Circulation in the central equatorial Atlantic: Mean and intraseasonal to seasonal variability

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[1] The zonal equatorial circulation of the upper 700 m in the central tropical Atlantic is studied based on 11 cross-equatorial ship sections taken at 23–29°W during 1999 to 2005 and on data from a pair of moored Acoustic Doppler current profilers deployed on the equator at 23°W during February 2004 to May 2005. The observations on the equator reveal the existence of two mean westward cores of the Equatorial Intermediate Current below the Equatorial Undercurrent. In contrast to the 2002 moored observations at the same position the intraseasonal variability during the mooring period is dominated by zonal instead of meridional velocity fluctuations. **Citation:** Brandt, P., F. A. Schott, C. Provost, A. Kartavtseff, V. Hormann, B. Bourlès, and J. Fischer (2006), Circulation in the central equatorial Atlantic: Mean and intraseasonal to seasonal variability, *Geophys. Res. Lett.*, *33*, L07609, doi:10.1029/2005GL025498.

1. Introduction

[2] Different from the Pacific and even Indian Ocean, time series of equatorial currents covering a complete seasonal cycle did not exist from the central tropical Atlantic until quite recently. Apart from a frequently repeated ship section along 35°W with Acoustic Doppler current profiler (ADCP) observations from which mean transports were established for the western tropical circulation branches [*Schott et al.*, 2003], only individual shipboard ADCP sections are available for the tropical Atlantic from the time period prior to 2001 [e.g., *Bourlès et al.*, 2002; *Stramma et al.*, 2005].

[3] While for the near-surface flows seasonal cycles could be determined from drifter currents [e.g., *Lumpkin and Garzoli*, 2005] and altimetry [e.g., *Schouten et al.*, 2005], reliable transports and seasonal cycle analyses of the subsurface flows from the interior tropical Atlantic that could serve as a calibration base for model simulations have not become available. Recently, however, time series from moored ADCPs were obtained within the context of the Pilot Research Moored Array in the Tropical Atlantic (PIRATA) [*Servain et al.*, 1998].

[4] A first deployment on the equator at 23°W, covering the year 2002, was evaluated by *Provost et al.* [2004] and *Giarolla et al.* [2005] for the seasonal cycle of the upper 120 m with the major result that the EUC at 23°W shallows during January to May and deepens in the other part of the year. Remarkable intraseasonal variability was found in these observations. *Grodsky et al.* [2005], combining the ADCP time series with other PIRATA and satellite data, demonstrated that the 20–30 day band variability was dominated by Tropical Instability Waves (TIWs).

[5] Here we present two new sets of information from the central tropical Atlantic. First, we have composed a mean section of zonal currents at 23–29°W (called 26°W section in the following) and derived transports of circulation branches for the latitude range between 5°S and 5°N. Second, the upper-layer ADCP of the existing 23°W PIRATA mooring was augmented by a downward-looking "Longranger" ADCP, yielding now a total depth range covered from 12 m to 700 m.

[6] Here, for the first time, the question about the mean and seasonal existence of a westward Equatorial Intermediate Current (EIC) below the EUC is addressed using more than one year of mooring data. Besides the evaluation of the seasonal cycle on the equator of the upper 700 m the time series also allow a study of the structure and vertical propagation of intraseasonal variability.

2. Mean Flow

2.1. Mean Ship Section of Zonal Currents

[7] A mean section of zonal currents was constructed from ADCP measurements obtained in the time period 1999–2005. In the 11 sections used here, shipboard ADCP covered the depth range between about 30 m and some intermediate depth, depending on instrument type used. During some cruises an LADCP was applied additionally at intermediate depths below the depth range of the shipboard ADCPs. Above 30 m the mean flow field was linearly interpolated toward the mean surface flow obtained from the surface drifter climatology [*Lumpkin and Garzoli*, 2005]. The 11 sections consist of four from *Meteor* (Mar./Apr. 2000, 23°W between 5°S and 4°N; May 2002, 28°W between 5°S and 2.5°N; Oct./Nov. 2002, 24°W between 0°N and 5°N; Aug. 2004, 28°W between 5°S and 2°N), three from *Seward Johnson* (all Jan. 2000, 23°W, 25.5°W both between 5°S and 4°N; 28°W between 5°S and 0°N), and one each from *Thalassa* (Aug. 1999, 23°W), *Sonne* (May 2003, 28.5°W between 5°S and 2.5°S), *Ron Brown* (Aug. 2003, ~27°W), and *Polarstern* (Jun. 2005, 23°W upper 300 m).

[8] The resulting mean zonal current section (Figure 1) that represents an average of sections acquired between 23–29°W was then evaluated for transports in the same isopycnal layers that had previously been used for analyzing the mean 35°W section [*Schott et al.*, 2003]. As there is

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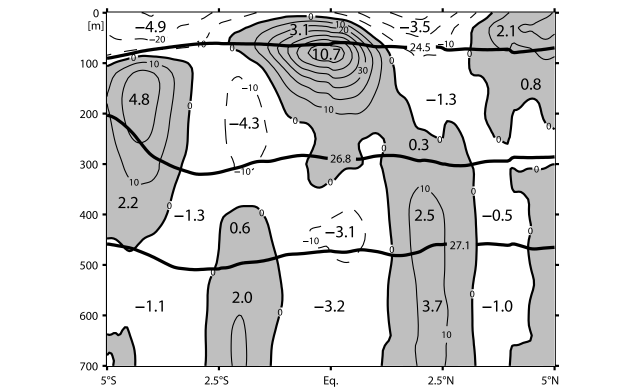

Figure 1. Mean zonal current distribution from 11 sections at 26°W (in cm/s), with layer transports (in Sv = 10^6 m^3s^{-1}) of different current branches overlaid on potential density (thick solid lines).

reasonable seasonal coverage of the available sections from the central tropical Atlantic, we expect only a minor seasonal bias. The EUC transports 13.8 Sv eastward, of which 3.1 Sv occur in the surface layer, above σ_θ = 24.5 kgm^{-3}, and 10.7 Sv in the thermocline layer 24.5–26.8 kgm^{-3}. The transports across the mean 26°W section can be compared with the transport across the mean 35°W section, in the western source region of the EUC.

[9] For this purpose the mean 35°W section of *Schott et al.* [2003], which was based on 13 ship surveys has been updated to 15 sections, now adding the subsequent *Sonne* and *Meteor* surveys of May 2003 and Aug. 2004, respectively. Furthermore, the top layer, for which *Schott et al.* [2003] extrapolated the ADCP shears to the surface, has been treated the same way as the 26°W section here, i.e., by applying mean surface drifter currents. The resulting mean EUC transport at 35°W amounts to 20.0 Sv, with 5.4 Sv above σ_θ = 24.5 kgm^{-3} and 14.6 Sv in the thermocline layer. While the mean EUC transport is about the same as the value of 20.9 Sv given by *Schott et al.* [2003], the combined effects of added cruises, different surface layer treatment, and reanalysis of earlier cruises result in a somewhat different distribution between surface layer and thermocline layer.

[10] The standard error of the estimated mean EUC transports at both longitudes was evaluated from the standard deviation of EUC transports calculated for each individual section under the assumption of independent individual realizations. The errors of the mean were determined to be 1.6 Sv at 35°W and 1.7 Sv at 26°W, respectively. Thus, there is a significant difference in the mean EUC transports: over about 1000 km of equatorial extent between both mean sections the EUC looses about 6 Sv.

[11] Underneath the EUC there is the westward core of the Equatorial Intermediate Current (EIC) transporting 3.1 Sv in the σ_θ = 26.8–27.1 kgm^{-3} density range. To either side of this westward flow, in latitude range 1–3°N and S, there are two narrow eastward cores, in correspondence to what was found at 35°W [*Schott et al.*, 2003], the Northern and Southern Intermediate Currents (NICC, SICC).

[12] The SEUC, with its core located at about 4.5°S and 160 m depth, transports 7.0 Sv eastward in the σ_θ = 24.5–27.1 kgm^{-3} density range, thus doubling its transport after leaving the 35°W section. The increase occurs solely in the σ_θ = 24.5–26.8 kgm^{-3} density range (from 1.3 to 4.8 Sv), while the lower thermocline layer stays almost constant (2.3 vs. 2.2 Sv). Inspection of the individual 9 sections that run to 5°S and extend to 500 m depth shows that the SEUC at 26°W actually extends southward to beyond 5°S, i.e., some transport fractions are lost in our average of Figure 1, and the SEUC increase along the way eastward from the 35°W section is even larger than our transport numbers express. Water mass properties indicate that the SEUC is not supplied out of the oxygen-rich and low-salinity NBUC, but is mostly made up of low-oxygen interior recirculation waters out of the SEC [*Schott et al.*, 1998], yet recognizable by admixtures of boundary waters [*Arhan et al.*, 1998].

2.2. ADCP Profiles on the Equator

[13] Mean profiles obtained by the upward and downward looking ADCPs at the equatorial 23°W mooring cover the depth range from 12 m to 700 m with a gap of 30 m between the two ADCPs at about 120 m depending on the rather small vertical mooring excursions. The mean profile of zonal currents (Figure 2a) shows the core of the EUC at 85 m, in good agreement with the corresponding profile of the mean ship section (dashed) from Figure 1. Below the EUC, the moored mean profile yields two depth ranges of significant westward flow with maxima of 7 cms^{-1} and 13 cms^{-1} at 250 m and 430 m, respectively. The standard error of the moored mean was estimated from the standard deviation and the degree of freedom determined from the autocorrelation of the time series. The time series from these core depths (Figure 3) show indeed that the zonal currents hardly ever reverse to eastward during the more than yearlong deployment. The occurrence of two westward

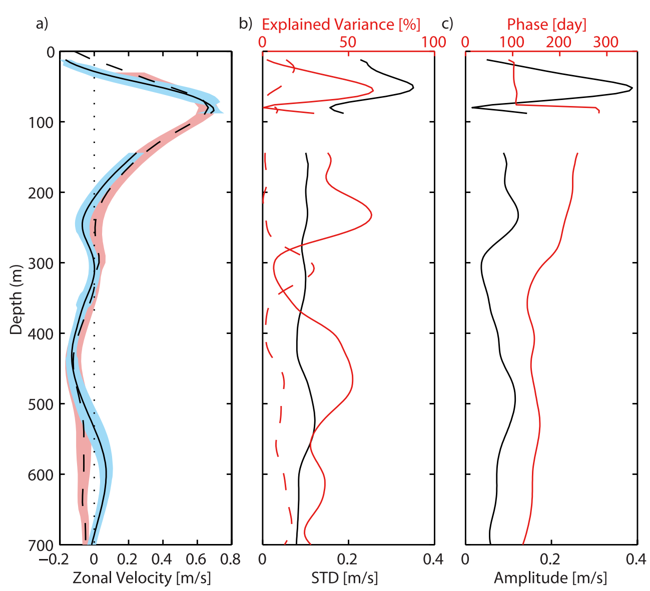

Figure 2. Equatorial profiles of zonal currents. (a) Moored mean at 23°W after subtracting annual harmonic (solid), its standard error (blue shaded), mean of ship sections at 26°W (dashed) and its standard error (red shaded). (b) Standard deviation (black solid) and explained variance of annual (red solid, top scale) and semiannual harmonic (red dashed, top scale). (c) Amplitude (black) and phase (red, top scale) of the annual harmonic.

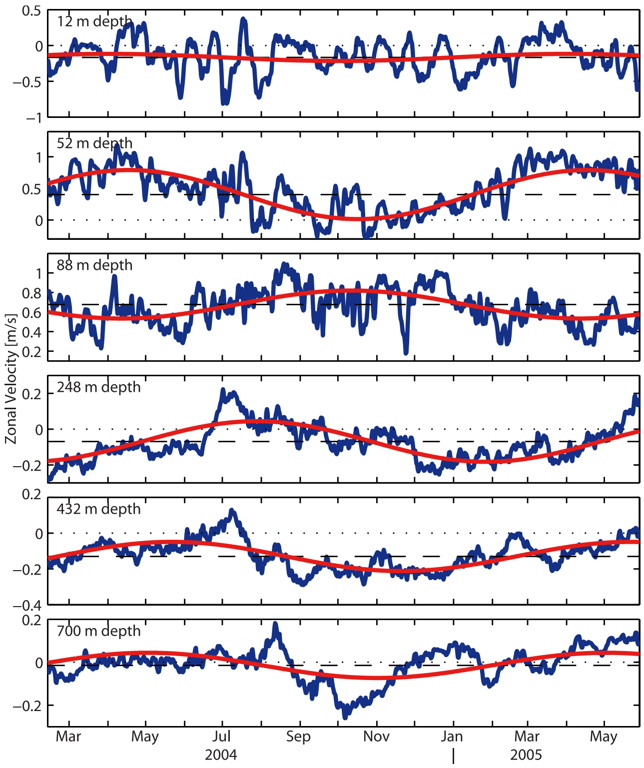

Figure 3. Time series of zonal velocity at 0°N, 23°W at different depths. Also given mean zonal velocity (dashed lines), and annual harmonics (red solid lines). Zero velocity is marked by dotted lines.

cores, an upper and a lower EIC, was suggested earlier for the Pacific by *Firing* [1987].

3. Seasonal Cycle

[14] The seasonal cycle of the moored zonal currents is dominated by the annual harmonic with minor contributions of the semiannual harmonic near the surface and at about 300 m depth (Figure 2b). There are strong maxima in the annual harmonic amplitude above and below the mean EUC core explaining more than 50% of the total variance in some of the 40-h low-pass filtered time series. The phase of the annual harmonic indicates maximum eastward flow during April/October above/below the mean EUC core, respectively. This behavior corresponds to an upward and downward movement of the EUC core at the equator. The vertical motion of the EUC has been associated with the seasonal cycle of the zonal wind field [*Provost et al.*, 2004], but a full dynamical interpretation is still pending. However, due to a shallower depth of the upward looking ADCP during 2004/05 compared to the prior deployment, currents were observed closer to the surface, with the first reliable bin at 12 m depth revealing a strong reduction of the annual harmonic amplitude toward the surface (Figure 2c).

[15] Below the EUC, two maxima of the annual harmonic are observed at about 240 m and 500 m. In this depth range, the annual harmonic generally shows an upward phase propagation (Figure 2c). A similar behavior of the annual harmonic was observed in shipboard data obtained along the 35°W section and was earlier explained as downward propagating Rossby beams, which exhibit additionally strong interannual variability [*Brandt and Eden*, 2005].

4. Intraseasonal Fluctuations

[16] Our observations during 2004/05 clearly show a dominance of zonal velocity fluctuations in the near-surface layer (Figure 4a) with particular enhanced levels of energy in the 20–30 days and 35–60 days bands. Calculating the coherence of the near-surface zonal velocity at 23°W with sea surface height anomalies everywhere in the tropical Atlantic (not shown), we found significant coherence for 45-day period fluctuations 2–3°N and S of the equator. For these fluctuations, the phase within the coherence pattern indicate westward phase propagation. Similar propagation patterns were associated with westward translating vortices by *Foltz et al.* [2004]. However, there is also a large patch of coherence at the equator between 30° and 40°W. This signal in the coherence is associated with eastward phase propagation. Thus, part of the intraseasonal fluctuations observed in the central equatorial Atlantic during 2004/05 may originate near the western boundary.

[17] Below the near-surface layer, zonal velocity fluctuations in the period range below the cut-off period of freely propagating Rossby waves, i.e., about 32 days, are strongly reduced. Instead meridional fluctuations dominate the short-period range of the spectrum (Figure 4b). The normalized wavelet energy of the meridional velocity component as

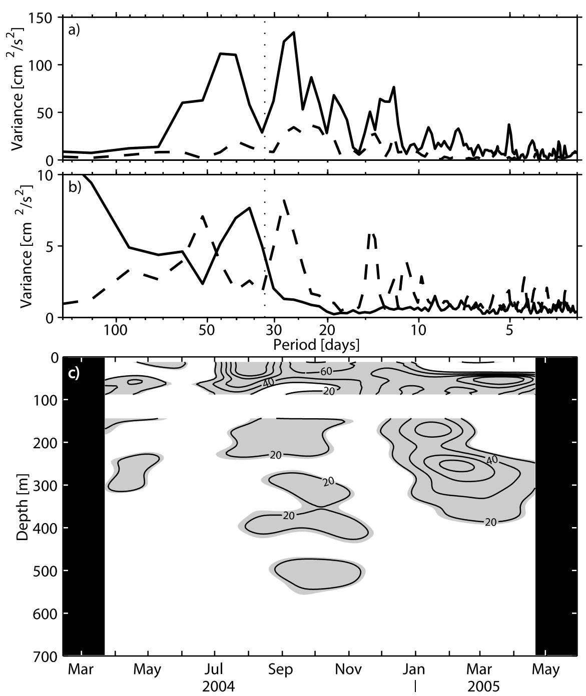

Figure 4. Variance conserving spectra of zonal velocity (solid lines) and meridional velocity (dashed lines) averaged (a) between 20 and 80 m and (b) between 200 and 700 m as well as (c) depth-time plot of the normalized wavelet energy of the meridional velocity for a period of 28 days. Dotted lines in Figures 4a and 4b mark the cut-off period of freely propagating equatorial Rossby waves. Gray shaded areas in Figure 4c are significant at the 95% level. Note the data gap at about 120 m in Figure 4c.

function of depth and time for the 28-day period (Figure 4c) indicates the presence of such intraseasonal fluctuations in the near-surface layer during boreal summer (July to August 2004) as well as during boreal winter (January to March 2005). In both cases a downward propagation of energy below the EUC can be observed. This semiannual cycle in the generation of meridional velocity fluctuations at the equator was also evident in the data from 2002 presented by *Grodsky et al.* [2005]. Earlier, *Weisberg and Weingartner* [1988] had already noted a semiannual cycle in the meridional shear of the zonal velocity with maxima in May and January. During their period of observations, however, only a very weak secondary maximum in the strength of meridional velocity fluctuations occurred in January.

5. Summary and Conclusions

[18] We composed a new mean cross-equatorial section of zonal currents at 26°W, based on 11 ADCP/LADCP ship sections, allowing the first mean transport estimates of the principal equatorial current branches in the central equatorial Atlantic. From an updated earlier mean zonal velocity section at 35°W near the western boundary [*Schott et al.*, 2003] and the new central equatorial Atlantic section, a reduction of the EUC transport by about a quarter is derived, suggesting substantial recirculation into westward flowing current branches surrounding the western EUC. Away from these recirculation cells in the western tropical Atlantic, the 23°W section seems to be an optimal place for studying the supply route of thermocline waters toward the eastern equatorial and off-equatorial upwelling regimes. As discussed by *Foltz et al.* [2003] for the seasonal cycle of the upper layer heat budget, zonal temperature advection is of particular importance for the cold tongue region during boreal summer. This might also hold for the interannual variability, with zonal advection contributing significantly to the zonal sea surface temperature mode, which is associated with interannual wind and rainfall variability of wide areas of the tropical Atlantic [*Kushnir et al.*, 2002].

[19] The repeated equatorial mooring at 23°W allowed estimates on the year-to-year variability in the strength of the EUC. We found a 10% reduction in the core velocity of the EUC from 77 cms^{-1} during 2002 to 70 cms^{-1} during 2004/05, which is hardly significant. Below the EUC, two westward flowing EIC cores were found. At these intermediate depths a strong seasonal variability is superimposed that explains up to half the variance in the moored time series. During 2004/05 the intraseasonal variability of moored velocity fluctuations was clearly dominated by zonal velocity fluctuations. Besides westward propagating fluctuations that were found in previous observations to be associated with TIWs and vortices [*Weisberg and Weingartner*, 1988; *Foltz et al.*, 2004], there is evidence for eastward propagating signals in the 35–60 days period band originating near the western boundary. The generally weak meridional velocity fluctuations in the near-surface layer during 2004/05 are in contrast to the very strong signals found during 2002 at the same position [*Grodsky et al.*, 2005]. This strong year-to-year variability in the appearance of intraseasonal velocity fluctuations might be the result of the interannual variability in the equatorial zonal current system. Geostrophic surface currents from altimetry (available at http://las.aviso.oceanobs.com/las/servlets/dataset) indicate strong westward current anomalies of nearly 50 cms^{-1} at the latitude range of the northern SEC during Dec. 2001 and Jun. 2002, while during 2004/05 much weaker signals were observed. The 23°W moored ADCP measurements are continuing with the promise of further insight into generation mechanisms of intraseasonal variability in the tropical Atlantic Ocean.

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