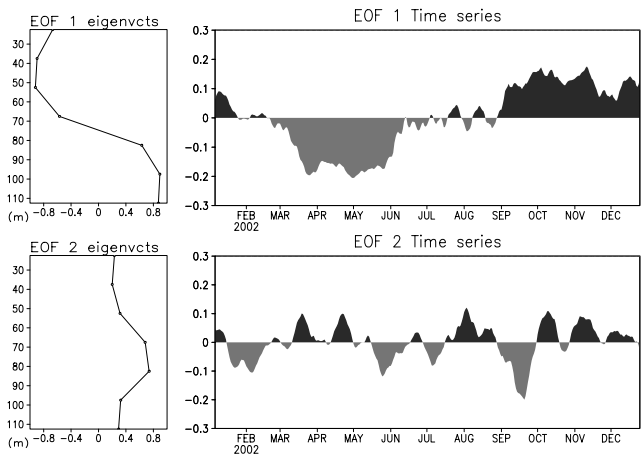

Figure 2. (left) Empirical Orthogonal Functions eigenvectors and (right) time series of coefficients related to the PIRATA zonal current data. Only two components are shown. (top) The first explains 63.7% of the total variance, and (bottom) the second explains 19.9% of the total variance.

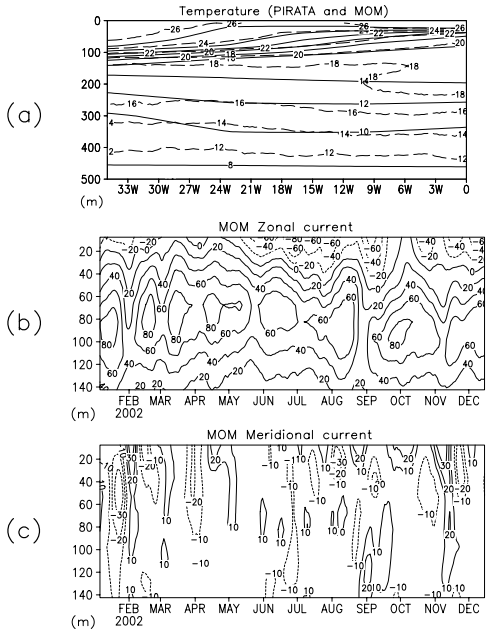

Figure 3. (a) Mean temperature profiles of PIRATA (solid lines) and MOM (dashed lines) in January 2002, in Celsius, at the equator and between 35°W and 0°E, and (b) MOM zonal and (c) meridional current in cm/s at 0°N, 23°W from 6 January to 20 December 2002.

component, the eigenvector pattern of each experiment is similar and the time series are well correlated (coefficients above 0.6) to the EOF computed with the PIRATA ADCP measurements.

[12] Figure 3 presents model results of the "best" simulation of the EUC strength and depth. The coefficient values are 2×10^5 cm^2 s for the "limiting" vertical diffusion and viscosity and 1×10^3 cm^2 s for the lateral viscosity and diffusion. In Figure 3a, the temperature mean profile along the equator, between 35°W and 0°E in January is compared to PIRATA observations (unfortunately, in 2002 only January has PIRATA data in all stations). There is a good agreement between the model and the data in the first 100 m, however, simulated temperatures are about 4°C higher than those observed at deeper waters.

[13] Concerning the zonal currents (Figure 3b), the simulated EUC is not as strong as that shown by PIRATA data, reaching speeds up to 90 cm/s at slightly deeper depths when compared to observations shown in Figure 1b. Yet, some of the seasonal features of observations were reproduced: the shallowing of the EUC between January and May, the decrease of the EUC magnitude in February and September, and the intensification of the EUC core in March, June, August, October, and November.

[14] Despite the good representation of the seasonal EUC variability in the zonal component, the meridional component simulated by the model (Figure 3c), mainly dominated by shorter time-scale fluctuations, has differences when compared to PIRATA component. This may be a consequence of the unrealistic representation of tropical instability waves by the model, which seem to present a clear signature in the PIRATA ADCP data shown in Figure 1c.

[15] This "best" experiment was chosen using the "joint EOF analysis", a technique used to identify common patterns of variability in two data sets. In this case, the difference is in the preprocessing stage: the model and the PIRATA data are joined before the EOF computation, and then the analysis results include the covariance between both model and observational data. Figure 4 shows the result of this analysis; there are eigenvector patterns for both PIRATA data and model results associated to only one time series. PIRATA eigenvector pattern differs slightly from the one obtained in separate analysis because of the model result influence. The chosen experiment presented the best similarity between the first EOF eigenvector patterns, especially in the upper 50 m.

5. Discussion

[16] In this work, the data provided by the ADCP at the 23°W, 0°N PIRATA site allowed a description of the EUC variability during 2002. Its mean position is 70 m, with maximum of 100 cm/s. The observational study of *Hisard and Hénin* [1987] described the core velocities of the EUC at 0°N, 23°W reaching 90 cm/s at a depth of approximately 80–90 m in January–February 1984, and 70–75 m depth in July–August 1984. These core positions agree well with those shown by the PIRATA data in Figure 1. However, *Bourlès et al.* [2002] showed observational evidence of the Atlantic EUC core at a depth of approximately 100 m during the boreal summer of 2000. Such depth of the EUC is probably anomalously deep, since there were other anomalous features observed during that period, e.g. the disappearance of the EUC at 6°E close to African coast in the boreal summer of 2000, which *Bourlès et al.* [2002] attributed to interannual variability of the EUC. In both papers, observations suggested that the core of the EUC at 23°W is deeper to the north of the equator than to the south of it.

[17] The Pacific has deeper thermocline and its EUC is stronger than its counterpart in the Atlantic [*Wacongne*, 1990]. Nevertheless, the Pacific EUC is highly affected

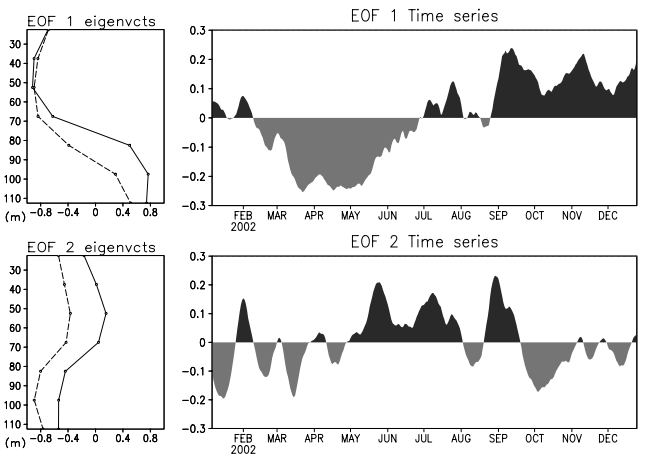

Figure 4. Joint Empirical Orthogonal Functions analysis: eigenvector coefficients for PIRATA (solid line) and MOM (dashed line) and the correspondent time series. Only two components are shown. (top) The first explains 46.7% of the total variance, and (bottom) the second explains 32.1% of the total variance.

during El Niño events, when the relaxation of the zonal slope of the Pacific thermocline causes the zonal pressure gradient, and hence the Pacific EUC, to disappear [*Philander*, 1990].

[18] Both PIRATA and modeled EUC present in 2002 a period of outcropping, some weeks after the minimum of zonal winds on surface. In fact, despite the interannual variability, the zonal surface winds in the western part of the equatorial Atlantic weaken seasonally between February–May, due to the southward migration of the Intertropical Convergence Zone (ITCZ). The implications of the weakening of surface winds in the EUC are discussed theoretically by *Philander* [1990]: a temporary decrease of surface winds, depending on the basin scale, leads to initial weakening and subsequent strengthening of the zonal pressure gradient, causing the EUC to decelerate and then accelerate. Numerical simulations by *Philander* [1990] using idealized winds with abrupt weakening and strengthening showed changes in the undercurrent depth and strength some weeks after the minimum of zonal winds. Besides, *Philander* [1990] also pointed out that if the trade winds, that maintain the EUC, experience and abrupt weakening, the unbalanced pressure force will result the shallowing of the EUC into a surface current, explaining the EUC outcropping which occurs in this situation.

[19] The OGCM results presented here, using a global tropical domain (40°S–40°N) and forced by daily reanalysis wind data, do reproduce the main seasonal variability of the EUC zonal component at 0°N, 23°W, as observed by ADCP data collected by the PIRATA Project during 2002. This OGCM is also used as the oceanic component of the ocean-atmosphere coupled model at CPTEC, and is currently being used to study climate variability and change over the tropical Atlantic and South America.

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