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Dynamics of Deep Sea Currents over Equatorial Indian Ocean (EIO) from Acoustic Doppler Current Meter (ADCP) and Recorded Current Meter (RCM) Observations

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Abstract:
The periodic variability of deep sea currents in the Equatorial Indian ocean (EIO) studied by analyzing the moored current meter data collected during 2000-2006. The moored current meter data recorded Zonal and meridional currents at mean depths of 500m, 2000m and 4000m at three locations WEIO (0, 77°E), CEIO (0, 83°E) and EEIO (0, 93°E) along Equator in the Equatorial Indian Ocean (EEIO). The spectral energies at 10-20, 20-50, 50-90 and >90 days by using band passed analysis computed for the zonal and meridional currents. The spectrum gives a quantitative estimation of the variability of currents with periodic oscillations at different frequency bands. The spectrum shows the dominance of semi-annual periodic oscillations in zonal currents. The energy near semi-annual oscillations (170 days) is very high even in deeper layers at 4000m. The energy at low frequency oscillations decreased from WEIO to EEIO from surface to deeper depths up to 4000m. The Good coherence (>.85) was noticed at semi-annual period at three locations with upward phase propagation. The spectral peaks noticed at intra-seasonal oscillations (ISOs) and Madden-Julian oscillations (MJO) up to 4000m at all these mooring locations. The peaks and high spectral energies at semi-annual, Madden Julian and biweekly oscillations in the wind stress spectra clearly indicate the influence of wind stress on the currents in the deeper depths at 500m, 2000m and 4000m. This analysis also revealed that the dominance of meridional component in the high frequency oscillations. The increase in the spectral energies in the meridional components of currents at the high frequency oscillations (10-20 days) and intra-seasonal oscillations from WEEIO to the EEIO is a significant feature. The features indicate that these variations may influence the high frequency variability of north south variations of periodic oscillations to certain extent and even extended to deeper layers. Also these may enhance the sub intra and intra-seasonal Oceanic processes from WEIO to EEIO in the Equatorial Indian Ocean (EEIO).

1. Introduction

The Indian national program of Ocean Observing system (OOS) has been launched by department Of Ocean Development (DOD), Government of India and is executed at the national institute of Oceanography, Goa, India since 1998. Among its four sub programs, one sub program is current meter moorings along the equator. Under is sub program deployment of three deep sea current meter moorings at 93E, 83E & 77E (Fig. 1) in the eastern Equatorial Indian Ocean has been planned. The major objective is to collect long term time-series currents data at different depths covering the upper Ocean, intermediate, deep and near –bottom depth regimes. The Eastern Equatorial Indian Ocean (EEIO) is dominated by semi-annually reversing monsoon winds across the Equator leading to strong currents on different time scales. The most important among them are the inter-monsoon equatorial jets or Wyrtki jets generated by westerly winds that occur during boreal spring (April – May) and boreal fall (October-November) (Wyrtki, 1973). The dynamics of these jets from the model studies (Hans et al.) indicate that the dominant forcing of these jets are winds and the semi-annual signals are stronger than the annual signals. Model studies (McCreary et al., 1993) also indicate that EIO plays a dominant role for the variability of currents by propagation of long period east ward Kelvin waves along the Equator. The EIO is less explored and the actual observations on currents and thermal structure are very less. To enhance the existing knowledge and to know the various periodic processes that define the equatorial flow regime, an array of current meter moorings was moored (deployed) along the equator at three longitudes 77°E (WEIO), 83°E (CEIO) and 93°E (EEIO) with current meters at six subsurface depths (100m, 300m, 500m, 1000 m, 2000m and 4000m). The results of the time-series current data indicated that the variability of currents was due to low frequency semi-annual waves and intra-seasonal oscillations such as the Madden-Julian (40-60 day period) and biweekly (10-20 days) oscillations (Murty et al., 2002 and Sengupta et al., 2004, Masumuto et al., 2005). These periodic oscillations play an important role in the equatorial dynamics and documented from the observed in the upper few hundred meters. Lack of time series data in deeper layers hamper the understanding of the variations of these oscillations in the deeper depths. The current meter data from deep sea moorings in the EIO is analyzed to give insight into these periodic oscillations. The variability of periodic oscillations can be defined and estimated by the spectral analysis for different frequency bands. Here we presented and discussed the spectra of currents at deeper depths (500m, 2000m and 4000m) along with spectra of wind stress components. The spectra estimated for the semi-annual (> 90days), seasonal/ Madden Julian (20-90 days) and sub seasonal /biweekly (10-20 days) ranges and compared the energies magnitudes of different periodic oscillations.

2. Data and Methodology

The data was collected from the current meters is used for these studies. The Aanderra rotor type Recorded Current meters (RCMs) were moored at three locations along Equator (Figure. 1). The first Ocean Observing System (OOS) current meter mooring was deployed with six current meters at six depths along the Equator, EEIO (93°E) location in February 2000. In the year 2001, this mooring was recovered and after securing the recorded data, it was re-deployed at the same location. A new mooring was deployed with six current meters at six depths at Central Equatorial Indian Ocean CEIO (83°E) along the Equator. In the year 2002, the 93°E and 83°E moorings were recovered and data were obtained from all the current meters. While these two moorings were redeployed at the respective locations, in addition, a third mooring was deployed at Equator, WEIO (76°E) location. In 2003, all these 3 moorings were recovered and redeployed at EEIO (93°E), CEIO(83°E) and WEIO (77°E) locations and recovered in the years 2004 and 2006 (Figure. 1). The rotor type Recording Current Meters (Aanderaa Instruments, Norway) were used for these moorings and the data were acquired at 1 hourly interval. The processing of the data was done as per the standard methods. The speed and directions are computed from the hourly zonal (U) and meridional (V) current components. The tidal oscillations were removed from the hourly data by computing 49 hours and daily moving averages. The time series of recorded pressure at each nominal depth of the instrument (Recording Current Meter) were averaged to get the mean depth of the instrument in each mooring in each year. In this study, we used the time series of currents and temperature data during 2000-2006 at the mooring locations WEIO (77°E), CEIO (83°E) and EEIO (93°E).

3. Results and Discussion

3.1. Zonal and Meridional Currents

The daily zonal (u) and meridional (v) currents at subsurface depths at mooring locations WEIO (0,77 °E), CEIO (0, 83°E) and EEIO (0, 93°E) are presented in (Figures 2.a,2.b,2.c). The zonal (u) components show strong semi-annual seasonal oscillations at WEIO (0, 77 °E) and CEIO (0, 83°E) and these oscillations comparatively weak at location EEIO (0, 93°E). The meridional flow dominated by sub-seasonal (< 30 days) oscillations. The magnitudes of meridional components are less than the zonal components at WEIO, CEIO and EEIO.

3.2. Sub-Intra Seasonal Oscillations (10-20 Days)

The spectrum of intra-seasonal oscillations (10–20 days) at 500m depth are showing the spectral energies of the meridional (v) oscillations are three times to the spectral energies of zonal (u) oscillations at all mooring locations (Figure.3a). In the meridional flow (13-15days) biweekly oscillations (Figure.3b) are highly dominating particularly at location EEIO (0, 93°E) and (Miyama et al. (2006) suggests that the biweekly mixed Rossby-gravity waves are resonantly excited in the Western Equatorial Indian Ocean (WEIO) by the meridional wind forcing at the biweekly period. The spectral energies of wind stress components (Figures 3c &d) clearly shows that the 10–20day oscillations in meridional wind stress is about 3 times more to that of zonal wind stress energy. The response to the sub seasonal variability of winds (Sengupta et al.. 2004, 2001) at bi- weekly / high frequency periodic oscillations are penetrated even to deeper depths up to 4000m. The biweekly signals are dominated at EEIO (0, 93°E). The biweekly oscillations are dominated in meridional currents at 2000m depth with high energetic spectra's of oscillations at EEIO than WEIO, CEIO. The signature of the bi-weekly oscillations (13-16days) in meridional components at 4000m depth is comparatively higher than the zonal components (Figures 5a & 5b). The lack of current observations at deeper depths may be the reason that impact of the winds on the bi-weekly oscillations in the deeper depths not reported earlier.

3.3. Intra Seasonal (20-90 Days) Oscillations

Direct observations of the upper ocean velocity in the eastern equatorial Indian Ocean by an acoustic Doppler current profiler, from November 2000 to October 2001 on the equator at 90 E, demonstrate that the dominant periods of variability in the upper layer zonal and meridional currents are in intra-seasonal frequency bands with periods of 30 to 50 days and 10 to 20 days, respectively. The strong intra-seasonal variability in the zonal current obscures the semiannual Wyrtki jets, which can be seen clearly in the monthly averaged field. In addition, a zone of strong vertical shear of the zonal current and a distinct Equatorial Undercurrent with semiannual period, are observed. The results provide us with a new perspective on importance of the energetic intra-seasonal variability in the eastern equatorial Indian Ocean, which indicates a strong correlation with the wind variability near the mooring location. [Masumoto, Y., H. Hase, Y. Kuroda, H. Matsuura, and K. Takeuchi (2005)]

The spectral energies of meridional (20-50days) oscillations at mooring location are greater than that of zonal components at all three mooring locations at 500m (Figure 6a & 6b). These seasonal periodic oscillations are due to Oceanic Kelvin waves by the low frequency variations of the Atmospheric Madden Julian oscillations (Madden- Julian, 1971, Han et al, 2001). The intra-seasonal oscillations (30-60days) are forcing the wind on development of 90 days oscillations over the equatorial Indian Ocean (Han et al., 2005). The Wind stress spectrum at 20-50days filtered data was presented in (Figures 6c & 6d). Wind stress zonal spectral energies are slightly higher than meridional energies. Near 41 days a dominant peek observed in zonal wind stress spectra and also in zonal current spectra at WEIO (0,77°E), CEIO (0,83°E) and WEIO (0,93°E) locations at 500m depth. But high energy concentrated at location CEIO (0, 83°E). The north, south meridional oscillations are comparatively stronger than the zonal oscillations noticed from wind as well as currents spectrum.

The influence of the wind stress at Madden Julian oscillations (45days) period was noticed in zonal and meridional (Figures 7a & 7b) spectral energies at EEIO (0, 93°E) near 2000m depth. The spectral energies at Madden Julian Oscillations at (45days) periods are higher at EEIO (0, 93°E) in 4000m depth (Figures 8a & 8b). The low frequency oscillations of 80days and 57days are dominating in the zonal components (Figures 9a & 9b) at locations WEIO and CEIO at the depth of 500m. The spectral energies are comparatively more at WEIO. There is a dominance of 56 to 69 days periodic oscillations were noticed at 2000m depth in WEIO (Figures 10a & 10b). The meridional components show peaks near 80days and also at 62days at the WEIO. The zonal spectral energies at 4000m depth (Figures 11a & 11b) are comparatively less than the energies of meridional component oscillations particularly at EEIO.

3.4. Low Frequency Oscillations (> 90 Days)

The spectra of low frequency (> 90 days) oscillations at mooring locations at 500m depth presented in (Figures. 12a & 12 b.) The semi-annual peak (near 186 days), having more dominance energy in zonal component than the meridional currents and the dominance is observed at WEIO, CEIO and absence at EEIO. The oscillations are the response of the Oceanic Kelvin waves to the eastward propagation of atmospheric winds (Hendon et al, 1998). The signature is clearly noticed with very strong peaks in the zonal currents at WEIO, CEIO and EEIO and the response is noticed significantly in deeper layers. The zonal wind stress spectra shows dominating peaks at 170days at WEIO (Figure. 12c) and with more spectral energy at WEIO than the CEIO, EEIO. The meridional wind stress shows a dominating peak at 341days (Figure. 12d) at three locations. The spectral energy is comparatively less at EEIO. The influence of the wind stress on periodic oscillations is seen clearly in the meridional currents spectra (Figures 12b) at three locations. The semi-annual signals were noticed at 2000m depths (Figures.13a & 13b) in zonal and meridional components. The semi-annual peak in the zonal component is very strong and the periodic oscillation observed near 168days. The semi-annual spectral energies are very less at 2000m on EEIO compared to WEIO and EEIO from zonal currents and wind spectra. The semi-annual peak does not exists over EEIO at 4000m depth (Figure. 14a & 14b), but the same signature observed at WEIO and CEIO. The dominant peaks of energies at 341days indicated the influence of low frequency oscillations of winds on the current structure up to the depth of 4000m.

The spectral energies of temperature at 500m shows the dominating peak (Figure.15 a) near semi-annual frequency (186days) and also energies increase towards lower frequencies comparatively stronger at western location WEIO than the CEIO, EEIO. The observed oscillations of temperature are also incoherence with the oscillations of currents. The spectral energy at 4000m depth clearly indicates the strong semi-annual (Figure. 15b) particularly at WEIO.

3.5. Coherence and Phases

The semi-annual oscillations (179day) are dominated over all three locations, with upward phase propagation at all depths, but downward propagation at 4000m between 77°E-93°E and 83°E-93°E. The MJO signals are very strong at 2000m depth at three locations with phase (.98) with down ward easterly flow. The MJO signals are very week between WEIO and EEIO, at 500m and 4000m with coherence (.25), but very strong between CEIO and EEIO with coherence (.92). The biweekly oscillations are very strong at 2000m and 4000m between WEIO and EEIO. The variation of periodic oscillations are depends on energy input to the Ocean from wind stress.

The coherence and phases of cross spectral estimates of zonal currents among the locations are presented in Table I. The good coherence (.85) near depth of 500m indicate the strong semi-annual rossby wave propagation from WEIO to EEIO with a phase lag towards EEIO. The east ward propagations also observed at 2000m depth with significance coherence (Table I). At 4000m depth, the good coherence is noticed between the locations and phase lead observed at EEIO. At seasonal periods (Madden Julian oscillations) are shows maximum coherence is seen at WEIO and CEIO with phase lagging at WEIO. The biweekly oscillation shows good coherence at CEIO and EEIO than at WEIO.

The coherence and phase between zonal currents at different depths (500 – 2000m and 2000m-4000m) are presented in **Table II.** At WEIO is good coherence (.94), indicate the semi-annual periodic oscillation between 500-2000 with an upward phase propagation. The zonal currents at 2000m – 4000m depth shows good coherence and upward phase propagation. But the meridional component at 2000m and 4000m shows less coherence. The zonal component shows good coherence (.70) and upward phase propagation at 500m-2000m depth over CEIO. The meridional component also shows good coherence (.97) with upward phase propagation.

4. Conclusions

In the EEIO (0, 93 °E), the disturbances of the bi-weekly oscillations (10-20days) dominates in the meridional flow and impact the sub seasonal scale bio – physical processes. The seasonal variations and Madden Julian periodic oscillations of the wind stress is reflected in the zonal current spectra at these mooring locations in the deeper layers. Very strong semi-annual oscillations and their dominant characteristics are noticed at all deeper depths, particularly in the zonal at western mooring WEIO and CEIO depicted in these spectral energies. Upward phase propagation from deeper layers and good coherence among zonal components with high spectral energies at semi-annual periods indicate that impact of low frequency oscillations on the physical processes in the deeper depths of Equatorial

Indian Ocean. The upward and downward phase propagation of the Equatorial Indian Ocean water column indicates existence of rossby waves at semiannual time period, Kelvin waves at intra-seasonal time period and gravity waves at biweekly time period.

5. References

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Annexure

Periodic oscillations	**Nominal RCM depth (m)**	**Zonal components**					
		0,77°E - 0,83°E		0,77°E –0, 93°E		0,83°E –0, 93°E	
		coherence	Phase	coherence	Phase	coherence	Phase
Semi-annual (170 day)	500	.98	48	.87	149	.85	107
	2000	.88	158	.69	166	.87	24
	4000	.85	43	.79	-93	.99	-138
Madden –Julian (56 day)	500	.98	-135	.51	53	.56	171
	2000	.94	-147	.94	-47	.82	158
	4000	.59	-21	.25	-125	.92	-118
Bi-weekly (13 days)	500	.27	-177	.60	176	.93	-15
	2000	.62	-69	.94	158	.65	-157
	4000	.79	-169	.57	55	.18	128

Table 1

Mooring Location	**Periodic oscillations**	**Coherence and phase of Zonal components between different depth layers at mooring locations**			
		500-2000 m		2000-4000 m	
		Coherence	Phase	coherence	Phase
Equator, 77°E	Semi-annual	.94	149	.81	20
	Madden-Julian	.86	41	.98	147
	Bi weekly	.38	-161	.89	74
Equator, 83°E	Semi-annual	.62	-95	.49	-132
	Madden-Julian	.97	129	.60	-9
	Bi weekly	.70	65	.89	-56
Equator 93°E	Semi-annual	.25	-93	.39	-14
	Madden-Julian	.83	-162	.32	-21
	Bi weekly	.19	-11	.34	-43

Table 2

Figures & Captions

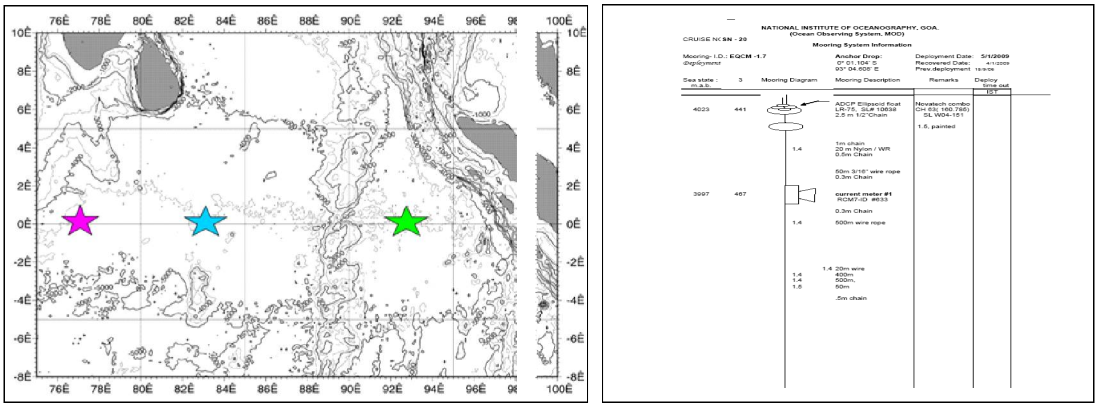


Figure 1) Location Map with mooring system which associated with current meters

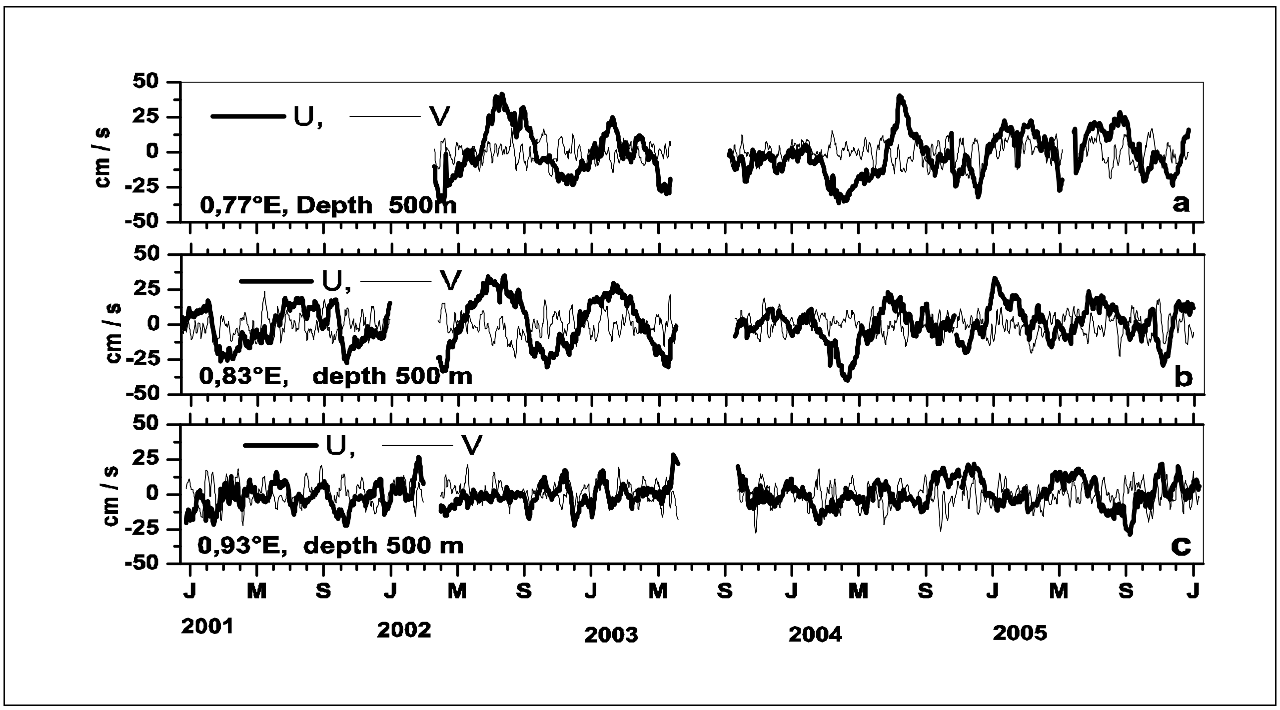
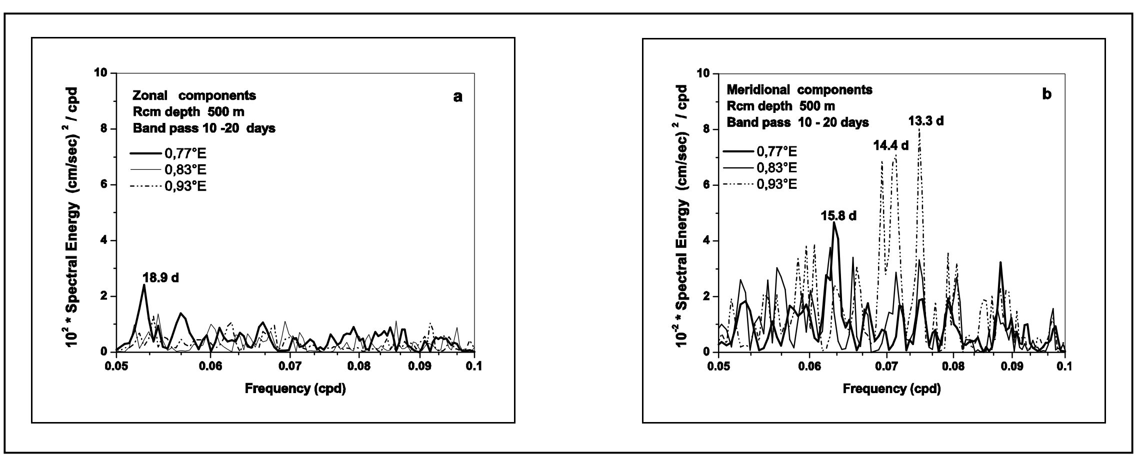


Figure 2a) Zonal and meridional currents at depths of 500m over WEIO (0, 77°E), 2 b) The zonal and meridional currents at 500m at CEIO, 2c) The zonal and meridional currents at 500m over EEIO (0, 93°E)



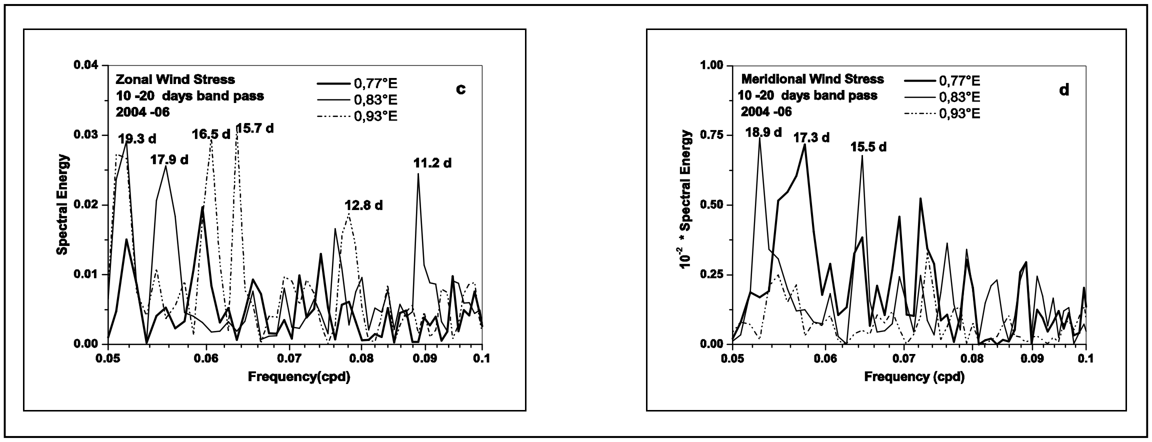


Figure 3a) The Spectra of 10-20 days band pass filtered zonal currents at 500m depth over WEIO,CEIO,EEIO, 3b) The spectra of 10-20day band passed filtered meridional currents at 500m depth over WEIO,CEIO,EEIO, 3c) The spectra of 10-20 day band passed of wind stress spectra of zonal current at 500m depth at three locations, 3d) The spectra of 10-20 day band passed of wind stress spectra of meridional currents at 500m depth at three locations.

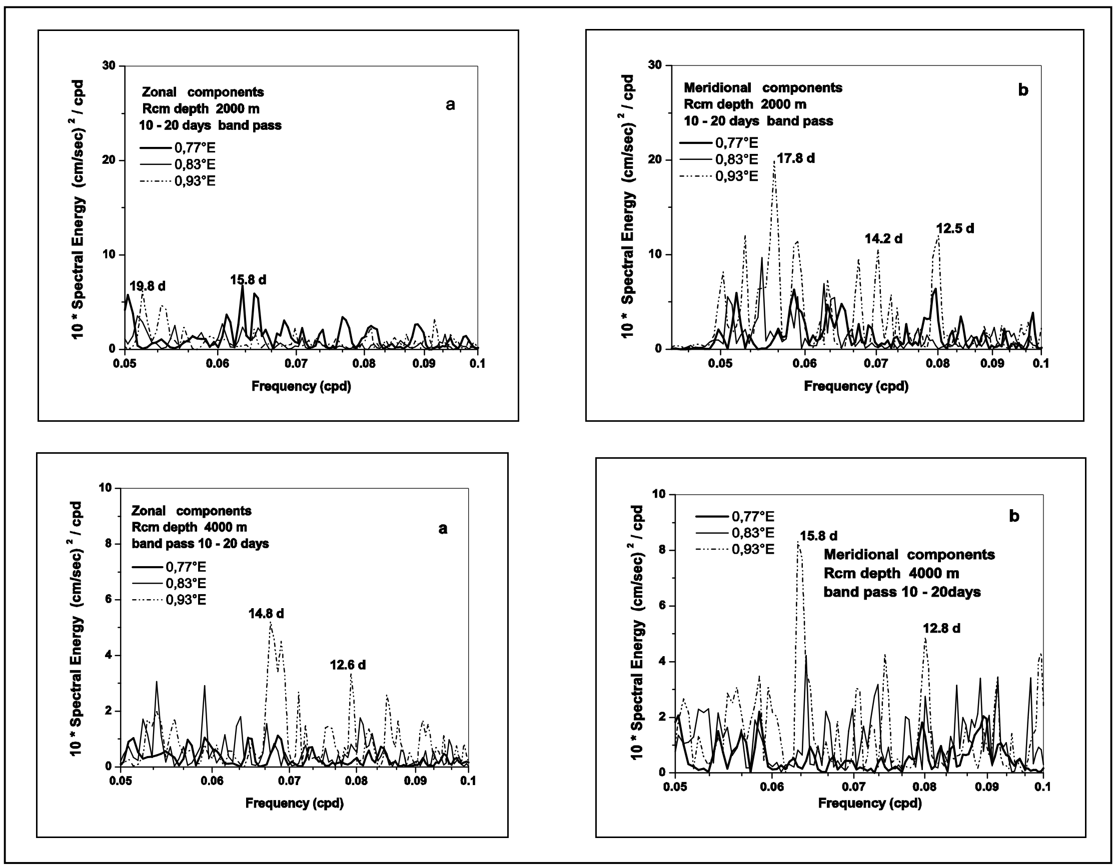


Figure 4a) The spectra of 10-20days band passed filtered zonal currents at 2000m depth over three mooring locations. 4b) The spectra of 10-20days band passed filtered meridional currents at 2000m depth over three mooring locations. 5a) The Spectra of 10-20days band pass filtered zonal currents at 4000m depth over WEIO,CEIO,EEIO, 5b) The Spectra of 10-20days band pass filtered zonal currents at 4000m depth over WEIO,CEIO,EEIO.

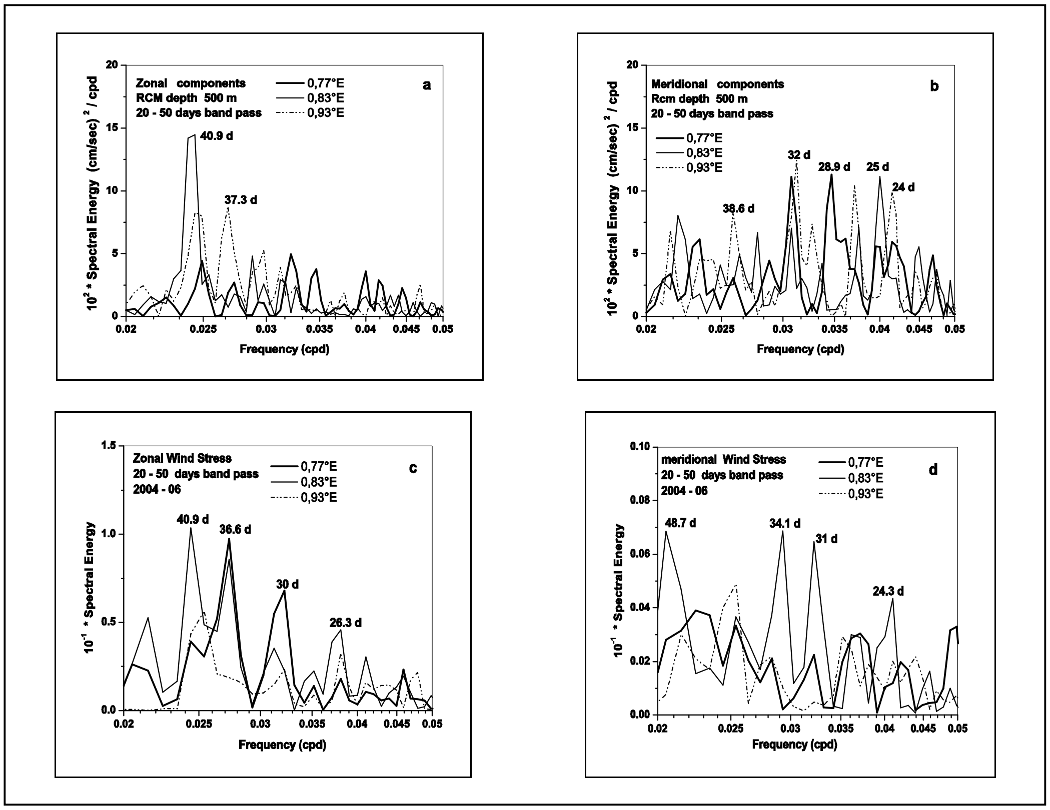


Figure 6a) The Spectra of 20-50days band pass filtered of zonal currents at 500m depth over WEIO, CEIO, EEIO, 6b) The Spectra of 20-50days band pass filtered of zonal currents at 500m depth over WEIO, CEIO, EEIO, 6c) The Spectra of 20-50days band pass filtered of meridional currents at 500m depth over WEIO, CEIO, EEIO, 6d) The Spectra of 20-50 days band pass filtered of meridional currents at 500m depth over WEIO, CEIO, and EEIO.

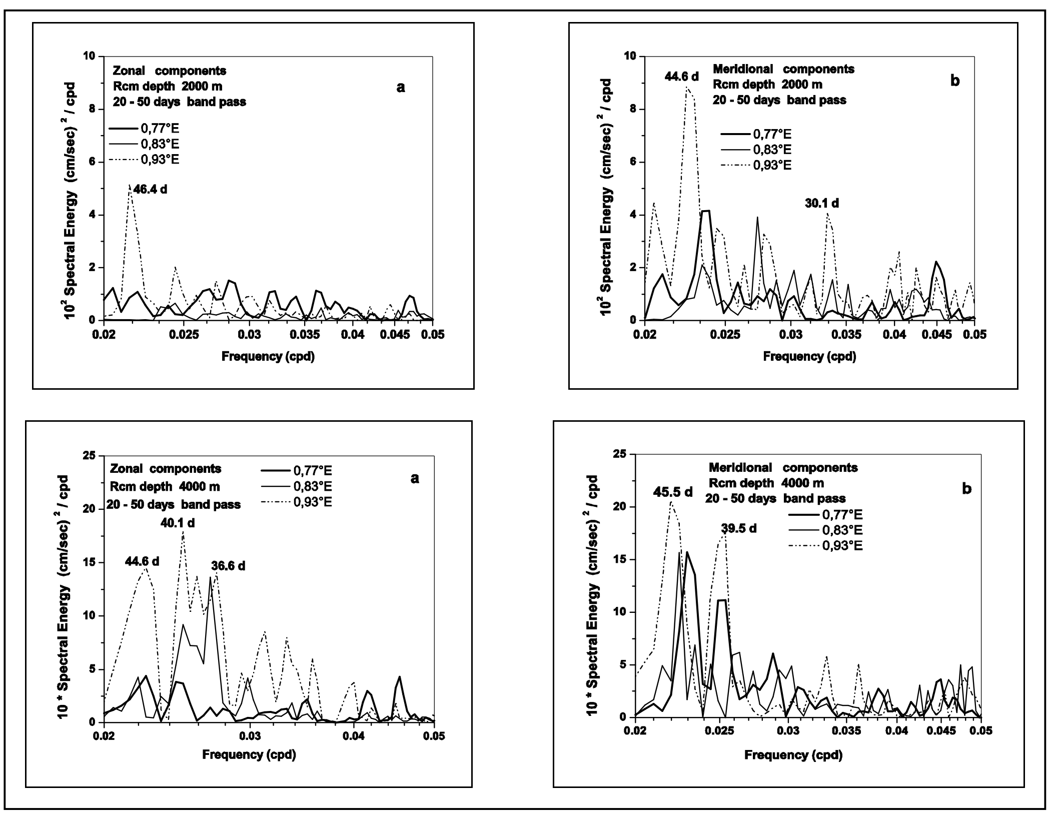


Figure 7a) The spectra of 20-50 days band pass filtered zonal currents at 2000m depth over WEIO, CEIO, and EEIO. 7b) The spectra of 20-50 days band pass filtered zonal currents at 2000m depth at WEIO, CEIO, and EEIO. 8a) The spectra of 20-50 days band pass filtered zonal currents at 4000m depth over WEIO, CEIO, EEIO, 8b) The spectra of 20-50 days band pass filtered meridional currents at 4000m depth over WEIO, CEIO, EEIO,

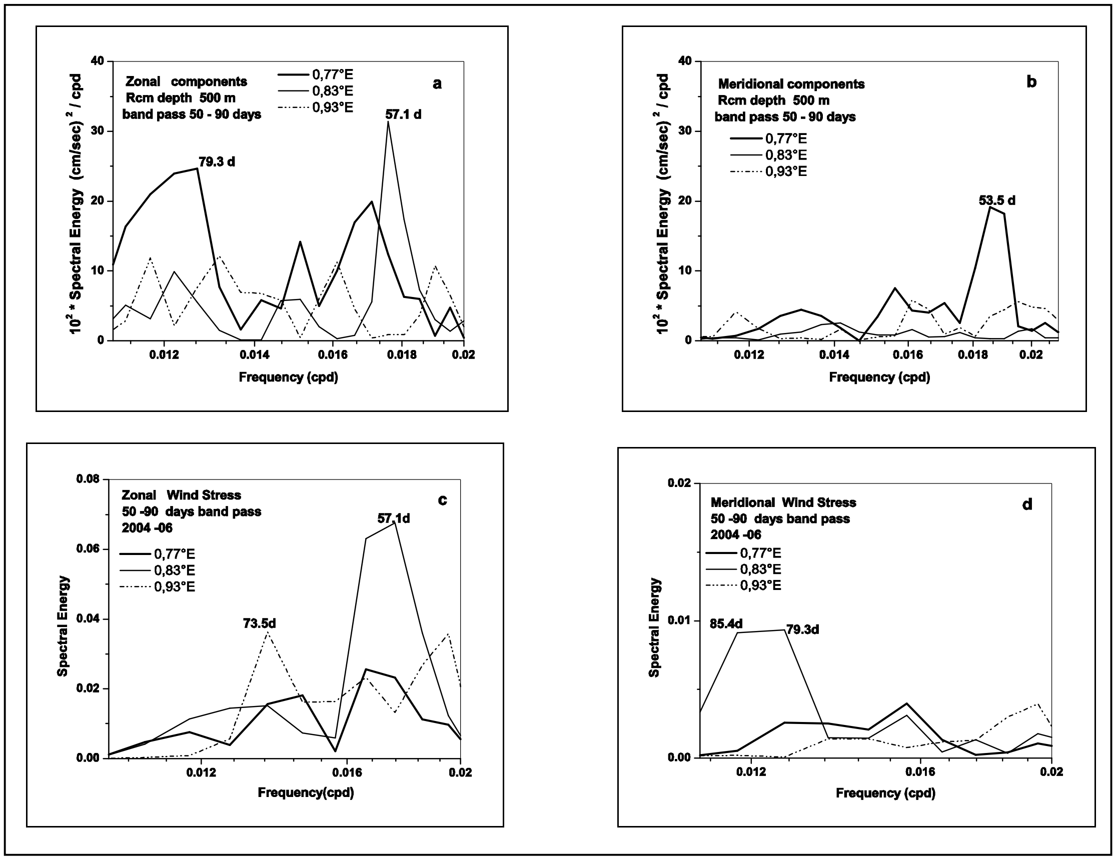
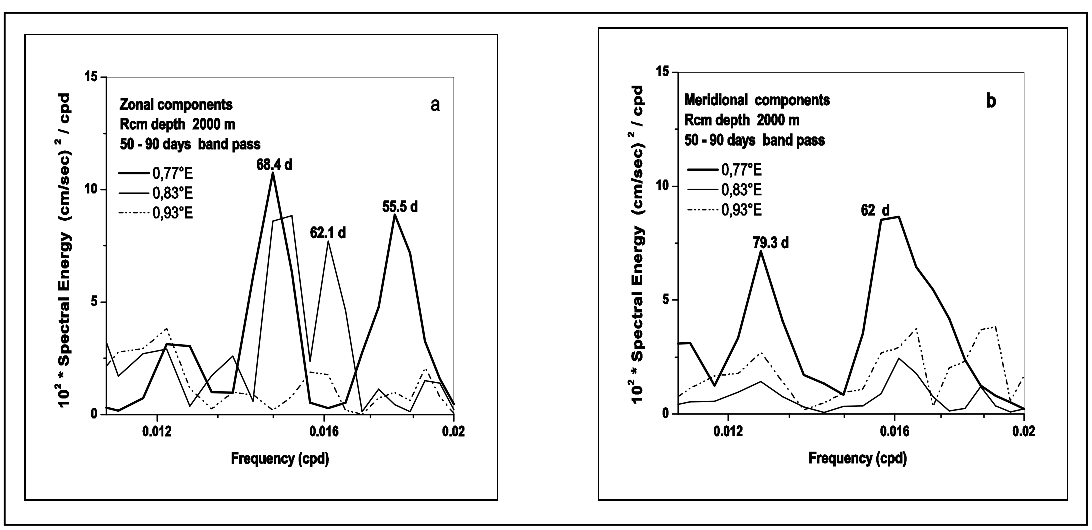


Figure 9a) The Spectra of 50-90 days band pass filtered zonal currents at 500m depth at WEIO, CEIO, EEIO, 9b) The Spectra of 50-90 days band pass filtered meridional currents at 500m depth at WEIO, CEIO, EEIO, 9c) The Spectra of 50-90 days band pass filtered wind stress of zonal currents at 500m depth over WEIO, CEIO, EEIO, 9d) The Spectra of 50-90 days band pass filtered wind stress of meridional currents at 500m depth over WEIO, CEIO, EEIO,



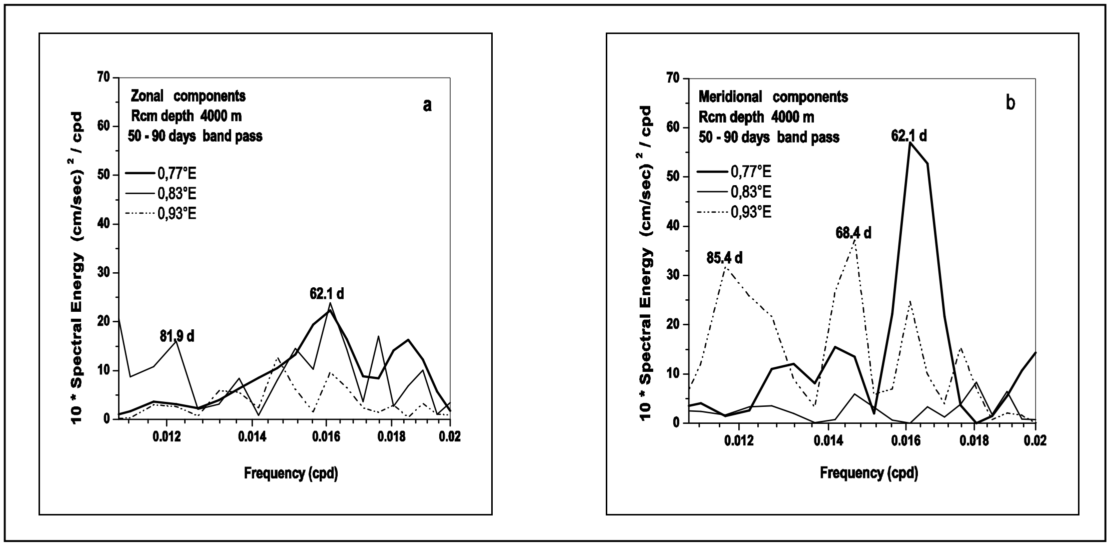


Figure 10a)The Spectra of 50-90 days band pass filtered zonal currents at 2000 m depth over WEIO, CEIO, EEIO, 10b) Spectra of 50-90 days band pass filtered zonal currents at 2000m depth over WEIO, CEIO, EEIO.

Figure 11a) The Spectra of 20- 90 days filtered data zonal currents at 2000m depth three locations. 11b) The Spectra of 20- 90 days filtered data meridional currents at 2000m depth at three locations.

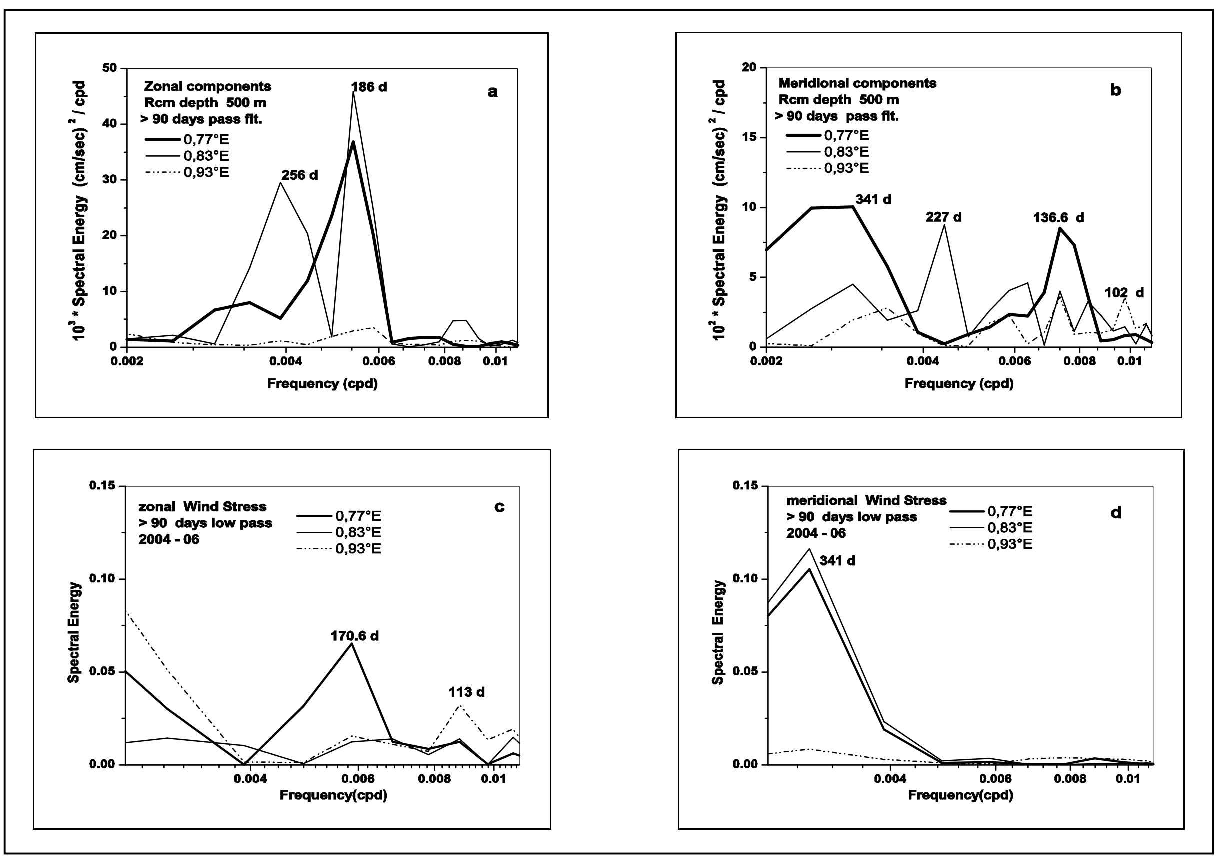


Figure 12a) The Spectra of < 90 days low pass filtered zonal currents at 500 m depth over WEIO, CEIO, EEIO, 12b) The Spectra of < 90 days low pass filtered meridional currents at 500 m depth over WEIO, CEIO, EEIO, 12c) The Spectra of < 90 days low pass filtered wind stress zonal currents at 500m depth over WEIO, CEIO, EEIO, 12d) The Spectra of < 90 days low pass filtered wind stress zonal currents at 500 m depth over WEIO,CEIO,EEIO,

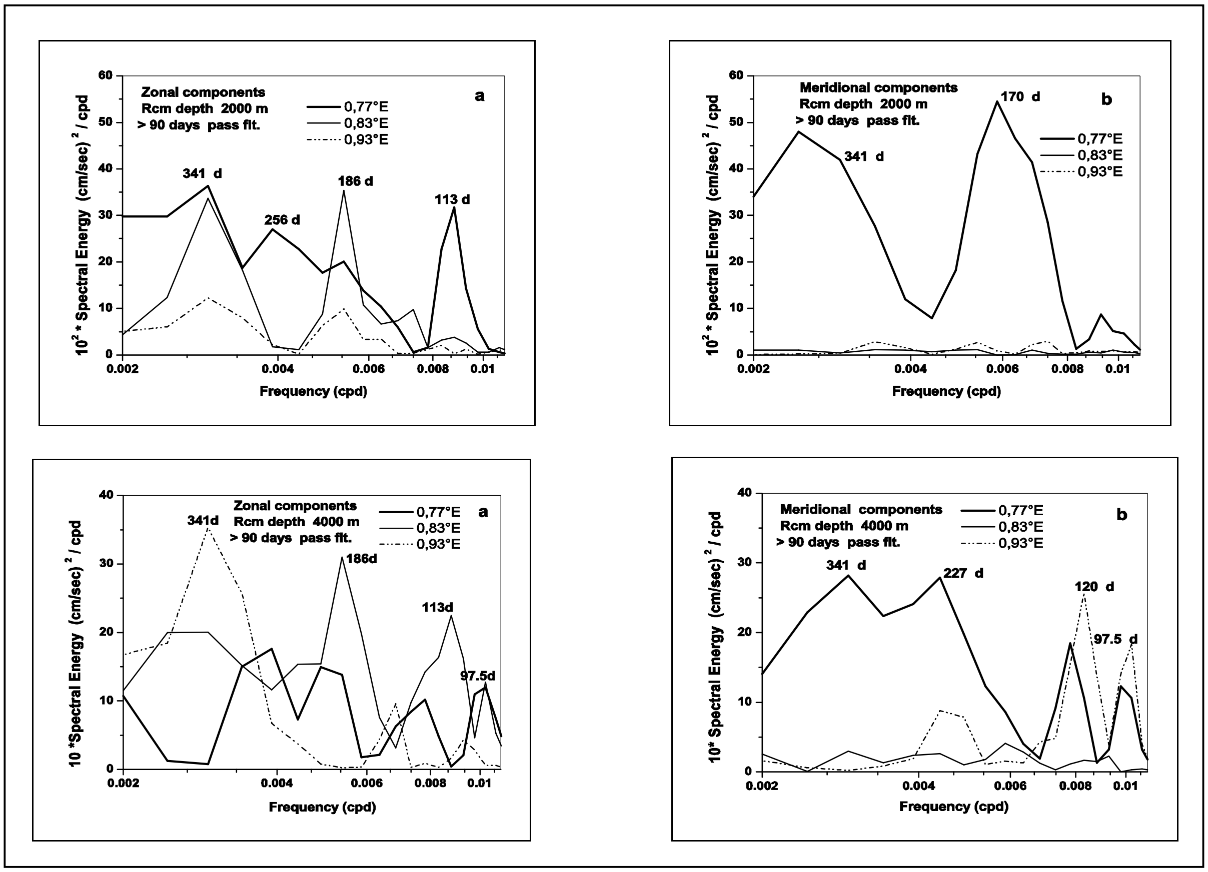


Figure 13a) The Spectra of <90 days low pass filtered zonal currents at 2000m depth at three locations. 13 b) The Spectra of <90 days low pass filtered meridional currents at 2000m depth at three locations. Figure 14a) The Spectra of <90 Days low pass filtered zonal currents at 4000m depth over WEIO, CEIO, EEIO, 14b) The Spectra of <90 Days low pass filtered zonal currents at 4000m depth over WEIO, CEIO, EEIO.

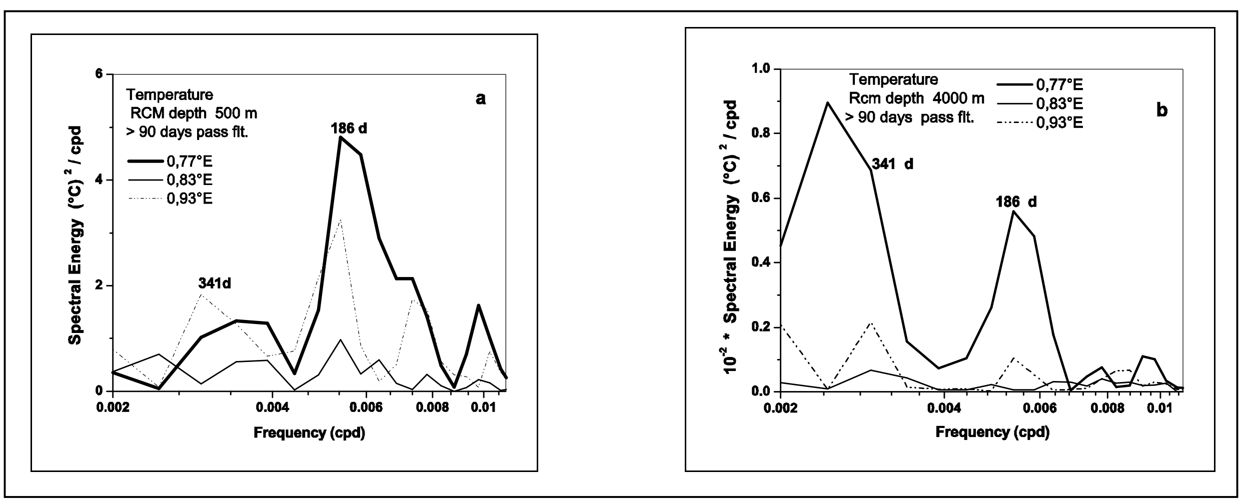


Figure 15a) The Spectra of < 90 days low pass filtered temperature at 500m depth over WEIO, CEIO, EEIO, 15 b) The Spectra of < 90 days low pass filtered temperature at 500m depth over all WEIO, CEIO, and EEIO.