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Zonal jets in the equatorial Atlantic Ocean

Miquel Rosell-Fieschi, Josep L. Pelegrí *, Jérôme Gourrion [1]

Departament d'Oceanografia Física i Tecnològica, Institut de Ciències del Mar, CSIC, Barcelona, Spain

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A B S T R A C T

We use position data from Argo floats, smoothed out over 400 km × 200 km zonal ellipses and interpolated onto a 0.5° grid, to investigate the zonal jet structure of the flow field at the sea surface and on three subsurface layers (Central Waters, CW, 200 m; Antarctic Intermediate Waters, AAIW, 1000 m; upper North Atlantic Deep Waters, uNADW, 1500 m) in the equatorial Atlantic Ocean (15°S to 15°N). The annual-mean fields exhibit narrow zonal jets, typically 4–5° wide at the sea surface and only 2° at the subsurface levels, with directions alternating in latitude and maximum speeds about 0.5 m s^{-1} at the surface, 0.1 m s^{-1} at CW and uNADW, and 0.03 m s^{-1} at AAIW. The available data also allows us to explore the seasonal variability of these jets at the surface and AAIW levels. The surface currents are dominated by an annual cycle between 4°N and 10°N and, to a lesser degree, by a semi-annual contribution close to the equator. This variability is an outcome of evolving zonal recirculations, with the North Equatorial Countercurrent (NECC) arising from the diversion of the northern branch of the South Equatorial Current (nSEC); the diversion begins in the eastern Atlantic and propagates west between April and August, following the Inter-Tropical Convergence Zone (ITCZ). The AAIW current field is largely affected by westward propagating anomalies, most visible near 3°S, 0°, 3°N and 7°N, which give rise to current reversals. Annual averaging produces the illusion of more (5 instead of 3) and slower (peak values about 0.03 m s^{-1} instead of 0.1 m s^{-1}) jets than found on any month.

Introduction

The equatorial oceans are characterized by the vertical and latitudinal staggering of eastward–westward currents (Table 1). The presence of a complex pattern of alternating zonal currents, at surface and subsurface depths, was first observed through acoustic dropsondes in the Indian (Luyten and Swallow, 1976) and Pacific (Hayes and Milburn, 1980; Eriksen, 1981) Oceans, and later in the Atlantic Ocean (Ponte et al., 1990; Send et al., 2002). The Atlantic equatorial system was initially studied assuming geostrophic balance (Katz, 1981; Eriksen, 1982; Merle and Arnault, 1985) but near the equator geostrophy fails and its improved description demanded direct velocity measures from instrumented moorings (Send et al., 2002; Brandt et al., 2006; Bunge et al., 2006, 2008), ship-borne current profilers (including Acoustic Doppler Current Profilers, ADCP, and Lowered-ADCP, LADCP) (Gouriou and Reverdin, 1992; Send et al., 2002; Gouriou et al., 1999, 2001; Brandt et al., 2006), acoustically tracked buoys and/or profiling floats (Richardson and Fratantoni, 1999; Schmid et al., 2001; Ollitrault et al., 2006; Lankhorst et al., 2009), or a combination of multiple measurements (Urbano et al., 2008; Perez et al., 2013).

The first descriptions of zonal jets in the equatorial Atlantic dealt with the near-surface structures. The predominant surface current is the westward flowing Southern Equatorial Current (SEC), the rather wide northern branch of the South Atlantic subtropical gyre which merges with the wind-driven equatorial currents. This current is composed of three, poorly differentiated, branches: central (cSEC, about 3°S to 5°S), equatorial (eSEC, near the equator when present) and northern (nSEC, about 2°N to 4°N). All these branches merge onto the North Brazil Current, the northwestward flowing western boundary current (Stramma and Schott, 1999; Schott et al., 2004; Lumpkin and Garzoli, 2005).

The North Equatorial Countercurrent (NECC), the major surface zonal jet in the tropical Atlantic, has also received considerable attention (Garzoli and Katz, 1983; Richardson and McKee, 1984; Richardson and Reverdin, 1987; Carton and Katz, 1990; Didden and Schott, 1992; Richardson et al., 1992; Polonsky and Artamonov, 1997; Bourlès et al. 1999; Fonseca et al., 2004; Artamonov, 2006; Hormann et al., 2012). The NECC is characterized by an intense annual cycle, its transport ranging between non-significant late winter values and summer-fall maxima (throughout this article we will always refer to astronomical boreal seasons). The NECC is found between the sea surface and depths of about

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* Corresponding author.

[1] Present address: Centre National de la Recherche Scientifique (CNRS), Division Technique de l'Institut de Sciences de l'Univers (DT-INSU), Plouzané, France.

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350 m, at latitudes between 4°N and 8°N (with a northern branch reaching up to 10°N in fall), north of a zonal band of maximum positive sea surface height values. Urbano et al. (2006, 2008) have reported the NECC to have a double-core structure in the western Atlantic, which is best defined in the western margin during summer and fall.

The seasonality of the NECC has been related to the annual cycle in the surface winds, specifically to the curl of the wind stress, resulting from the latitudinal displacements of the Inter-Tropical Convergence Zone (ITCZ) (Garzoli et al., 1982; Merle and Arnault, 1985; Richardson and Walsh, 1986; Richardson and Reverdin, 1987; Arnault, 1987; Richardson et al., 1992; Urbano et al., 2006, 2008). Schouten et al. (2005) and Yang and Joyce (2006) have also associated the NECC variability to equatorial wind forcing and its generation of westward propagating waves.

Other major zonal currents are observed at subsurface levels, flowing east under the wind-driven westward SEC. These are the Equatorial Undercurrent (EUC), centered at the equator and 100 m depth, and the off-equatorial South/North Equatorial Under Currents (SEUC/NEUC), centered at some 150–200 m and 4°N/4°S (e.g. Metcalf et al., 1962; Tsuchiya, 1986; Stramma and Schott, 1999). The EUC feeds from the retroflection of the NBC, typically as a very tight loop near the equator (Flagg et al. 1986; Schott et al. 1998; Hüttle-Kabus and Böning, 2008; Claret et al., 2012). The strength of the EUC decreases as it flows east, with a maximum transport of about 20 Sv, while there are fewer reports on the spatial and temporal variations of the northern and southern branches (Gouriou and Reverdin, 1992; Bourlès et al., 1999; Schott et al., 2003, 2004; Brandt et al., 2006; Hüttle-Kabus and Böning, 2008). During spring the EUC surfaces and increases its speed (Brandt et al., 2006; Urbano et al., 2008).

Several authors have shown that zonal jets in the equatorial Atlantic are also found far from the sea surface (Gouriou et al., 1999, 2001; Richardson and Fratantoni, 1999; Bourlès et al., 2003; Schott et al., 2003; Brandt and Eden, 2005; Brandt et al., 2006). The circulation schemes by Stramma and Schott (1999), amended by Schmid et al. (2003) for intermediate waters, indeed emphasized the predominance of zonal jets at deep levels in the equatorial Atlantic region. Equatorial Deep Jets (EDJs), trapped between 2°S and 2°N, are found at depths between 300 and 2500 m. These jets have relatively short meridional scales, as little as only 1°, and display alternating directions on vertical distances of 400–600 m, with maximum velocities about 0.2 m s^{-1}. Their vertical structure is quite consistent through one same season but changes with season. The EDJs are surrounded by eastward columns of Extra Equatorial Jets (EEJs), sometimes named subsurface countercurrents (after Tsuchiya, 1986), located at about 3°S/N and extending from as shallow as 200 m down to near the sea floor. The EEJ velocity cores are found at the depth of the westward EDJs (about 500 m), suggesting the existence of elongated recirculation gyres as observed in the Pacific (Firing et al., 1998). Hüttle-Kabus and Böning (2008) proposed the eastward EEJs to feed on the subtropical cell via tropical instability waves from the EUC; these authors found that these flows are dominated by an annual and, to a lesser degree, a semiannual harmonic.

The introduction of Lagrangian buoys has substantially enhanced our skill to observe the horizontal coherence of the equatorial jets at several depths. Ollitrault et al. (2006) used acoustic drifters near 800 m and profiling floats parked at 1000 m to propose the existence of a system of rather narrow zonal jets, changing direction about every 2° in latitude: South Equatorial Intermediate Current SEIC (4°S), Southern Intermediate Countercurrent SICC (2°S), Equatorial Intermediate Current EIC (0°), Northern Intermediate Countercurrent NICC (2°N), and North Equatorial Intermediate Current NEIC (4°N). According to Ollitrault et al. (2006), the SEIC and NEIC flow west, the SICC and NICC flow east, and only the EIC reverses sign with season, westward in fall and eastward in winter. In Table 1 we include neither SICC nor NICC, as we will argue later that their differentiation from the SEIC and NEIC arises only from the seasonality of the intermediate currents (section ‘AAIW velocity variability’).

Lankhorst et al. (2009) combined Argo float and acoustic drifter data within intermediate (600–1050 m) and upper-deep (1200–2050 m) layers to look at the interaction between boundary and zonal flows. The northward flowing North Brazil Under Current (NBUC), which extends from under the surface mixed layer down to 1000 m (Stramma et al., 1995), could possibly be one main source for the eastward intermediate flows, although we will later present observations of seasonal changes in direction which point at the predominance of propagating anomalies. At the upper-deep level, the southward-flowing DWBC decreases in intensity as it interacts with the interior zonal flows.

In November 2007 the Argo program achieved its goal: over 3000 simultaneous profiling floats in the Global Ocean that drift at several depths and perform over 100,000 profiles per year, with a mean resolution of about one profile per year in a 60 km × 60 km grid. Presently, the dataset is large enough to map mean velocity fields at several water depths and even to examine the seasonal variability at surface and intermediate layers. In this study we use the equatorial and tropical Atlantic Argo data to describe the equatorial current system at four different levels (the sea surface and three additional drifting levels). The results confirm the existence of the zonal current system and give further insight into its spatial distribution, as well as its seasonal variation, at the surface and intermediate levels.

Data set and methods

Argo-inferred velocities

Only a few studies have obtained and disseminated an Argo-derived velocity data base (Ollitrault et al., 2006; Lebedev et al., 2007). Here we use a simple approach to produce our own data

Table 1
Major characteristics of the zonal jets in the equatorial Atlantic Ocean at surface and sub-surface levels.

Level	Current	Core latitude	Flow seasonal cycle (boreal seasons)
Sea surface	North Equatorial Countercurrent, NECC	5–8°N	East, with fall maximum up to 0.5 m s^{-1}
	Northern South Equatorial Current, nSEC	2–3°N	West, with summer-fall maximum up to 0.6 m s^{-1}
	Equatorial Under Current, EUC	0°	East at subsurface, surfaces in the western basin on summer reaching 0.3 m s^{-1}
	Central South Equatorial Current, cSEC	4°S	West with spring–summer maximum up to 0.4 m s^{-1}
1000 dbar	North Equatorial Intermediate Current, NEIC	3–4°N	West in spring, up to 0.07 m s^{-1}; east in fall, less than 0.05 m s^{-1}
	Equatorial Intermediate Current, EIC	0°	West in summer, up to 0.14 m s^{-1}; east in winter, up to 0.10 m s^{-1}
	South Equatorial Intermediate Current, SEIC	2–4°S	West in winter–spring, up to 0.07 m s^{-1}; east in summer-fall, up to 0.05 m s^{-1}
Sub-surface	Equatorial Deep Jet, EDJ	2°S to 2°N	Between 300 and 2500 m, alternate directions in vertical scales of 400–600 m, direction changes with season
	Extra-Equatorial Jets, EEJs	3°S and 3°N	From 200 m down to the sea floor