High frequency variability of *in situ* wind, temperature and current measurements in the equatorial Atlantic during the FOCAL/SEQUAL experiment

Winds
Currents
Temperature
Spectrum
Gulf of Guinea

Vent
Courants
Température
Spectres
Golfe de Guinée

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ABSTRACT

The high frequency variability of *in situ* wind measurements in the western (1°N 29°W) and eastern (0°4°W) equatorial Atlantic are described and for the first time compared. The data were obtained from meteorological sensors placed respectively on St. Peter and St. Paul Rocks and at the top of a surface buoy moored in the Gulf of Guinea during the SEQUAL/FOCAL experiment from February 1983 to September 1984. Spectral and cross-spectral analyses of the simultaneous time series show energetic oscillations from 60 days to the inertial gravity wave band. The main peaks observed in the wind stress spectra correspond to period bands of 20-50, 10-20, 7-9, 5-6 and 3-4 days. Except for the 40-50 day oscillation period, the other oscillations are coherent in the zonal direction. In the Gulf of Guinea, power density spectra of moored temperature and current measurements obtained at the same time and location as the wind measurements exhibit peaks of energy in the period bands 20-50, 10-20, 7-9 and 3-4 days; the largest amplitudes of the peaks are observed in the first two period bands; a cross-spectral analysis between the wind and oceanic records show that all these oscillations are atmospherically forced at 0°4°W.

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RÉSUMÉ

Variabilité haute fréquence du vent, de la température et des courants en zone équatoriale atlantique pendant FOCAL/SEQUAL

Les variabilités haute fréquence du champ de vent en deux points, à l'équateur, dans l'Océan Atlantique (1°N, 29°W et 0°4°W), sont décrites et pour la première fois comparées. Les données ont été obtenues à partir de stations météorologiques disposées respectivement au sommet du Rocher Saint-Pierre Saint-Paul et d'une bouée de surface ancrée par 5 100 m de fond, de février 1983 à septembre 1984, pendant le programme FOCAL/SEQUAL. Les analyses auto- et interspectrales des deux enregistrements de vent montrent la présence de pics d'énergie statistiquement significatifs et s'étalant dans la plage de périodes comprises entre 60 jours et les ondes d'inertie-gravité. Ces pics sont localisés dans les intervalles 20-50, 10-20, 7-9, 5-6 et 3-4 jours. Hormis le pic d'énergie correspondant à l'oscillation centrée dans l'intervalle 40-50 jours, les enregistrements montrent dans le sens zonal une parfaite cohérence. Dans le golfe de Guinée, les spectres des enregistrements de température et de courants obtenus simultanément avec les enregistrements de vent, montrent aussi la présence de pics d'énergie statistiquement significatifs, centrés également dans les plages de périodes 20-50, 10-20, 7-10 et 3-4 jours. L'analyse interspectrale des enregistrements de vent, de température et de courant montre que les oscillations observées dans l'océan à 0°4°W sont forcées par l'atmosphère.

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INTRODUCTION

Knowledge of the high frequency variability of wind stress permits determination of forced oceanic oscillations. Atmospheric waves in the tropics have been observed previously in both the Pacific and Atlantic Ocean (*i. e.* Yanai, 1971, and Hayashi, 1973 for a detailed review of observed atmospheric disturbances). Although the meteorological literature often contains information on wind fluctuations above the planetary boundary layer, there is much less information at sea level. In the Pacific, atmospheric fluctuations and the inferred oceanic response have been studied using surface oceanic data and weather stations on tropical islands (*i. e.*, Luther, 1980). In the western equatorial Atlantic, atmospheric forcing at sea level was determined by the wind time series obtained at St. Peter and St. Paul Rocks (SPP) during the First GARP Global Experiment (FGGE; Garzoli *et al.*, 1982) and during the first part of the SEQUAL experiment (Garzoli, Katz, 1984). In the East (0°N 4°W), *in situ* wind measurements were available only during the boreal winter and spring of 1979 (Colin, Rual, 1982).

The study of the response of the Equatorial Atlantic Ocean to the seasonal varying winds, was the main objective of the joint Programme Français Océan Climat en zone équatoriale AtLantique (FOCAL) and the SEasonal response of the éQUatorial AtLantic experiment (SEQUAL). As part of the field work, simultaneous and continuous *in situ* wind observations were obtained from February 1983 through August 1984 in the Gulf of Guinea (0°N 4°W, Colin *et al.*, 1986) and from February, 1983 at St. Peter and St. Paul Rock (1°N 29°W, Garzoli, Katz, 1984). The objective of these observations was to determine the local forcing at both sites of the basin, at low and high frequency alike, and to validate the wind field product deduced from cloud displacement during the experiment. The ocean was monitored at nearby locations to study the local response. In the Gulf of Guinea (GG, 0°N 4°W), the wind recorder was mounted on top of a surface mooring; wind speed, wind direction, air and sea surface temperature (SST) were measured. Close to St. Peter and St. Paul Rocks (SPP, 1°N 29°W), an inverted echo sounder and moored current meters were deployed at 0°N 28°W (Katz, 1984; Weisberg, 1984).

The simultaneous analysis of the low frequency variability of the wind observations (seasonal) at both monitored locations was done by Colin and Garzoli (1987). The high frequency response of the ocean to the winds observed at SPP has been studied as part of a more general analysis by Garzoli (1987), west of 10°W. The objective of this paper is twofold: *a*) to describe, analyze and compare the high frequency variability of the wind observations obtained at both locations; *b*) to study the high frequency response of the ocean to the winds in the Gulf of Guinea (GG) and to compare these results with those obtained further west (Garzoli, 1987; Weisberg *et al.*, 1987).

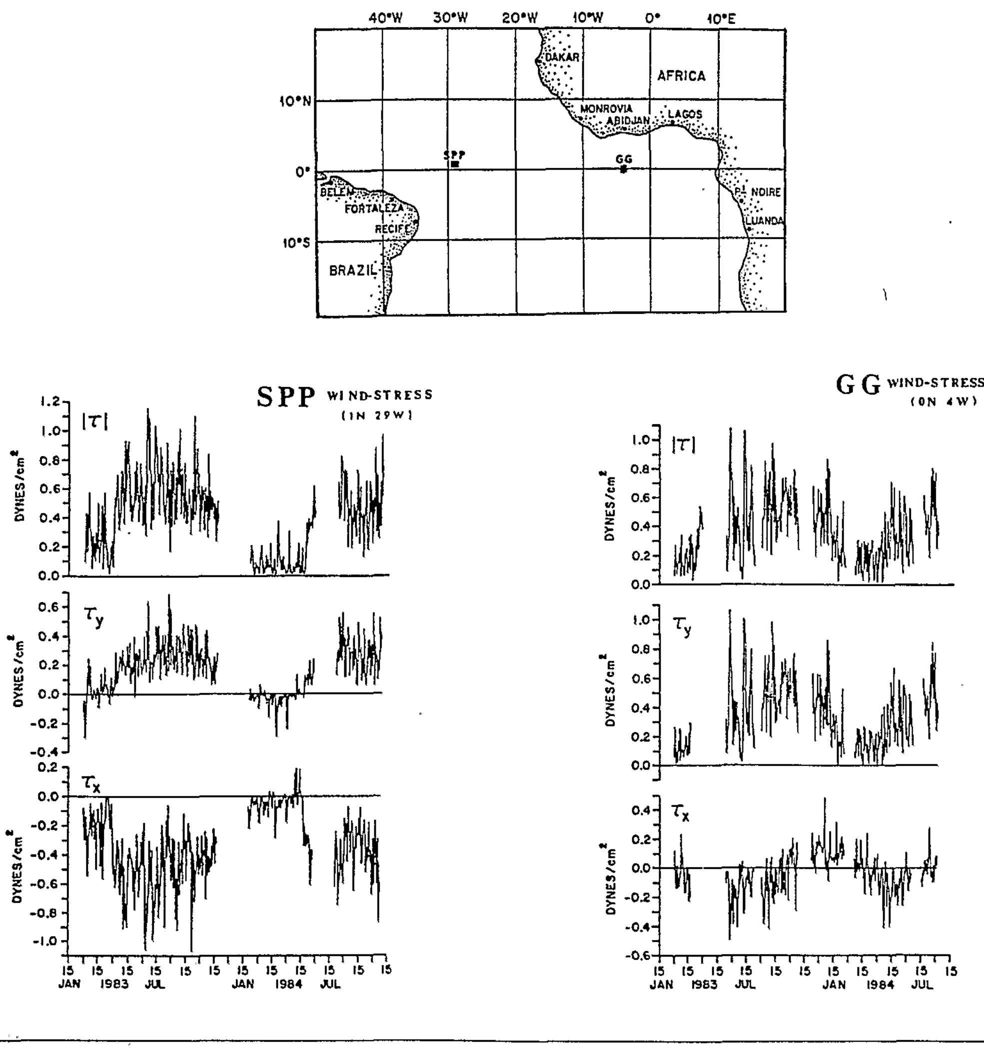


Figure 1

Location (top panel) of the two analyzed wind recorders deployed during the SEQUAL/FOCAL experiment: (GG) surface mooring (0°N-4°W); (SPP) St. Peter and St. Paul Rock (1°N 29°W).

The daily mean time series of the total wind stress (dynes/cm²) and of the meridional and zonal wind stress components at both locations are shown respectively on the lower left (SPP), from 02/16/83 to 09/20/84, and on the lower right (GG), from 02/16/83 to 08/16/84, panels of the figure.

Localisation géographique des deux unités météorologiques placées pendant le programme FOCAL/SEQUAL. GG correspond à l'unité disposée sur la bouée de surface ancrée à 0°4°W, et SPP à celle fixée au sommet du Rocher Saint-Pierre et Saint-Paul.

Les enregistrements représentant l'intensité totale du vecteur tension du vent (dynes/cm²) ainsi que les composantes méridienne et zonale sont localisés dans la partie gauche (droite) pour SPP (GG). Les valeurs horaires sont moyennées sur un jour.

OBSERVATIONS AND DATA ANALYSIS

The characteristics of the instruments and the data processing are described in Colin and Garzoli (1987). At GG, the data start on February 16, 1983 and end on August 16, 1984 with 5 gaps of 10-20 days each. At SPP the data analyzed in this paper start on February 16, 1983 and end in October 1984 with two gaps at the end of 1983 and mid 1984. The geographical location of the instruments as well as the daily mean time series of the wind stress components inferred from the wind observations at SPP and GG are given in Figure 1.

The high frequency variability of the wind stress series is studied in this paper through the spectral analysis technique. Due to the occurrence of non-simultaneous gaps in the data at both locations, the spectral analysis of the truncated records was performed in the following way: 1) the mean and trend of each piece were removed in order to fulfil the ergodicity condition; 2) the different pieces were then connected together and the spectral density estimates of the resulting series were averaged over 9 (running mean) frequency bands. The suitability of this technique was tested using: 1) two continuous inverted echo sounder (IES) records at 0°N 28°W and 0°N 10°W of the same length as the wind records, with the gaps included, respectively at SPP and GG; and 2) the same records cut into the same number of pieces and to the same length as the wind component records at SPP and GG respectively. Results are shown in Figures 2 and 3. Figure 2 exhibits the variance preserving spectra of both the continuous (solid line) and truncated (dashed line) records obtained at 0°N 28°W[a] and 0°N 10°W[b]. The agreement between the two spectra at both locations is good for periods less than 100 days. Figures 3 *a* and 3 *b* show the coherence and phase spectrum between the two continuous (solid line) and the two truncated (dashed line) time series; when the coherence is significant, the agreement is excellent. Houghton and Colin (1987) obtained in the autospectrum of continuous time series of shorter duration (February 24 to June 24, 1984) of the meridional components of both the wind stress and surface current, at 0°N-4°W similar features for periods less than 20 days. On the basis of these results, the technique described above was applied to the two sets of wind stress components time series, and later to the oceanic records at 0°N-4°W.

Figure 4 shows the rotary spectrum of the wind stress components at both locations. The solid and dashed lines represent respectively the power density spectrum (PDS) of the velocity vector in the clockwise and counter-clockwise sense. The universal slope $f^{-5/3}$ where f is the frequency is superimposed. Differences in the slopes at high frequencies can be related to mooring and sensor noise motions in the surface mooring mounted wind recorder (GG). The main differences between the two spectra occur for frequencies between 0.1 and 0.01 cpd. For periods greater than 60 days most of the energy at GG is in the clockwise sense while at SPP the energy is equally distributed. This is similar to the surface wind stress curl distribution

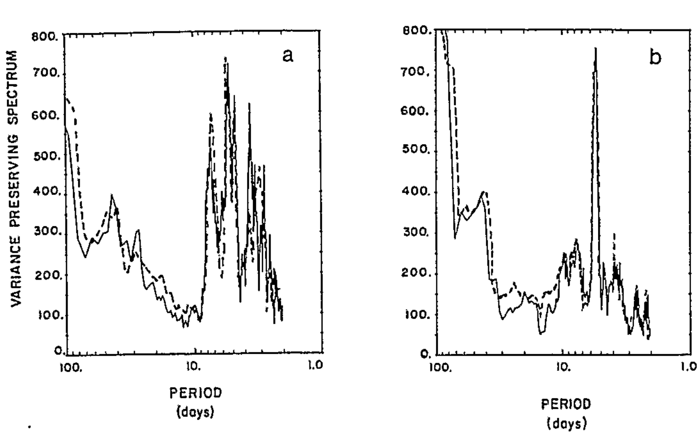


Figure 2

Variance preserving spectra (travel time²) versus periods in days of: a) a daily mean continuous inverted echo sounder record at 0°N-28°W (solid line) of the same duration as the wind record at SPP and of the same record cut in pieces (dashed line) as the wind at SPP (see *text*)*; b) the same as in Figure 2 a but using an inverted echo sounder record at 0°N-10°W with the same length and the same number of pieces as the wind record at GG.*

Spectre de la variance conservée de : *a*) un enregistrement (moyennes journalières) d'échosondeur inversé (IES) obtenu à 0°N-28°W, de durée totale similaire à celui de SPP (ligne continue) et de ce même enregistrement IES, fractionné en un nombre de morceaux de durée identique à ceux de SPP (*cf.* texte); *b*) même chose que pour la figure 2 *a*, mais relatif à un enregistrement IES et de vent obtenus respectivement à 0°N-10°W et GG.

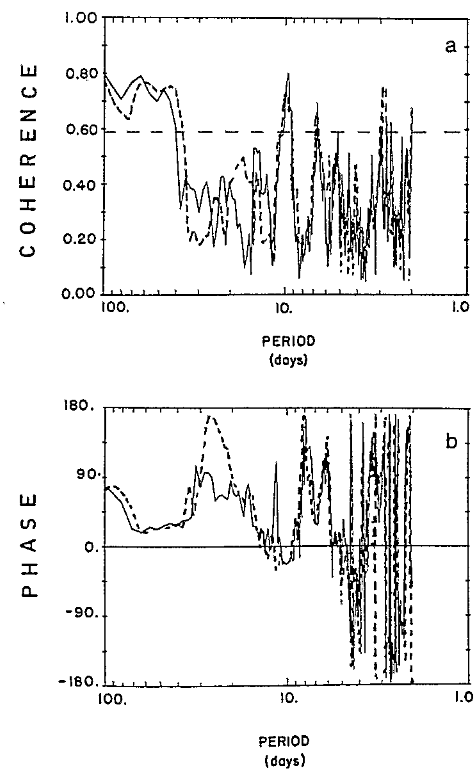


Figure 3

Coherence (*a*) *and phase* (*b*) *between the two continuous* (*solid line*) *and the two truncated* (*dashed line*) *inverted echo-sounder records defined in Figure 2. The horizontal dashed line indicates the 90% confidence limit.*

Spectres de cohérence et de phase entre les deux enregistrements IES continus (ligne continue) et fractionnés (pointillés) selon la procédure définie dans la figure 2, obtenus à 0°N-28°W et 0°N-10°W. La ligne pointillée horizontale indique la limite de confiance au seuil 90%.

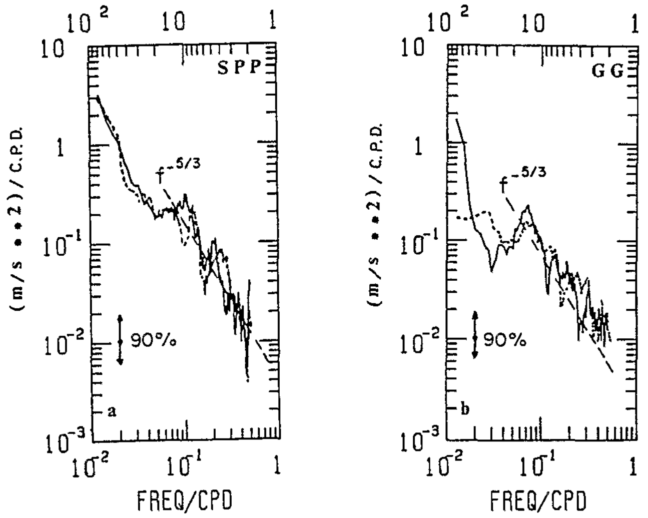


Figure 4

Rotary spectra of the wind stress records (daily mean values) at SPP and GG as shown in Figure 1. The solid and dashed lines represent respectively the clockwise and counter-clockwise senses of rotation. The universal slope $f^{-5/3}$ and the 90% confidence limit are shown on the figure.

Spectres rotatoires des enregistrements (moyennes journalières) des tensions de vent à SPP et GG (*cf.* procédure définie dans le texte). Les lignes continue et pointillée représentent respectivement les spectres correspondant aux rotations dans les sens rétrograde et direct. La pente —5/3 et l'intervalle de confiance sont indiqués sur la figure.

calculated from monthly mean values by Hastenrath and Lamb (1977) at both locations. They obtained a permanent negative wind stress curl at GG (clockwise) while at SPP the curl changes during the year (counter-clockwise in January and April, clockwise in July and October).

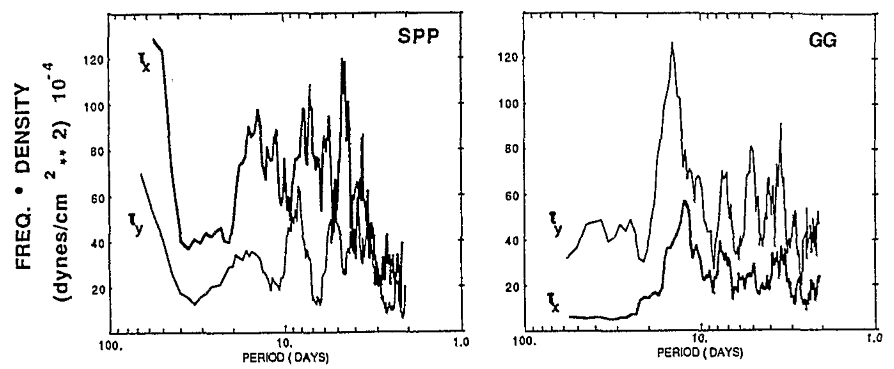
The variance preserving spectrum (power density times frequency) of the wind stress components at each location are shown in Figure 5. They both exhibit strong energetic peaks in the meridional component at GG and in the zonal component at SPP. These results agree with the dominant mean wind direction observed at SPP and GG (Colin, Garzoli, 1987). The main peaks occur in the 3-20 day period band at both locations either in the zonal or meridional directions. For periods greater than 40 days, the spectrum of the wind stress components is more red at SPP than at GG.

The coherence and phase spectrum of the two zonal (TAUX) and the two meridional (TAUY)wind-stress components are shown in Figure 6 and summarized in the Table. In this paper, due to the large distance (2800 km) which separates SPP and GG, no quantitative statements will be made, from the phase spectrum on the horizontal phase speed.

Figure 5

Variance-preserving spectra of the zonal (Tx) and meridional (Ty) wind-stress components (daily mean values) at 1°N-29°W and 0°N-4°W from reconstituted wind component time series (see 0°*N*-4°*W from reconstituted wind component time series* (see *text*).

Spectres de la variance conservée des composantes zonale (Tx) et méridienne (Ty) du vecteur tension de vent (moyennes journalières) à SPP et GG.



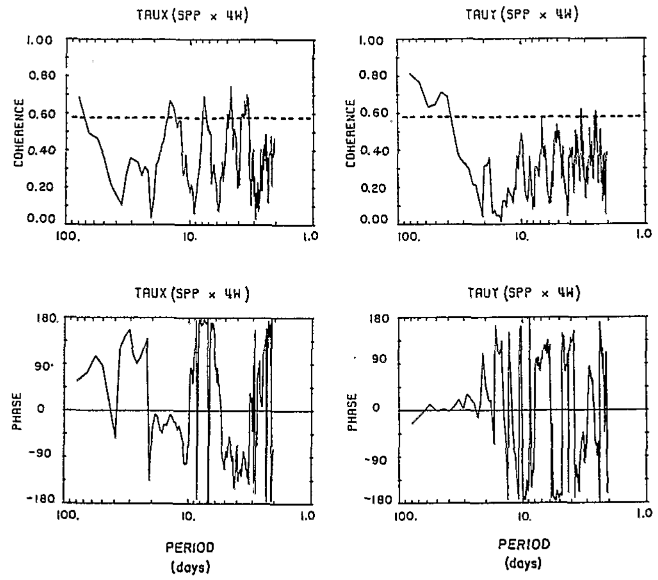


Figure 6

Coherence and phase spectra between the two zonal (left side) and the two meridional (right side) wind stress components at SPP and GG (daily values) as observed during the SEQUAL/FOCAL experiment. The dashed lines in the coherence spectra indicate the 90% confidence limit.

Spectres de cohérence et de phase des composantes zonales (gauche) et méridiennes (droite) des enregistrements de tension de vent (moyennes journalières) à SPP et GG.

Table

Periods and amplitudes of the peaks in a cross-spectral analysis between the two zonal and the two meridional components of the wind-stress at 1°N, 29°W and 0°N-4°W. The 90% confidence limit (relative to 18° of freedom) for the coherence spectrum is 0.58.

Périodes et amplitudes des pics observés dans les spectres de cohérence et de phase obtenus entre les deux composantes zonales (partie supérieure) et les deux composantes méridiennes (partie inférieure) des tensions de vent à 1°N, 29°W et 0°N-4°W.

				τ^x, τ^x			
Period (days)		14.7	7.6	5.2	4.6	3.6	
Coherence		.67	.69	.50	.75	.67	
			τ^y, τ^y				
Period (days)	40-45		9.9	5.2	—		2.6
Coherence	.72		.43	.50	—		.59

WIND OSCILLATIONS

In this section the structure and the intensity of the main peaks observed in the spectra (Fig. 4, 5 and 6) at SPP and GG will be discussed. The period band classification below corresponds only to energetic bands which appear in the power density variance preserving and coherence spectra.

Periods greater than 20 days

For periods centred at 35-40 days the rotary spectrum at GG is 2.5 times more energetic in the counter-clockwise than in the clockwise sense. At SPP, the opposite is observed with, however, a smaller difference. The corresponding ellipse stability (significant at the 90% confidence limit at both locations), mean orientation (major axis) and rotary coefficient (Gonella, 1972) indicate a more rectilinear and zonal orientation at SPP (118°) than at GG (167°). The discrepancy in the rotary spectrum between SPP and GG will also appear in the variance preserving spectrum of the wind components.

The variance preserving spectra (Fig. 5) show, at periods centred at 40 days, an increase of energy in the meridional component at GG. At SPP, the energy increases in both components, but no significant peak is observed. The cross-spectral analysis shows significant coherence (0.70) only between the two meridional wind stress components with a zero phase lag (Fig. 6).

The period band 30-40 days is known to be an energetic frequency for the tropical troposphere. Its existence was first reported by Madden and Julian (1971; 1972) from wind and surface pressure observations in the tropics (Pacific Canton Island). They associated the fluctuation with the eastward propagating global scale perturbation (zonal wave number 1) whose largest amplitude is found in the western Pacific Ocean. Lau and Chan (1985) also found in the Indian/Western Pacific Ocean an eastward propagation with a mean speed of 4-5 m/s. Meridionally propagating systems of troughs and ridges have been also observed during the Indian summer monsoon (Sikka, Gadgil, 1980); the meridional propagation of the 40-days mode is related to the active/break cycle of the monsoon at that time (Murakami, 1984). The high coherence observed in the spectrum between the two meridional wind stress components at SPP and GG at that time scale could be, as in the Indian Ocean, related to the oscillations originated by the West African Monsoon.

Periods from 10 to 20 days

An energetic oscillation appears in both components at SPP and GG, with a larger amplitude in the meridional direction for GG and in the zonal direction for SPP. The oscillation is centred at 14.7 days (Fig. 5). It was previously observed during 1979 at both locations (Colin, Rual, 1982; Garzoli *et al.*, 1982) and during the first part of SEQUAL in 1983 (Garzoli, Katz, 1984). The rotary spectrum presents at GG a higher energy level (61%) in the clockwise than in the counter-clockwise sense, associated with a mean orientation of 125° and a significant (0.44) ellipse stability at the 90% confidence level. At SPP the energy level is the same in both senses, associated with a mean orientation of 150°. The structure of the oscillation, like the two described above, is different at GG and SPP. Oscillations with periods centred around 15 days have previously been observed in the stratosphere and attributed to eastward propagating Kelvin waves (reviewed by Yanai, 1971) but with no apparent influence on the troposphere (Yanai, Maruyama, 1966). However, spectral analysis of wind observations both in the upper and lower troposphere have shown the presence of a 15-day oscillation associated with a westward propagation (Parker, 1973). Krishnamurti and Krishnamurti (1980) described the characteristics of the 15-day oscillation and associated it with westward propagating modes. The cross-spectral analysis shows (Fig. 6) a preferential zonal propagation with no significant eastward or westward direction.

At 11-day period, the variance preserving spectrum of the two zonal wind stress components exhibit a high energy level; the components however are not coherent. Such a fluctuation has already been observed over the Indian monsoon domain (Krishnamurti, Bhalme, 1976).

Periods less than 10 days

Energetic oscillations in the frequency band 7-9 days are present in the time series of both wind components and at both sites; the energy level is larger at SPP than at GG. The cross-spectra show a significant peak (0.70) at 7-8 day period only between the two zonal components. This period corresponds roughly to half the period of the energetic peak found at 14.7 days and could be therefore identified as an harmonic. However, according to the theory of linear waves, and using a typical mean stratification, this period corresponds to an atmospheric Kelvin wave that propagates with a phase speed of 60 m/s (*i.e.* Gill, 1980). Similar fluctuations have been pointed out in satellite-observed clouds in the North Pacific Ocean (Murakami, Ho, 1972*a*; 1972*b*) and in the surface wind field of the Equatorial Pacific (Luther, 1980) with lower energy levels in the East than in the West (Chiswell *et al.*, 1985).

A very energetic oscillation with periods from 4 to 6 days appears at both locations and with the same amplitude. At GG, the amplitude is three times higher in the meridional component spectrum than in the zonal component one. At SPP two peaks of energy (4.8 and 5.8 days) are present in the zonal component spectrum (Fig. 5). The cross-spectral analysis shows a significant coherence centred between 4 and 5 days but only in the zonal direction (Fig. 6).

Energy in the wind spectrum at this particular frequency has been detected in wind observations worldwide. It was first found both in the meridional wind components and satellite-observed cloud data (Murakami, Ho, 1972*a*; Burpee, 1972; Mistra, 1972). The maximum amplitude, however, appears at low latitudes (Murakami, Ho, 1972*a*; Hayashi, 1973) and seems to be related to the latitudinal excursion of the Intertropical Convergence Zone. All authors associated this fluctuation with an easterly first meridional mode inertial gravity wave. According to Wallace (1971) the oscillation in the 5-6 days band might correspond to the mixed Rossby-gravity wave mode associated with the first baroclinic atmospheric mode. Results from the present analysis tend to confirm this hypothesis in the Gulf of Guinea, where the energy level is much larger in the meridional wind stress component than in the zonal one (Fig. 5).

A 3-4 day oscillation clearly appears in both components at SPP. At GG this oscillation is present with a higher energy level in the meridional than in the zonal direction. The coherence level (0.65) is of the same order of magnitude as that found for the 4-6 day oscillation for the two zonal components (Fig. 6). This oscillation was first observed in the Pacific (Groves, Miyata, 1972), then in the North Atlantic and finally in the equatorial areas (Halpern, 1979 for the Pacific Ocean and Garzoli and Katz, 1981 for the Western Atlantic). It corresponds to a first mode inertial gravity wave. The present analysis shows that this oscillation is also present in the eastern side of the equatorial Atlantic.

OCEAN RESPONSE

In this section, the high frequency variability of the oceanic records obtained in the Gulf of Guinea during 1983-1984 will be analyzed in conjunction with the previously described local wind field. Results will be compared and interpreted on the basis of similar analyses performed west of the Gulf of Guinea (Garzoli, 1987; Weisberg *et al.*, 1987).

At 0°N 28°W, Garzoli (1987) as part of a large equatorial scale study of the oceanic high frequency oscillations (west of 10°W), analyzed the wind stress components at SPP in conjunction with travel time records obtained by two inverted echo sounders (IES) deployed nearby. The main results can be summarized as follows: three dominant bands of energy are observed in the combined spectrum of the ocean and the atmosphere: 20-30 days, 13-16 days and the inertial gravity wave band (periods less than 10 days). Oscillations at 30 day period are not wind forced; they are related to instability waves (Philander, 1978; Weisberg, 1984). A forced oscillation that can be distinguished from the fortnightly tide dominates the oceanic spectrum at periods centred at 14.7 days with maximum amplitude off-the equator. The oscillations at 5.2 and 3.4 day period correspond to first baroclinic mode forced inertial gravity waves associated respectively with n = 1 and n = 3 meridional structure. From a spectral analysis of the temperature and current measurements at 10, 100 and 200 m depth, Weisberg *et al.* (1987) also found large peaks of energy centred around 35, 14 and 7.5 day period at 0°N-28°W.

In this section, a similar analysis will be performed between the wind data at 0°N 4°W and the time series of the temperature and current measurements obtained directly by current meters fixed on the mooring line, respectively at 10, 35, 60, 85 and 110 m depth. The comparison of the temperature observations obtained at 0°N-4°W and 0°N-28°W will be achieved through the vertically integrated thermal field. Garzoli (pers. comm.) showed at 0°N-28°W that: 1) the variance preserving spectra of the integrated temperature obtained both from the sounder and from the surface mooring temperature measurements are comparable; and 2) despite a weak difference in the energy level between the two spectra, the two time series are highly coherent (0.80) up to 60 days.

The Power Density Spectrum (PDS) of the temperature and current records at 0°N-4°W have been obtained using the technique described in section II. The PDS of the temperature (T) and of the zonal (E-W) and meridional (N-S) components of the velocity of the current at 10 m depth (surface) are shown in Figure 7 *a*. The PDS of the vertically integrated (10-110 m) temperature (IT), zonal (IE-W) and meridional (IN-S) currents are shown in Figure 7 *b*. Both the surface and the integrated PDS of the temperature and the zonal velocity component exhibit a similar behaviour; the energy decreases from the very low frequency (seasonal time scale) up to 0.05 cpd. The PDS's of N-S and IN-S show in that frequency range a mean constant energy level. For periods less than 60 days, the PDS's exhibit

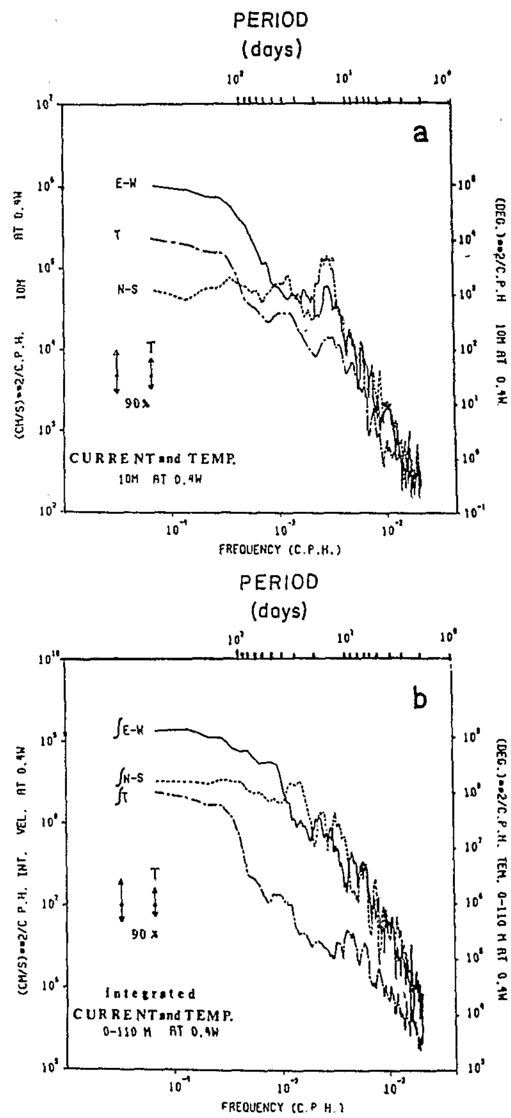


Figure 7

Power density spectra of daily mean values at 0°N-4°W of the: a) temperature and horizontal components of the current at the surface; and b) vertically integrated temperature and horizontal components of the currents (10-110 *m*) *from reconstituted time series* (see *text*). *The records last from* 02/13/83 *through* 09/27/84. *The vertical arrows indicate the* 90% *confidence limit.*

Spectres d'enregistrements (moyennes journalières) à 0°4°W de : *a*) température (T) et de courant [composantes zonale (E-W) et méridienne (N-S)] de surface; et *b*) de température (IT) et des composantes zonale (IE-W) et méridienne (IN-S) intégrées de 10 à 110 m. Les enregistrements débutent le 13/02/83 et s'achèvent le 27/09/84. Les intervalles de confiance correspondant au seuil 90% sont indiqués.

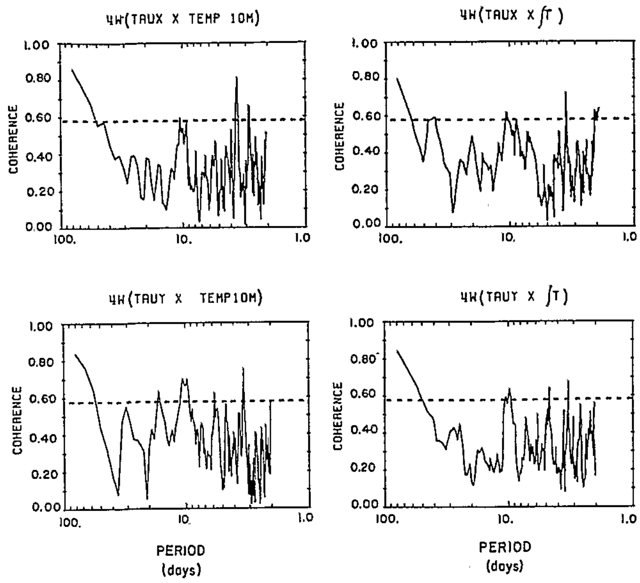


Figure 8

Coherence spectra at 0°N-4°W between the horizontal components of the surface wind stress with the temperature at 10 m depth (left side) and with the vertically integrated temperature (right side). The data correspond to daily mean values.

Spectre de cohérence entre les enregistrements (moyennes journalières) des composantes zonale (TAU X) et méridienne (TAU Y) du vecteur tension de vent à GG avec les enregistrements (moyennes journalières) à 0°N-4°W de : 1) la température à l'immersion 10 m (partie gauche) ; et 2) la température intégrée de 10 à 110 m (partie droite).

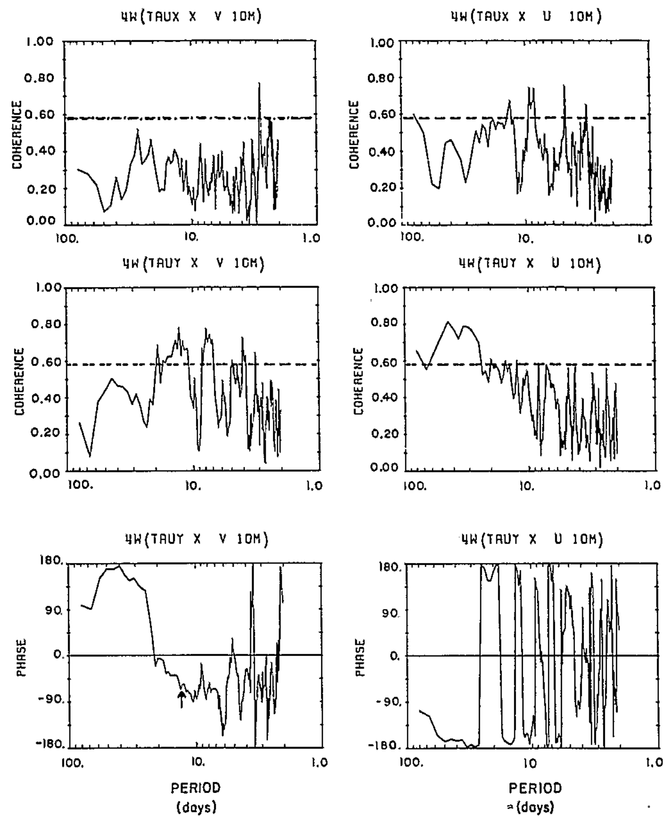


Figure 9

Coherence and phase spectra at 0°N-4°W between the horizontal wind-stress components (daily mean values) and the meridional (left side) and zonal (right side) component of the surface current. The phase spectrum between the two meridional (lower left panel) and the two zonal (lower right panel) components of both the wind stress and the surface current are shown. The dashed lines corresponds to the 90% confidence limit. A negative phase lag indicates that 1 leads 2.

Spectres de cohérence entre les enregistrements (moyennes journalières) des composantes zonale (TAU X) et méridienne (TAU Y) du vecteur tension de vent avec les composantes méridienne (V) et zonale (U) du courant à l'immersion 10 m. Les spectres de phase mentionnés sur cette figure concernent seulement les deux composantes méridiennes (bas à gauche) et les deux composantes zonales (bas à droite) du vent et du courant à 10 m. La ligne pointillée horizontale indique la limite de confiance au seuil de 90%. Une valeur négative du spectre de phase indique que le vent conduit le courant.

peaks of energy in the 34-42, 13-15 and 7-12 day period bands for the temperature and in the 34-42, 26-34, 12-17 and 5-10 day bands for the current measurements.

The oceanic peaks of energy observed at 0°N-4°W will be analyzed in correlation with the local wind stress variability and compared with those observed further west (in particular at 28°W) in the following period bands: 20-50, 10-20, 7-10 and 3-6 days.

Period band 20-50 days

The T and NS PDS's are energetic in the 33-45 day period band; the peaks are centred around 38 days; the E-W PDS exhibits no significant peak in that period band (Fig. 7 *a*). Subsurface: 1) the IT is also energetic but the amplitude and the width of the peak are smaller; 2) the IN-S is energetic but at a different time scale; the amplitude maximum is now found in the 26-34 day period band (Fig. 7 *b*). The IE-W PDS, like the surface one, presents no significant peak in that period band.

Maxima of coherence are found at 31 days between the meridional component of the wind stress with both the horizontal component of the surface current (90% confidence limit) and the surface temperature (80% confidence limit; Fig. 8, 9). The phase lag (Fig. 9) which appears in the phase spectrum between the meridional component of the wind stress and the zonal component of the surface current in the 30-50 day period band is $-\pi$ which means that intensifications of the southerly wind lead the increases of the South Equatorial Current.

Weisberg *et al.* (1979) found from moored current measurements (1976 through 1978) at 0°N-4°W and at 500 m depth, a peak of energy in the N-S PDS, centred at 31 day period that propagates zonally and vertically; they identified this oscillation as a mixed Rossby-gravity wave; they also found no significant peak in the corresponding temperature and east-west current velocity spectra in the 34-42 day period band. At 0°N-28°W, the T, N-S, IT and IES PDS's exhibit a significant peak of energy in the 20-42 day period band (Garzoli, 1987; Weisberg *et al.*, 1987); the temperature PDS's are particularly energetic in the 28-42 day period band at 10 m depth and in the 20-30 day period band at 100 m depth. Legeckis and Reverdin (1987) observed in infrared satellite images meridional oscillations of a zonally oriented SST front in June-July 1983 (24 days, 1 000 km) with maximum amplitude to the West of 10°W.

In the 25-30 day period band, the oscillations at 0°N-28°W are not forced by the atmosphere (Garzoli, 1987) but by the barotropic instability waves (Philander, 1978; Weisberg, 1984) induced by the large meridional shear which prevails in boreal summer between the North Equatorial Counter Current and the South Equatorial Current. At 0°N-4°W, the only significant peak of energy at that time scale is found in the IN-S PDS with no significant coherence with the wind; the presence of such a peak at 0°N-4°W below the surface could be explained through the internal Rossby-gravity wave process which is able to carry the energy eastward and downward at locations remote from the generation area (Cox, 1980; Weisberg *et al.*, 1979).

Period band 10-20 days

The T, N-S and E-W PDS's show a significant peak of energy in the 13-15 day period band (Fig. 7 *a*). Subsurface, differences are observed (Fig. 7 *b*); the peak in the: 1) IT PDS has completely disappeared; 2) IE-W PDS is centred at 17.8 day period; and 3) the IN-S PDS presents two peaks respectively centred at 16.0 and 12.4 day period.

The cross-spectral analysis shows a significant coherence level between the meridional component of the wind stress and the surface temperature for periods located in the 15.5-17.7 day period band (Fig. 8). The coherence is also significant at that time scale between the two zonal and the two meridional (absolute maximum coherence) components of both the wind stress and the current velocity (Fig. 9); this is in agreement with the rotary spectra results which both show the same ellipse orientation and the same prominent clockwise rotation (figure not shown here). The phase spectrum, in the meridional direction (Fig. 9, bottom and left panel) indicates that the wind leads the current by 1.8 ± 0.8 day.

During GATE (Global Atlantic Tropical Experiment), Weisberg (1979) found from moored current meter measurements obtained at 0°N 10°W during the 1974 boreal summer a peak of energy centred around 16 days in the N-S PDS but with no corresponding significant peak in the E-W PDS. The same oscillation was also observed at the same time by Duing *et al.* (1975) in the space and time distribution of the meridional component of the current velocity deduced from profiling current measurements along the equator. Colin and Rual (1982) pointed out, from moored current measurements at and below the surface at 0°N 4°W, at 15-16 day period oscillation during the CIPREA (Circulation et Production de la zone Équatoriale Atlantique) programme. At 0°N 28°W, contrary to 0°N 4°W, the PDS of the meridional component of the current velocity, in the 11-15 day period band, is only significant at 100 m depth. The temperature PDS, on the other hand, exhibits a peak of maximum amplitude at that time scale, at the surface. Below 200 m depth, the peak has completely disappeared (Weisberg *et al.*, 1987); the variance preserving spectrum of the IES record at 0°N 28°W (full line) presents no significant peak in that period range (Fig. 2 *a*).

In conclusions, differences are observed in the PDS's of the temperature and horizontal components of the velocity of the current at 0°N 4°W and 0°N 28°W, in the 10-20 day period band: 1) at 0°N 4°W, the amplitude of the peak is maximum at the surface for both the temperature and the meridional component of the velocity of the current, while at 0°N 28°W this occurs only for the temperature; 2) the amplitude of the peak in the T and N-S PDSs strongly decreases with depth at 0°N-4°W. Cross-spectral analysis shows coherence in the 13-15 day band at 0°N 4°W between the atmosphere and the ocean. At 0°N 28°W coherence is surprisingly observed between the wind and the IES record although no significant peak appears in the variance preserving spectrum of the oceanic record at that period.

Period band 7-10 days

The PDS of the surface current (zonal and meridional components) exhibit peaks of energy centred at 9 and 7 day period (Fig. 7 *a*). Subsurface, the peak is only significant in the IE-W and IT PDSs. The amplitude and the width of the peak in the IT PDS increase with depth (Fig. 7 *b*).

The cross-spectral analysis shows a significant coherence between the horizontal components of the wind stress both with the temperature (surface and integrated records) and the horizontal components of the surface current (Fig. 8, 9); in particular, maxima of coherence (0.70) are observed between the two zonal components of both the wind stress and the surface current. The two meridional components are, on the other hand, highly coherent in the 7-8 day period; the phase spectrum (Fig. 9, bottom and left) shows a mean negative value of −67°, which indicates that the meridional component of the wind stress leads the meridional component of the current by 1.4 ± 0.4 day in that period range.

Weisberg (1979) found at 0°N-10°W and at 125 m depth, a peak centred at 9 days in the E-W PDS, without any peak at 10 m depth. At 0°N-28°W, the only significant peak in that period band is: 1) observed in the integrated temperature PDS; and 2) centred at 7-8 day period. The cross-spectral analysis shows that the wind (zonal component) forces the ocean in the 8-8.5 day period band (Garzoli, 1987).

In conclusion, the 9-day period appears at 0°N 4°W (surface and subsurface for E-W, subsurface for IT) and at 0°N 10°W (subsurface) but not at 0°N 28°W. This oscillation is atmospherically forced and seems specific to the Gulf of Guinea. The 7-8 day period oscillation on the other hand is found both at 0°N 4°W and at 0°N 28°W and is atmospherically forced at both places.

Period band 3-6 days

The N-S and E-W PDSs present a significant peak at 3.8-4.0 day period (91 to 96 hours) which is not significant either in the T, IT, IN-S and IE-W PDS's. Cross-spectral analysis shows that the two meridional components of both the wind and the surface current are significantly coherent in the 3.8-4.0 day period band (Fig. 9). The wind and the temperature are, on the other hand, significantly coherent at 3.4 day period.

At 0°N-28°W, the N-S PDS shows a peak of energy centred at 3.8-4 day period which is not significant in either T or E-W PDSs. The variance preserving spectrum of the integrated temperature record (IES) exhibits, however, a peak in the 3.2-3.4 day period band; the two components of the wind stress are surprisingly coherent with the IES record at that time scale (Garzoli, 1987).

In conclusion, the current and the temperature records at the surface are coherent with the horizontal component records of wind stress respectively at 3.8-4 and 3.4 day period. Furthermore, the 3.4 day period oscillation observed in the thermal field at 0°N 4°W could correspond, like that observed at 0°N 28°W in the IES record, to a forced first baroclinic inertial gravity wave (Garzoli, Katz, 1981; Garzoli, 1987).

CONCLUSIONS

The synoptic and continuous *in situ* measurements obtained during the FOCAL/SEQUAL programme at extreme sides of the equatorial Atlantic basin permits for the first time, a precise description and classification of the high-frequency variability (periods less than 100 days) of the wind at sea surface level (1°N 29°W, 0°N 4°W) and of the oceanic response at 0°N-4°W.

The spectra of the wind time series show energetic oscillations with periods that spread from the synoptic to the inertial gravity wave scale. The wind stress component spectra exhibit peaks of energy at 1°N 29°W and 0°N 4°W in the 20-50, 10-20, 7-9, 4-6 and 3-4 day period bands with significant coherence between the two stations at 40, 14.7, 7.6, 4.6 and 3.5 periods. The oscillation centred at 40-day period presents more energy in the counterclockwise than in the clockwise sense at GG. The opposite is observed at SPP. The oscillations are coherent (North-South direction) and in phase at both sites. The 14-15 day period peak is particularly energetic at both locations and in both zonal and meridional components. The cross-spectral analysis shows preferential zonal propagation. In the 7-8 day period band, the coherence spectrum exhibits a significant peak between the two zonal components of the wind stress. At GG more energy is, however, observed in the meridional than in the zonal component. The 5-6 day oscillation is energetic at GG and SPP and mainly appears at both locations in the meridional components. The 3-4 day period oscillation is observed in both analyzed sites and the coherence is only significant in the zonal direction.

The power density spectra of the surface (10 m depth) and integrated (10-110 m) temperature and current records at 0°N 4°W exhibit peaks of energy in the 20-50, 10-20, 7-10 and 3-4 day period band. Amplitude maxima are observed in the first two bands. The amplitude is larger in the surface records than in the integrated ones except however for the 9 day period oscillation. The 40-50 day period oscillation appears at the surface in the temperature and meridional component of the current velocity records. Subsurface, this oscillation is only present in the temperature field. Cross-spectral analysis shows that the meridional component of the wind stress and the zonal component of the surface current are highly coherent at that time scale. At periods centred in the interval 14-16 days, the power density spectra of the oceanic records are energetic except for the integrated temperature. The meridional components of both the wind stress and surface current are coherent at that time scale, with the wind leading the current by 1.8 ± 0.8 day. The 9-day period oscillation clearly appears at the surface (current) and in the integrated temperature and seems to be specific to the Gulf of Guinea; it has also been observed at 0°N-10°W but not at 0°N-28°W. Significant coherence is observed at that time scale at 0°N-4°W between the zonal components of both the wind stress and surface current. The 7-8 day oscillation period, on the contrary, appears at 0°N-4°W in the coherence spectrum between the meridional component of the wind stress and the meridional component of the surface current, with the wind leading the current by 1.4 ± 0.4 day. The 3.8-4 and the 3.4 day oscillations which are observed respectively in the surface current and surface temperature are atmospherically forced at 0°N 4°W.

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