Chapter 3: Variability at Intermediate Depths at the Equator in the Atlantic Ocean in 2002-2005: Equatorial Deep Jets and Low-Frequency Meridional Flows

Abstract

Simultaneous time-series of high vertical resolution currentmeter measurements were obtained between 600 and 1700 m depths at two locations, 10ºW and 23ºW, on the equator in the Atlantic. The temporal mean zonal velocity component bears the characteristics of equatorial deep jets (EDJ, which have amplitudes of ~8 cm/s and vertical scale of ~500 m), is longitudinally coherent between the two locations and suggests a time-scale of 5 years. The zonal component also presents a downward-propagating signal with amplitude and vertical scale in the EDJ range and with a period of approximately 18 months, and a seasonal cycle with larger vertical scales than those of EDJ. At 23ºW, the meridional component presents low-frequency fluctuations of about 6 cm/s in amplitude and 600 m in vertical scale, which could be linked to EDJ and the presence of the Mid-Atlantic Ridge.

3.1. Introduction

Equatorial Deep Jets (EDJ) are characterized by vertically stacked alternating eastward and westward jets with small vertical scales (400-600 m in the Atlantic). They are confined to a narrow equatorial band (total width less than 3° latitude), and to depths between the thermocline and 2500 m (e.g. Gouriou et al., 1999; Bourles et al., 2003). Their zonal extent in the Atlantic Ocean has been estimated to reach 25º-27º (Gouriou et al., 2001; Schmid et al., 2005). Their

time-scale is controversial. Some authors suggest a periodic wave-like behavior with periods of at least 5 years (Johnson and Zhang, 2002), whereas others suggest an intermittent behavior (Send et al., 2002) of variable duration which may be as short as a few months (Bunge et al., 2006a).

EDJs as well as other semi-permanent currents at intermediate depths are potentially important features in the mass transfer of Antarctic Intermediate Water and North Atlantic Deep Water. Estimates of the transport of these two water masses along the equator by EDJs are difficult because the temporal nature of EDJs is unknown (permanent, oscillatory or intermittent).

We present here the first simultaneous time-series of high vertical resolution current meter measurements at intermediate depths (600-1700 m) at two locations on the equator, 10ºW and 23ºW. This exceptional data set provides some insight into the temporal nature of EDJs as well as allowing new estimates of the amplitude and phase of the annual cycle at intermediate depths. Furthermore, for the first time at these latitudes and depths, low-frequency meridional flows with small vertical scales have been detected.

3.2. Data

The data consist of 2 years of horizontal velocity measurements gathered by Vector Averaged Current Meters (VACMs) at intermediate depths (600-1700 m) at 23ºW and 10ºW. At 10ºW, the two year long time series are continuous from May 2003 to June 2005. At 23ºW, the time series are discontinuous: a first period is from December 2001 to December 2002 and a second period from February 2004 to May 2005. Thus, the two sites were instrumented simultaneously from February 2004 to May 2005.
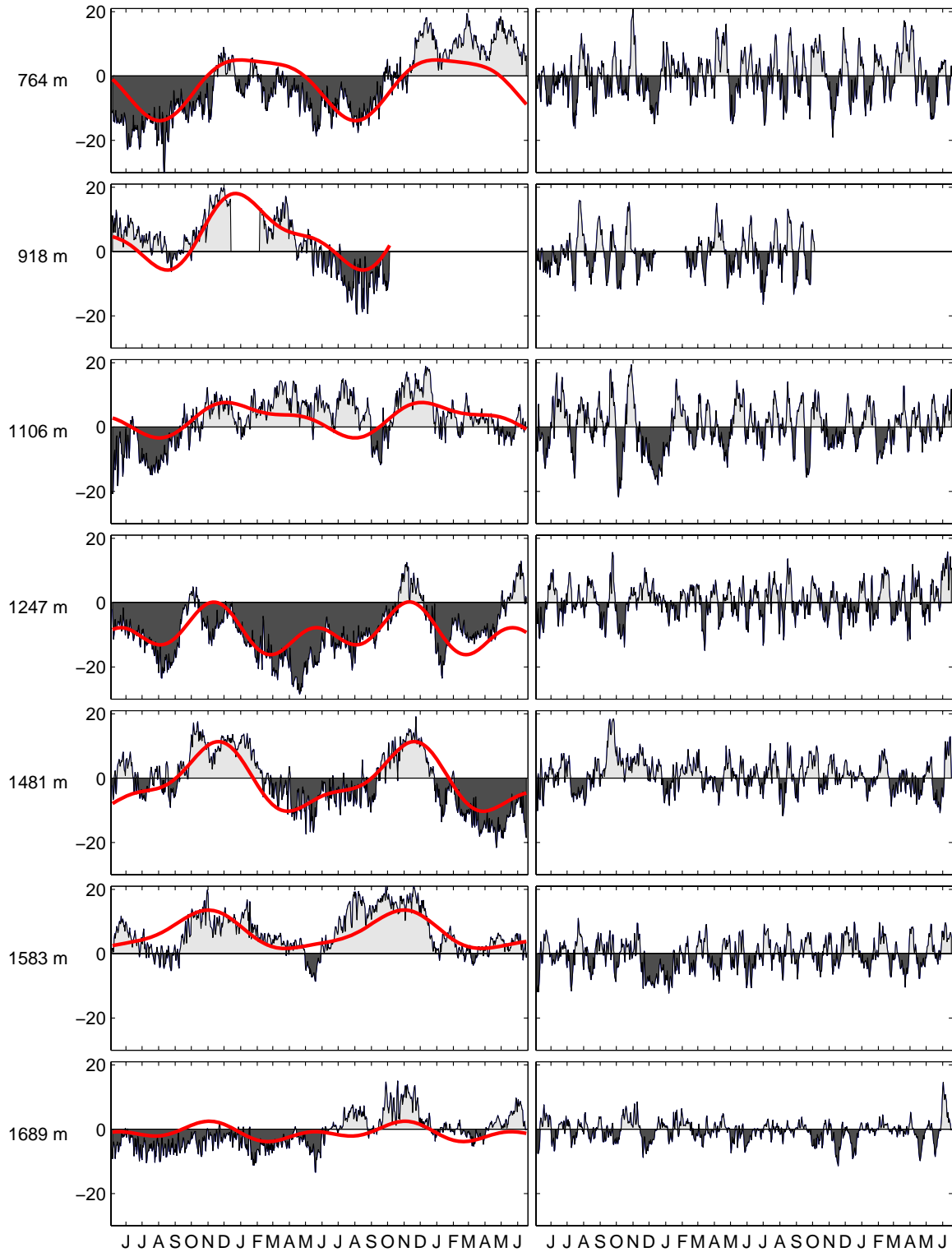
Figure 1: Velocity data from 10º W and the equator. Left panel: zonal velocity component and least square fit (red). Right panel: meridional velocity component. Depth of the instruments is indicated to the left. X-axis indicates time in months starting in May 2003 (duration May 7, 2003 – June 17, 2005). Y-axis indicates velocity in cm/s.
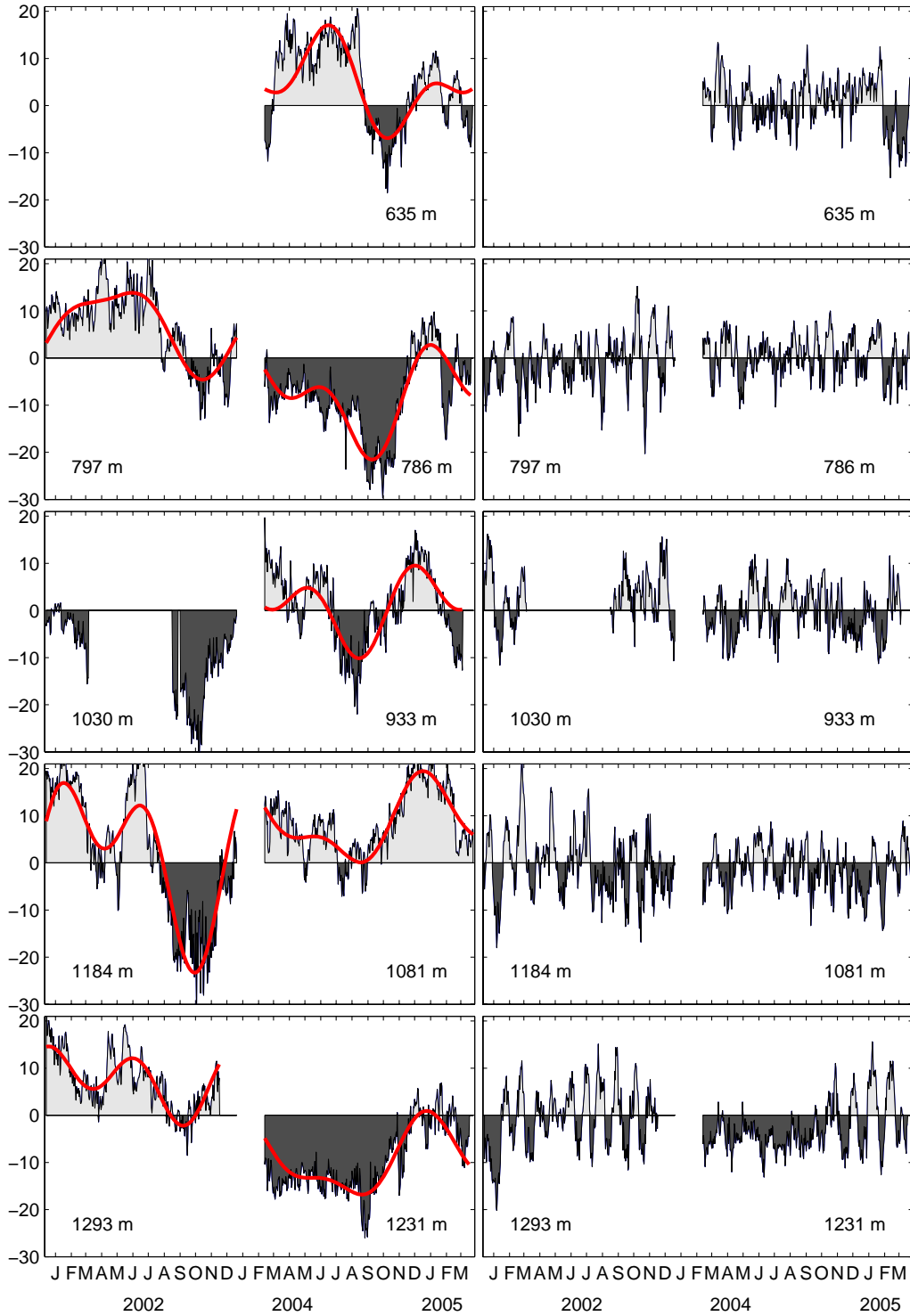
Figure 2: Velocity data from 23° W. Left panel: zonal velocity component and least-square fit (red). Right: meridional velocity component. Depth of the instruments is indicated below each time series. Note that depths of instruments in the same panel may vary. *X*-axis indicates time in months from December 2001 to March 2005. Note that the time line is not linear; there is a gap in the data from December 2002 to February 2004. *Y*-axis indicates velocity in cm/s.

The VACMs were calibrated at the Institut français de recherche pour l'exploitation de la mer (Ifremer), in Brest, for velocity and pressure; details of the data calibration and validation can be found in Kartavtseff (2003), Kartavtseff 2004, and Kartavtseff (2006). The hourly data were averaged over 25 hours to remove tidal frequencies and re-sampled to provide daily resolution (Fig. 1 and 2).

3.3. Zonal Component

3.3.1 Equatorial Deep Jets

The signature of the EDJs, vertically stacked alternating eastward and westward jets with vertical scales of about 500 m and peak-to-peak amplitudes of more than 10 cm/s, was detected in the temporal mean zonal velocity profiles (Fig. 3). Mean zonal velocity profiles at 23ºW and 10ºW for the common period of time (February 2004 to March 2005) presented eastward and westward jets at approximately the same depths, suggesting continuity of the jets between 23ºW and 10ºW, in agreement with previous observations (Gouriou et al. 2001; Schmid et al. 2005). In contrast, the zonal mean velocity profiles at 23ºW (years 2002 and 2004-2005) showed jets with opposite direction at approximately 800 m, 1100 m, and 1300 m, demonstrating the non-permanent nature of the jets. Furthermore, the zonal mean profile using the entire time series at 10ºW (May 2003 to June 2005) showed an intermediate configuration of the jets between 800 m and 1100 m, when compared to the mean profiles at 23ºW for the year 2002 and 2004 (Fig.3). This evolution of the zonal mean profile with time (at 23ºW, jets with opposite direction in 2002 and 2004; at 10ºW, an intermediate configuration of the jets between 800 m and 1110 m in 2003), suggests a time scale for these jets of approximately 5 years, which is consistent with time-scales estimations from LADCP sections (Johnson and Zhang, 2002).
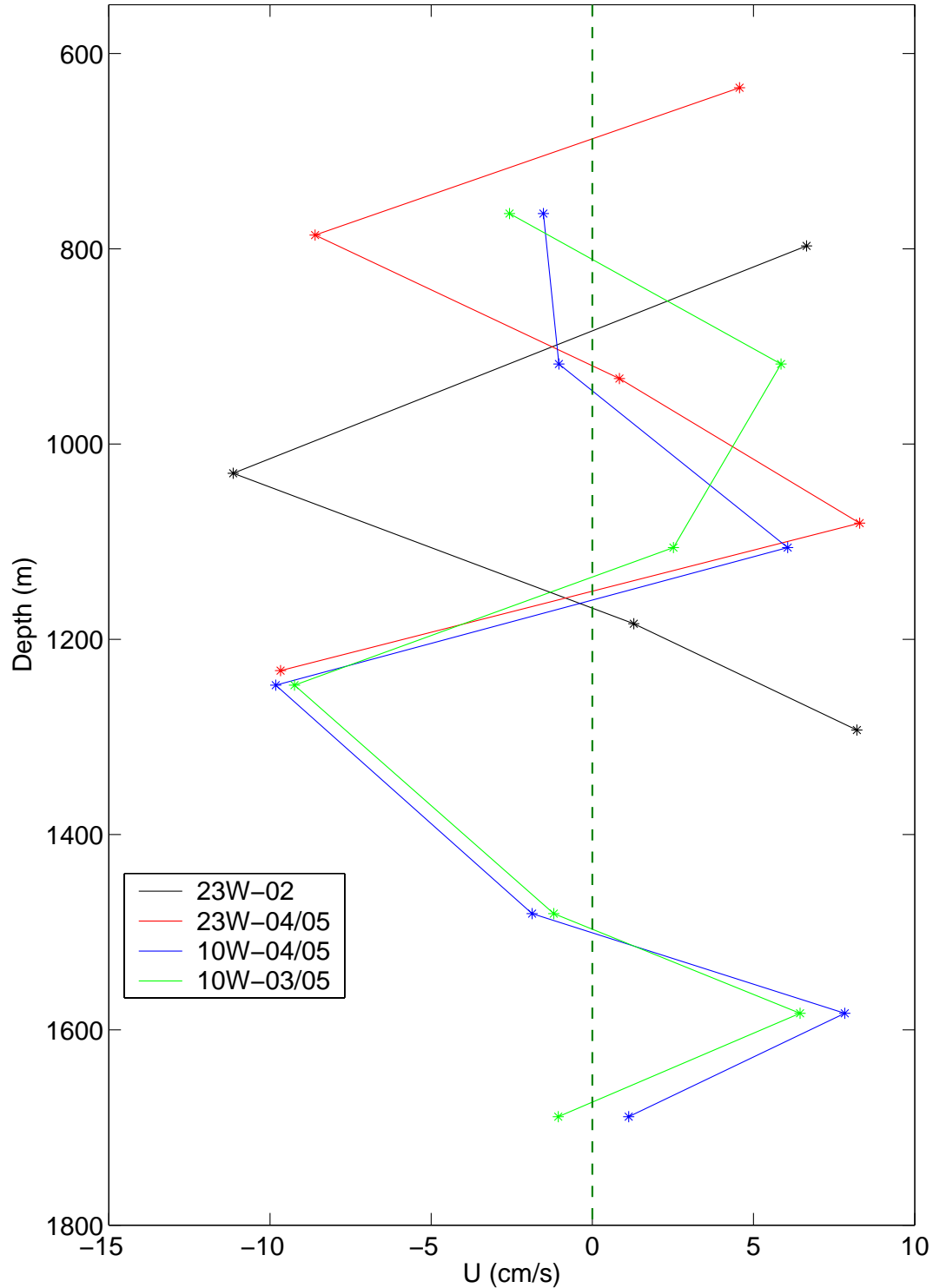
Figure 3: Mean zonal velocity component after extracting the seasonal and semiseasonal harmonics. Green: 10º W for the entire 25-month record; blue: 10º W from February, 2004 to March, 2005; red: 23º W from February, 2004 to March, 2005; black: 23º W for 2002. Positive is westwards, negative eastwards. Note that the time-series from 10º W at 930 m and from 23º W at 1030 m have gaps (cf Fig. 1 and 2); the mean in that case is computed from the available data (blue and green and black curves).
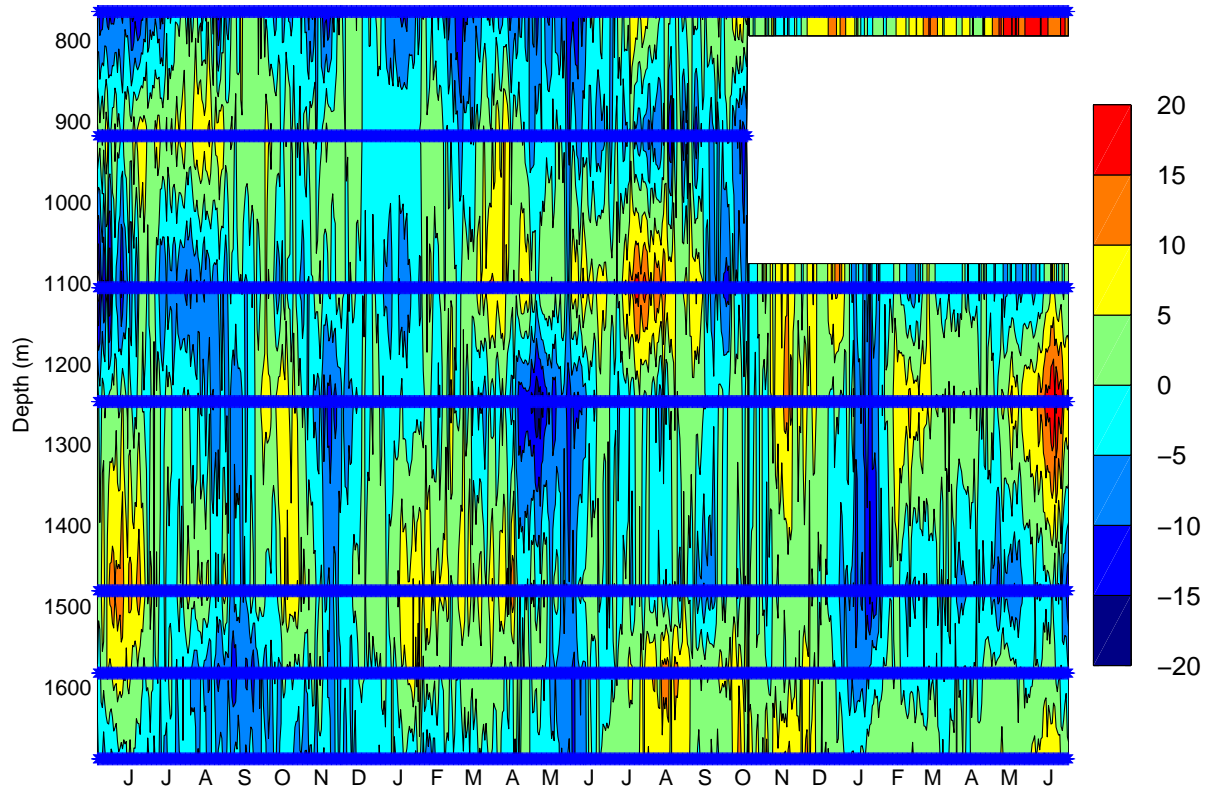
Figure 4: Zonal velocity component anomalies at 10º W. The temporal mean and the seasonal and semiannual signals have been subtracted. Horizontal lines indicate the depth and the length of the time-series. Positive is westwards, negative eastwards. *X*-axis indicates time in months from May 2003 to June 2005.

The other signal with the EDJ imprint in this data set became clear after removing the mean, seasonal, and semiannual signals (Figs. 1 and 2) from the time-series at 10ºW. Figure 4 shows a downward propagating signal with vertical scales of approximately 500 m. The downward phase velocities are reminiscent of the changes in EDJ depths with longitude observed by Schmid et al. (2005), who suggested that vertically propagating, equatorial trapped waves could lead to the alternating sign in the velocity profiles typical of EDJ. The downward propagation began around October 2003 and lasted until the end of the measurements (June 2005). A downward phase speed of roughly 330 m over 12 months ($c=1.06\times10^{-5}$ m/s) could be deduced from data as well as

a vertical wave number $m = 2\Pi / 500$ m^{-1} and a frequency $\omega = cm$. Thus, the period of these signals is about 18 months.

At 23ºW, vertical propagation was unclear (not shown). This may be because the data sets at 23ºW are shorter in time as well as in vertical extent than the data set at 10ºW (1 year and 496 m or 596 m, compared to 2 years and 925 m). Instead, the residues at 23ºW suggested variability with time-scales on the order of a few months. Bunge et al. (2006a) found time-scales of ~7 months for the EDJ at 10ºW from a 1-year-long time-series. The propagation pattern observed in Figure 4 is noisy. Note that examination of one year of the 2-year data set at 10ºW, between February 2004 and February 2005 (Fig. 4), for example, could lead to the mistaken conclusion that EDJs lasted only a few months because the propagating signal was only observed during a few months at a particular depth.

3.3.2 Semiannual and Annual Cycle

Together with the EDJs, a seasonal signal of large vertical scale is observed in the zonal velocity component. A sinusoidal curve containing annual and semiannual harmonics was fitted to the data using the least-squares method (Figs. 1 and 2). Table 1 indicates the amplitude, phase and percentage of variance explained by each harmonic and by their sum. Even though time series are short for the estimation of an annual signal, the phase of the annual signal estimates present a coherent structure in the vertical, providing confidence to the analysis.

With a few exceptions, the annual harmonic was more important than the semiannual harmonic in both locations (the exceptions are at 10ºW and 1247 m and at 23ºW and 1293 m – see Table 1). The annual harmonic had maximum amplitudes of about 10 cm/s, and presented upward phase propagation in all three datasets. This upward phase velocity propagation was

consistent with a downward-propagating odd meridional-mode Rossby beam, as already

observed in models and other data (e.g. Brandt and Eden, 2005; Thierry et al. 2006).

Instrument depth (m)	Amplitude (cm/s)		Phase (days)		Percentage of explained variance		
	semi-annual	annual	semi-annual	annual	semi-annual	annual	total
10ºW 2003-2005							
764	2	9	-109	29	2	39	42
918	4	10	-50	17	10	56	67
1106	2	4	-97	12	3	18	22
1247	5	4	-91	-67	20	13	35
1481	3	9	-58	-56	5	54	62
1583	1	6	-99	-68	1	40	43
1689	2	2	-102	-80	6	6	13
23ºW 2004-2005							
635	6	8	-9	139	19	38	58
786	6	8	-23	44	18	42	67
933	6	6	-81	25	23	26	51
1081	4	8	-41	2	13	56	72
1231	3	8	-24	5	8	53	65
23ºW 2002							
797	3	9	16	111	6	61	67
1030	-	-	-	-	-	-	-
1184	11	13	0	80	34	46	81
1293	6	4	-43	50	41	25	67

Table 1: Semiannual and annual cycle: amplitude, phase and amount of explained variance (in percent). The first number in each principal column refers to the semiannual fit and the second number to the annual fit. In the last column the third number refers to the percentage of explained variance combining the semiannual and annual fits. The phase is estimated in days with respect to January 1, 2003. The percentage of explained variance is computed as one minus the ratio of the variance of the residuals over the variance of the original series.

In velocity data from 2003-2005, at depths where the seasonal signal was important (i.e. explaining a large amount of the variance (see Table 1), phases varied similarly with depth at both locations (a phase of about 30 days at ~800 m; 10, at ~ 1100 m; and 70, at 1600 m), suggesting a coherence in the signal between 10ºW and 23ºW. The coherence failed, however, for the record at 635 m and 23°W. The 635-m zonal velocities were eastward during the boreal winter as in all other 23ºW time-series. However, unlike the other 23ºW time series, the 635-m

zonal velocities presented a very energetic eastward event of 6- months duration in the boreal spring and summer, which we believe biased the resulting phase of the annual cycle fitting. The 6-month eastward flow was most probably not related to an annual cycle, since it showed no coherence with the annual signals in the data from greater depths (Fig. 2). The seasonal cycle in 2002 at 23ºW also showed different phase when compared with the seasonal cycle in years 2004-2005 at the same location. Those differences are of about 60 days when comparing similar depths between the two intervals of time. We cannot be certain on whether those differences are the result from incertitude on the method or from intraseasonal variability. However, the consistency among phase shifts in the vertical between the two intervals of time at 23ºW, suggests that the observed differences could be the result of interannual variability.

In summary, at about 800 m depth, the data from 2003-2005 bore a seasonal cycle with maximum eastward velocity during the boreal winter and maximum westward velocity during the boreal summer. Below, at about 1600 m depth, maximum eastward velocities occurred in the boreal fall and maximum westward velocities occurred in boreal spring. At 23ºW in 2002, the phase of the seasonal signal at 800 m showed maximum eastward velocities during boreal winter-spring and maximum westward velocities during boreal summer-fall. Other observations of the annual cycle at 800m depth in the center and the west of the basin indicate eastward velocities during the boreal winter and westward velocities during the boreal fall (Ollitrault et al., 2006) and eastward velocities in the boreal summer and westward velocities in the boreal fall (Schott et al., 2003). Comparisons of our results with the results of these two papers are difficult since 1) we have a difference of about 60 days in the annual cycle phase estimation depending on the year analyzed and 2) the annual cycle in the papers mentioned above is not symmetric along the year (i.e. maximum eastward and westward flows do not occur on opposite seasons of the

74

year). Nonetheless, below 1300 m, the seasonal cycle certainly varies from the west to the east of the Atlantic Basin. Indeed, the two-year-long series of VACM measurements between 1300 m and 1900 m depths at 35ºW discussed by Send et al. (2002) showed no annual signal at all whereas Thierry et al. (2006), in a 2-year VACM series at 1700 m and 15ºW, found similar amplitude and phase to the signal derived here from the record at 1689 m at 10ºW. Finally, a linear regression using values from Table 1[*] led to rough estimates of the parameters of the annual cycle: a phase velocity between 9.7×10^{-5} ms^{-1} and 6.9×10^{-5} ms^{-1} and a vertical scale between 2190 m and 3066 m, a much larger vertical scale than that of the EDJs.

The semiannual signal was more important at 23ºW than at 10ºW (Table 1). The vertical phase structure was complicated, since it changed direction with depth (Table 1). For example, at 23ºW for the measurements of 2004-2005, the phase propagation was upwards between 635 m and 933 m and downwards between 933 m and 1231 m. Thierry et al. (2006) found similar phase changes in the water column, but the reason for that behavior remains unclear.

3.4. Mean and Low-Frequency Signal in the Meridional Velocity Component

The mean meridional velocity component was small (less than 1.5 cm/s), except at 1231 m at 23ºW, where it reached 3 cm/s. Indeed, the meridional velocity component at 1231 m in the year 2004 showed southward velocities for over 7 months (Fig. 2). Although periods less than 50 days dominated the variations in the meridional velocity at both locations, vertically coherent flows at longer time-scales were observed at 23ºW, especially on data from 2004-2005. A 50-day low pass filter was applied to the residual meridional velocity, once the mean was taken out. The low-pass filtered time series (Fig. 5), revealed fluctuations with amplitudes reaching 6 cm/s, an

---

[*] Values corresponding to VACM at 630 m at 23ºW and at 1247 m at 10ºW were not used for the linear regression.

upward phase propagation, a vertical scale of ~600 m and a period of about 10 months. The values for the time and vertical scales are rough estimations, since the time duration of the series as well as the vertical extent are not long enough to resolve those scales properly. With these cautionary remarks in mind, to our knowledge, no such flows in the meridional component with such small vertical scales have been reported yet.
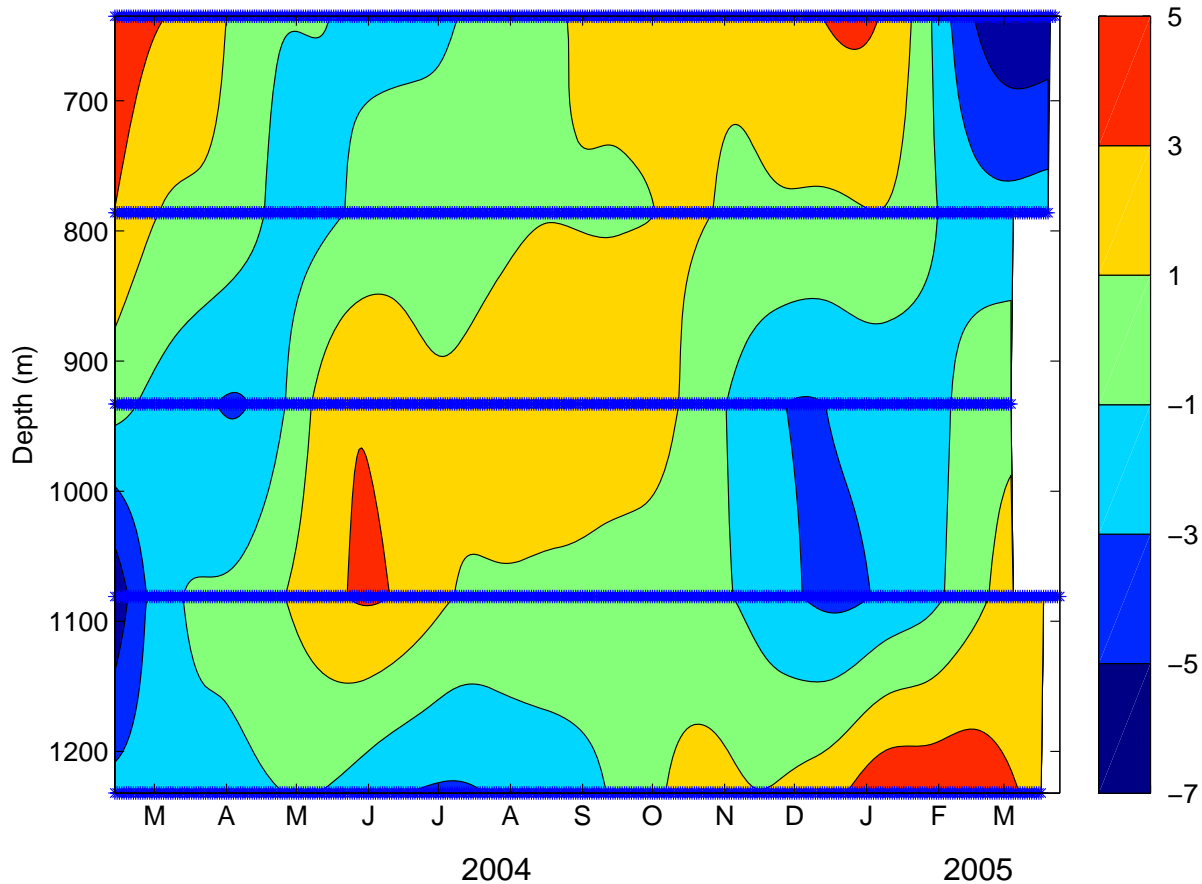

Figure 5: 50-day low pass filtered meridional velocity component anomalies at 23º W for the years 2004-2005. The temporal means have been subtracted. Horizontal lines indicate the depth and the length of the time series. Positive is northwards, negative southwards. *X*-axis indicates time in months from February 2004 to March 2005.

One of the differences between 10ºW and 23ºW is the presence of the Mid-Atlantic Ridge at 23ºW. McPhaden and Gill (1986) studied the scattering of low-frequency, equatorial Kelvin-wave energy by a submarine ridge. They found that the presence of a submarine ridge in the path

of propagation of a Kelvin wave induced meridional motions. The model they used was of very low vertical resolution and their results cannot be compared with these data. However, we suggest that more work on the lines of McPhaden and Gill's (1986) could help to explain the low-frequency fluctuations observed in the meridional component.

3.5. Discussion

The difficulties in establishing an appropriate time-scale for assessing the variation in the parameters of EDJs through observations resides in the lack of long time-series of data with high vertical resolution. The mooring at 10ºW provided the data set with the longest duration and high vertical resolution for the depths sampled at the equator. The results from these data suggested that different features sharing similar vertical scales and amplitudes and different time scales coexist, along with a seasonal cycle with a much larger vertical scale. A numerical model (D'Orgeville et al., 2006) based on a recent theory of the mechanism of EDJ formation (Hua at al., 2006) suggests that the instability of mixed Rossby–gravity waves at the equator forced by the Deep Western Boundary Current may trigger small vertical-scale zonal flows. In the model presented by D'Orgeville et al. (2006), the structure of the jets can have a standing-mode pattern or a vertical propagating pattern, depending on the amplitude of the excited mixed Rossby-gravity wave. They also found that the time scales of these EDJs corresponded roughly to equatorial basin modes (~5 years in the Atlantic for a first equatorial basin mode of vertical number 20) and that these basin modes may also present horizontal patterns corresponding to a second or higher equatorial basin mode, in which cases, the period would be drastically reduced (e.g., ~2.5 years for the second equatorial basin mode). In that sense, EDJs in the Atlantic would have time scales of 5 years and less, in agreement with the time scales estimated from observations. Moreover, the meridional structure of the EDJ presented in D'Orgeville et al.

(2006) corresponds to Kelvin and Rossby waves. This information, combined with the results of McPhaden and Gill (1986), suggests that there is a possible link between EDJs, the Mid-Atlantic Ridge and the low-frequency flows of small vertical scale in the meridional component observed at 23ºW.