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Remotely forced biweekly deep oscillations on the continental slope of the Gulf of Guinea

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Abstract:

Current meter measurements on the continental slope of the Gulf of Guinea (at 7°20′S and 1300 m depth) have revealed biweekly oscillations of the currents, bottom intensified and oriented along the bathymetry. We develop a three-dimensional primitive equation model of the Gulf of Guinea to study the oscillations and their forcing mechanism. The high resolution (1/12°) regional model reproduces remarkably well the main characteristics of the deep currents on the continental slope. Experiments with different forcings demonstrate that the biweekly variability at 1300 m depth is remotely forced by equatorial winds. Deep Yanai waves generated by the wind propagate eastward along the equator. Upon reaching the African coast, the energy propagates poleward in both directions as coastal trapped waves. The selection of the dominant biweekly period is explained by the absence of equatorial waves with westward group velocities in that frequency band. Contrary to a previous hypothesis involving tidal forcing, our interpretation is coherent with the significant interannual variability of the biweekly energy.

Keywords: Coastal trapped waves; numerical modeling; Gulf of Guinea

1. Introduction

There has been recently a renewed interest for the intra-seasonal variability in the tropical Atlantic, both in the atmosphere and in the ocean. The African monsoon is characterized by significant variability of rainfall as well as winds at periods between 10 and 60 days (*Janicot* [2001]). Biweekly oscillations of the winds are emphasized by *Grodsky and Carton* [2001] as well as *Mounier and Janicot* [2004]; the associated modes of variability cover the whole tropical Atlantic, from the Gulf of Guinea to the intertropical convergence zone. In the equatorial band the variability of surface winds is the main driving mechanism for the ocean, and indeed oceanic variability is found in the equatorial Atlantic ocean at periods between 10 and 60 days. *Garzoli* [1987] used inverted echo sounders to document oscillations of the upper thermocline and their relationship with the atmospheric variability. Recently *Bunge et al.* [2006] analyzed current meter measurements at 10°W along the equator. They found variability at periods ranging from 5 to 40 days, down to a depth of 1500 m, and suggested that the wind is probably the most important driving mechanism for periods shorter than 20 days.

In the deep ocean farther south (at 7°20'S), biweekly current oscillations have been observed recently on the continental slope off Angola (*Vangriesheim et al.* [2005]). The measurements were carried out during the Ifremer (Institut Francais de Recherche pour l'Exploitation de la Mer) pluridisciplinary program so-called BIOZAIRE, whose main focus was the study of benthic ecosystems. Long term moorings of sediment traps and current meters have been installed near the sea floor between years 2000 and 2003, in a water depth of 1300 m (Fig. 1). Four year time-series of current velocities at 30 m above the bottom are shown in Fig. 2. The currents exhibit remarkable biweekly oscillations, with a peak-to-peak amplitude of 20-30 cm/s, which completely dominate the signal at sub-inertial frequencies. The oscillations are bottom-intensified and clearly oriented along the bathymetry, which is why *Vangriesheim et al.* [2005] have tried to explain them in terms of linear topographic waves. The Coastal Trapped Waves (CTWs) model of *Huthnance* [1978] has been found the most adequate to describe the observations. This model assumes a topographic slope which is uniform in the direction of the coastline, so that the linear solution is a superposition of modes propagating along the coast, with a fixed cross-slope and vertical structure. For mode i, the velocity changes sign i times across the slope. *Vangriesheim et al.* [2005] show that modes 3 and 5 are consistent with the observed data, so that the biweekly oscillations could be explained by a superposition of CTW modes. However, they consider only the simplest model, one of free coastal trapped waves propagating along an infinite slope. Such waves exist at all sub-inertial frequencies, so that the free solutions cannot explain the selection of the biweekly frequency in the observations. Moreover, the simple model does not allow a quantitative study of the mechanisms that could generate these deep oscillations.

Vangriesheim et al. [2005] were the first to report biweekly current oscillations in the Gulf of Guinea at such a depth (1300 m), but biweekly variability of sea level and temperature had been observed before (in the 1970s) on the continental shelf (e.g., *Picaut and Verstraete* [1979]). At that time, tidal forcing was proposed as the most likely mechanism (*Houghton* [1979], *Clarke and Battisti* [1983]). In the present paper we explore the surface wind as a forcing mechanism for the deep biweekly oscillations observed on the BIOZAIRE site. Our approach is motivated by the new evidence for a strong biweekly signal in the atmosphere, but also by preliminary results reported by *Vangriesheim et al.* [2005]. They considered a three-dimensional, primitive equations numerical model, with a 1/6° horizontal grid and 42 vertical levels (ATL6), forced by daily atmospheric winds, heat and freshwater fluxes from the ECMWF center. Although the model did not include tidal forcing, it did reproduce biweekly oscillations, oriented along the bathymetry. The ATL6 model results were not completely satisfactory, though. The kinetic energy spectrum simulated at the BIOZAIRE site had two peaks at the 14-day and 30-day periods, but the 14-day period did not dominate the signal. The amplitude of the modelled currents was lower than the observations by a factor of 5 to 10, and the bottom intensification was too weak. The main aim of the present study is to demonstrate that a regional model with improved vertical and horizontal resolution is able to reproduce the observed currents at the BIOZAIRE site, much better than ATL6. This is an important goal since the biweekly oscillations are the dominant subinertial signal at that location; their correct representation in a general circulation model is a necessary step before such models can be used in various contexts such as the study of the deep environment or the design of offshore platforms or pipelines.

The second section of this paper is devoted to a discussion of additional, unpublished current data at the BIOZAIRE site. Time series collected by TOTAL in 1997-1998 confirm the existence of the bottom-trapped oscillations and better document the vertical structure of the signal. We also discuss the hypothesis of tidal forcing by performing a harmonic analysis of the continuous 4-year series of deep current measurements now available at BIOZAIRE. Section 3 presents our new high resolution model of the Gulf of Guinea with a 1/12° horizontal grid and 100 vertical levels, which overcomes the deficiencies found by *Vangriesheim et al.* [2005] in the ATL6 model. A detailed validation of the model at the BIOZAIRE site is presented in section 4. The model is then used to investigate the generation of the deep biweekly oscillations on the slope (section 5). Using a suite of sensitivity experiments we demonstrate that the oscillations are remotely forced by equatorial winds. In section 6 we study the propagation of the signal and propose a mechanism explaining the selection of the biweekly frequency.

2. Observations

The first BIOZAIRE current data at 7°20'S,11°30'E, fully described in *Vangriesheim et al.* [2005], were carried out at three depths: 410 meters above bottom (mab), 150 mab and 30 mab, from March 2000 to January 2001. Measurements at 410 mab and 30 mab are available up to February 2003. The amplitude of the oscillations varies from year to year with a maximum in 2000 (Fig. 2).The biweekly current oscillations at 30 mab are oriented almost parallel to the local isobaths although in 2003 the orientation exhibits more variability (Fig. 2). The mooring at site A near the 1300 m isobath gives information on the vertical structure of the signal (which is bottom intensified) and an additional mooring located at 4000 m near the foot of the continental rise has been used by *Vangriesheim et al.* [2005] to discuss the cross-slope structure of the signal. They found that the biweekly oscillations were consistent with modes 3 and 5 of CTWs. The corresponding along-slope wavelengths and phase speeds for a biweekly frequency are 1200 and 680 km and 0.9 and 0.4 m/s, respectively.

In addition, unpublished current data provided by TOTAL are available at approximatively the same location, from a mooring deployed in 1385 m water depth at 7°40'S,11°40'E between September 1997 and October 1998. This mooring provides measurements over the whole water column, with 6 Aanderaa RCM 7/8 current meters at 385 m, 585 m, 785 m, 985 m, 1185 m and 1370 m below mean sea level. These new profiles will allow additional model validation.

Both mean velocities and eddy kinetic energy of the TOTAL mooring agree with the BIOZAIRE data (Table 1). Near the bottom, in both datasets, the mean flow is oriented to the south-east. The total eddy kinetic energy which is 19 $cm^2.s^{-2}$ at the shallower depth (385 m), decreases to 13 $cm^2.s^{-2}$ at 785 m and then increases to 23 $cm^2.s^{-2}$, its maximum value, at 1185 and 1370 m. The TOTAL data stick-plots (Fig. 3) exhibit intra-seasonal oscillations similar to the BIOZAIRE data. The orientation of the currents along the topography is not present for the shallower data, but well-marked at 1185 m and 1370 m. At the deepest level (15 mab) the current ellipse is less tight than for the BIOZAIRE measurements. The amplitude of the oscillations is smaller than those observed during the first year of the BIOZAIRE data but in good agreement with other, less energetic years as shown in Table 2. Kinetic energy spectra have been computed for all the levels and are displayed in Fig. 4. At all depths, peaks appear at a period close to 14 days. The magnitude of those peaks is nearly the same at the three shallower depths (358 m, 585 m and 785 m) but increases from 985 m to the near-bottom level where the 14-day period is the most energetic. Those results confirm the previous analysis of *Vangriesheim et al.* [2005] who showed an intensification of the 14-day oscillations between 410 mab and 30 mab. Note that contrary to the spectra displayed by *Vangriesheim et al.* [2005], we have not filtered inertial motions in Fig. 4 (the inertial period at the BIOZAIRE site is close to 4 days). The observations do not show a large signal at the inertial frequency. At periods of a few days, the currents are more energetic at 385 m than in the deep layers, contrary to the biweekly period.

Vangriesheim et al. [2005] used three years of current meter measurements; an additional year (2003) is now available at the same location, for the deepest level only (30 mab). We can thus compare the kinetic energy in the frequency band around 14-day (12-17 days) for four different years (Table 2). The 14-day eddy kinetic energy has a strong interannual variability since the signal in 2000 is twice as energetic as the years 2001, 2002 and 2003. A wavelet analysis of the currents (*Guiavarc'h* [2007]) confirms the temporal intermittency of the 14-day signal. Those results suggest that those biweekly oscillations are not forced by the tide, since the astronomical forcing has no interannual variability. *Picaut and Verstraete* [1979] calculated spectra of sea surface height time series along the northern coast of the Gulf of Guinea. Two distinct peaks appeared at the 13.7 days and 14.7 days periods, corresponding to two tidal components (Mf and MSf). *Picaut and Verstraete* [1979] suggested that because the direct tidal forcing at those periods is weak, the biweekly sea-level oscillations must be due to the nonlinear interaction between the higher frequency components, M2 and S2 for the 13.7 day period and M2 and K2 for the 14.7 day period. We do not see such well separated peaks in the BIOZAIRE velocity spectra. Even in nonfiltered spectra (*Guiavarc'h* [2007]), there is an increased energy over a wide band (12 to 17 days). To further investigate this question, we have performed an harmonic analysis using the four years BIOZAIRE current data at 30 mab. None of the tidal components mentioned by *Picaut and Verstraete* [1979] appear to be significant, and their amplitude differs from year to year. It is quite likely that although low frequency tidal signals affect the sea surface height, they have a very small effect on currents because the phase variations of the biweekly tides in the Gulf of Guinea are small (R. Simon, personal communication). We thus conclude that atmospheric forcing is the most likely candidate to generate the observed oscillations, and we design our modelling strategy accordingly.

3. Model description

The GUINEA model developed for this study is based on the primitive equation code NEMO/OPA.9 developed at LOCEAN (http://www.lodyc.jussieu.fr/NEMO). It is a second order finite difference model with a free surface, formulated in z-coordinates. The implementation of partial step bathymetry with a new momentum advection scheme has led to large improvements of the representation of current-topography interactions (*Barnier et al.* [2006], *Le Sommer et al.* [2007]), which makes it a suitable model for our study. The horizontal grid is a Mercator grid with a resolution 1/12°, covering the Gulf of Guinea from 15°S to the Northern African coast near 5°N and from 2.5°W to the Eastern African coast. The vertical grid has 100 levels with 5 m resolution at the surface and 70 m resolution below 1500 m. This vertical resolution allows to resolve the strong stratification in the surface layers of the Gulf of Guinea as well as the currents near the bottom. The model bathymetry is based on ETOPO2 (*Smith and Sandwell* [1997]) smoothed by applying twice a Shapiro filter. The vertical mixing is performed by a second order closure (TKE scheme). Bottom friction is nonlinear, with drag coefficient $Cd = 1.10^{-3}$. A horizontal biharmonic operator is used for the lateral mixing of both tracers and momentum with coefficient equal to $5.10^{9} m^{4}.s^{-1}$. A Laplacian operator with a coefficient equal to $350 m^{2}.s^{-1}$ has been added at the equator (between 3°S and 3°N) in the upper 500 m following *Arhan et al.* [2006]. This additional mixing in the upper equatorial band was needed to control the strength of the equatorial undercurrent.

Open boundary conditions have been applied at the west and south boundaries following the method described in *Treguier et al.* [2001]. We added "sponge layers" for the two boundaries, with an additional Laplacian operator for momentum, to prevent the generation of spurious eddies. At the boundaries we need data for temperature, salinity and the velocity component normal to the boundary. Our study of 14-day oscillations requires high frequency boundary forcing (daily), which can be obtained only from a numerical model. We believe that it is important to ensure consistency between forcing at the open boundaries and the surface atmospheric forcing. For this reason we have used a lower resolution model (1/4°) in a larger domain including the GUINEA model region, and forced with the same atmospheric data. This model, called NATL, is similar to the one described in *Le Sommer et al.* [2007], except for a reduced northward extension and the absence of an ice model. It covers the Atlantic ocean from 24°S to 70°N with a 1/4° horizontal resolution and 46 vertical levels. A special strategy detailed in *Guiavarc'h* [2007] has been implemented to output daily fields in the region covered by the GUINEA model.

Both GUINEA and NATL are initialized using the Levitus climatology. The models are spun up during 5 years (1995-1999) using the forcing dataset of *Large and Yeager* [2004]. This dataset has been designed for CORE (Coordinated Ocean Reference Experiments) and includes carefully balanced data from various origins. The daily radiative fluxes and monthly precipitations are from satellite observations. The 6-hourly temperature, specific humidity and 10 m winds come from the NCEP/NCAR reanalysis. The turbulent fluxes are calculated using the CORE bulk formulae. In addition, monthly climatological river runoffs from the study of *Dai and Trenberth* [2002] are implemented as described by *Bourdalle-Badie and Treguier* [2006]. To avoid a large model drift due to the uncertainties in the freshwater fluxes, there is a relaxation of sea surface salinity to the LEVITUS climatology with a coefficient of 0.25 m.day^{-1}. The QUIKSCAT satellite scatterometer produces high quality daily wind fields since 2000 (*Bentamy et al.* [2002]). We prefer these to the NCEP/NCAR reanalysis winds for our reference experiment (REF) which is integrated over years 2000-2004 following the spin-up. Humidity, air temperature, radiative fluxes and precipitations are from the CORE dataset, but turbulent fluxes are calculated using QUIKSCAT winds in the CORE bulk formulae.

The REF experiment has been validated in *Guiavarc'h* [2007]; details are not repeated here. The surface circulation in the Gulf of Guinea (the Guinea current and the south Equatorial current) are adequately reproduced, as well as their strong seasonal variability. In the subsurface, the Equatorial Undercurrent agrees with the observations documented by *Arhan et al.* [2006] and displays a strong seasonal cycle. In the deep layers, the circulation is in agreement overall with *Stramma and Schott* [1999] and *Arhan et al.* [2003]. The drifts of salinity and temperature over the 10-years of simulation are relatively weak. However, the stratification at the equator differs from the climatology. The shallow and thin thermocline observed in the Eastern Tropical Atlantic is very difficult to capture in numerical models: in our case it is too deep and too thick, perhaps due to deficiencies in the forcing field as well as in the parameterization of vertical diffusion.

The main objective of the REF simulation is to reproduce the observed biweekly oscillations on the continental slope. In order to investigate their origin, a set of sensitivity experiments has been carried out by changing wind forcing and/or open boundary forcings from daily to monthly. Our strategy for sensitivity experiments with monthly wind forcing is the following. We continue to use daily wind speed to calculate turbulent heat fluxes and evaporation, but we force the momentum equation with a monthly averaged wind stress calculated from the reference experiment. In this way, we study the effect of high frequency momentum input by the wind in isolation, without modifying the turbulent heat flux.

4. Biweekly oscillations in the reference experiment

The main characteristics of the variability revealed by the BIOZAIRE data is the bottom intensification, the orientation of currents parallel to the topography, and a kinetic spectrum dominated by the biweekly frequency. Let us consider how these motions are reproduced by the REF experiment of the GUINEA model. Fig. 5 presents the velocities along the local isobath and the variance ellipses for the period around 14-day. Biozaire data are plotted together with the model velocities at the model grid point closest to the BIOZAIRE site, for each year (2000-2003). The agreement is good in general. The model reproduces very well the orientation and the period of the observed currents, although with a somewhat underestimated amplitude. This is a clear improvement over the ATL6 model, which had a peak-to-peak amplitude 5-10 times smaller than the observations. Biweekly oscillations are polarized along the bathymetry, except in 2003 when the observations show a wider ellipse not reproduced by the model. However, the model signal is not in phase with the observations. Coherences have been computed and vary from 0.43 to 0.72 for the 14-days period band, but are not significant at the confidence level 95%. Kinetic energy spectra have been computed at model levels close to the depths of the TOTAL mooring (Fig. 6). The energy level agrees well with the observed spectra (Fig. 4), confirming the visual impression of the along-slope velocity plots. The model spectra display a significant peak at all levels at a period close to 14 days, like the observations, and the bottom intensification is similar. This result is another improvement compared to the ATL6 model where the 30-day period was more energetic than the 14-day one. At shorter periods (a few days) the model kinetic energy is larger at the top level (389 m) than in the deep ocean, a feature that also appeared in the observed spectra.

We indicate the values of eddy kinetic energy integrated over the 12-17 days frequency band in Table 2 for a quantitative comparison with the data. The energy in the model is slightly lower than the observations both for TOTAL and BIOZAIRE data (except in 2001) but displays a similar interannual variability, with almost a factor of two between the least energetic year (2002) and the most energetic one (2000). For both model and data, kinetic energy over the 12-17 days period band represents the half of the total kinetic energy for subinertial frequencies (between 42 and 63% for the model, between 39 and 47% for the data). A profile of eddy kinetic energy averaged over 5 years (2000-2004) is plotted in Fig. 7. Values from TOTAL (year 1998) and Ifremer (two-year average at 410 mab and four-year average at 30 mab) are indicated for comparison. This figure confirms that the model captures well the observed bottom intensification of the 14-day signal. The kinetic energy ratio between the depths 1163 m and 772 m is about 3-5 (according to the width of the frequency band considered). This is close to the kinetic energy ratio between 1185 m and 785 m for the TOTAL data (2.8-5).

It is clear that the high resolution model GUINEA overcomes the major defects of the ATL6 model considered by *Vangriesheim et al.* [2005]. Various differences between the models can explain the improved results. First, a better forcing field is used (Quikscat winds) and the representation of bottom topography is made more realistic by a partial cell formulation (the latter has been found to improve the quality of a global version of this model by *Barnier et al.* [2006]). These improvements are also present in the larger domain, lower resolution NATL configuration (which is used to force the open boundaries of GUINEA). This leads to a better representation of the kinetic energy spectrum: in both NATL and GUINEA the 14-day period is dominant compared to the 30-day one, which was not the case in ATL6. Comparison of NATL and GUINEA shows that the increase in model resolution is necessary to represent the bottom intensification of the signal (Fig. 7). The very good results of the GUINEA model, which does not include the tides, confirm that tidal forcing is not necessary to reproduce the observed variability.

Note that our results are not strongly dependent on the wind product used for the forcing. In Fig. 8 the kinetic energy spectrum near the bottom at BIOZAIRE is reproduced (black curve, like Fig. 6) and the same spectrum for an experiment with CORE NCEP winds is indicated (experiment EXP6): there is no significant difference between the spectra.

5. Forcing mechanism of the biweekly oscillations

We now use sensitivity experiments to investigate the generation of the oscillations, as described in Table 3. Over the whole Gulf of Guinea, the wind exhibits 14-day variability (Fig. 12). The energy is larger in the northern part of the model domain (see Fig. 5 in *Bunge et al.* [2006]), in agreement with the analysis of *Grodsky and Carton* [2001] and *Mounier and Janicot* [2004]; however there is 14-day wind variability at the BIOZAIRE site. Local winds have often been invoked to explain the generation of coastal trapped waves (*Pizarro and Shaffer* [1998]). To test this hypothesis we have performed EXP1 forced by daily winds only in a local box along the African coast (Fig. 1). Elsewhere in the model, the daily wind stress is replaced by a monthly averaged wind stress computed from the REF experiment. For the EXP1 sensitivity experiment, there is no evidence of biweekly oscillations of the deep currents (contrast the red dashed curve in Fig. 8, with the reference in black). The large difference between EXP1 and REF exists at all depths for the 14-day frequency band (not shown). It is thus clear that the biweekly oscillations at BIOZAIRE are not generated by the local winds. On the contrary, in both experiments REF and EXP1, the kinetic energies at shorter periods (4-5 days) are much more similar. Local winds certainly play a part in generating the deep near-inertial motions.

Biweekly oscillations thus appear to be remotely forced in the model, and the most likely mechanism is the propagation of perturbations coming from the equatorial wave guide. This mechanism has been found to generate the intra-seasonal coastal trapped waves that are observed at the eastern boundary of the Pacific ocean, near the south American coast. *Shaffer et al.* [1997] describes low frequency fluctuations (50-day period) off Chile, which can be traced back to Kelvin wave events along the equator. *Enfield et al.* [1987] analyze oscillations at periods of 1-2 weeks that can be related to equatorial Mixed-Rossby-Gravity or Yanai waves. Both Kelvin and Yanai waves propage energy eastward along the Equatorial wave guide. *Clarke* [1983] has demonstrated that the reflexion properties of those waves at an eastern boundary are similar; they are partially reflected as Rossby waves and partially transformed into coastal Kelvin waves, which become coastal trapped waves in the presence of a bottom slope. With the strong stratification of the tropical oceans, the properties of coastal trapped waves are close to those of the coastal Kelvin waves (*Vangriesheim et al.* [2005]). The influence of the equatorial winds on the biweekly oscillations has been explored in the EXP2 experiment (Table 3) where the high frequency forcing is restricted between 5°N and 5°S. We observe oscillations along the topography with a peak-to-peak amplitude similar to the REF experiment (not shown). The kinetic energy spectrum (Fig. 8) exhibits a peak at the same period as REF with similar amplitude. The model results are compelling evidence that the 14-day oscillations at the BIOZAIRE location are remotely forced by equatorial winds, in agreement with the interpretation of similar measurements along the south American coast by *Enfield et al.* [1987] and *Shaffer et al.* [1997].

One may wonder whether it is the wind variability in the Gulf of Guinea itself, or rather the variability of the winds in the western part of the tropical Atlantic, that is more important to generate the coastal trapped waves that propagate to the south. Because GUINEA is a regional model we investigate this question by comparing two experiments, EXP3 and EXP4 (Table 3). In EXP3 we remove the high frequency winds over the GUINEA domain, but keep the influence of high frequency forcing outside the domain (we use monthly winds, but daily open boundary forcing). We do the contrary in EXP4. For those two simulations, we observe intra-seasonal oscillations oriented along the topography with similar amplitude, smaller than in REF. This is shown by the kinetic energy spectra (Fig. 8). We conclude that the energy of the 14-day coastal trapped waves found at BIOZAIRE is forced to a similar degree by the high frequency winds west of 2.5°W, and the winds east of that longitude (in the Gulf of Guinea).

So far, we have assumed that the biweekly oscillations have been forced by equatorial winds without taking in account the Tropical Instability Waves (TIW) present in the Atlantic at intra-seasonal periods. Those waves develop mainly between 10°W and 25°W and between 2°N and 5°N (*Caltabiano et al.* [2005], *Grodsky et al.* [2005]), outside the GUINEA domain at periods between 20 and 40 days. It is quite possible that such instabilities of the mean currents, rather than direct wind forcing, generate the 14-day variability that is present in the forcing at the open boundary in REF and EXP3. To test this possibility we perform experiment EXP5 which is like EXP3, but using daily open boundary conditions (OBCs) provided by a special NATL experiment forced by monthly winds. The possible influence of nonlinear instabilities both inside and outside the domain is thus taken into account in EXP5, unlike experiment EXP1 in which the influence of TIW was filtered by using monthly OBCs. On the kinetic energy spectra (Fig. 8), we find that EXP5 (like EXP1) has no peak at 14 days, which confirms that the energy in that band is directly forced by the wind rather than indirectly by flow instabilities. This is not true at lower frequencies: indeed for periods longer than 40 days we find that all experiments with daily open boundaries have similar energy, whether the direct wind forcing over the GUINEA domain is daily (REF), monthly (EXP3), or a combination (EXP2 and EXP5). On the contrary, the two experiments with monthly open boundary forcing (EXP4 and EXP1) stand out with a lower energy level (Fig. 8).

6. Propagation and period selection

Our sensitivity experiments support the scenario of wind-forced equatorial waves which then propagate poleward as coastal trapped waves upon reaching the African coast. Let us examine the characteristics of those equatorial waves in the reference experiment. At the equator at 0°E, the kinetic energy spectrum at various depths (Fig. 9) shows several peaks at period around 10, 14 and 35 days, the 35-days peak being the largest (unlike the kinetic energy spectrum at BIOZAIRE where the 14-days period dominates). Those three peaks at the equator at 0°E agree with the observations of *Bunge et al.* [2006] at 10°W. They carried out spectral analysis of current data between 800 m and 1500 m and found peaks at 7-day, 14-day, 24-day and 33-day periods. They attributed the 24 and 33-day oscillations to tropical instability waves, but concluded that periods shorter than 20 days were likely wind-forced. The 14-day oscillations had the symmetry characteristics of Yanai waves, i.e. a signal symmetric with respect to the equator for the meridional velocity and anti-symmetric for the zonal velocity. To expose the nature of the biweekly equatorial waves reproduced by GUINEA, we show energy maps for the 14-day period for both meridional and zonal velocities. To draw these maps (Fig. 10), we have performed spectral analysis for the two components along the equatorial section at all depths and extracted the signal for periods between 12 and 17 days. Since currents are much more energetic near the surface, Fig. 10 shows separately the surface layer and the depths below 200 m. At all depths, the meridional component of the signal is more energetic than the zonal component. This confirms the results from *Bunge et al.* [2006] that the biweekly oscillations at the equator are mainly due to Yanai waves (because of their symmetry, Yanai waves have zero zonal velocity at the equator, while Kelvin waves on the contrary have zero meridional velocity). In the equatorial Indian ocean, *Miyama et al.* [2006] show the existence of similar biweekly oscillations due to wind-forced Yanai waves. At biweekly period, both Yanai and Kelvin waves can exist in the tropical Atlantic ocean (Fig. 13). Biweekly variability in the atmospheric fields is predominant in the zonal wind stress component (*Grodsky and Carton* [2001]) and assymetric compared to the equator (more energetic north to the equator). So the biweekly variability of the wind stress is mainly projected into Yanai waves although less energetic Kelvin waves are present near the surface, as appears in Fig. 10. This same figure reveals that the signal is more energetic in the Eastern part of the domain. This is consistent with the eastward group velocity of Yanai waves. As shown on Fig. 10, the 14-day signal at the equator has a complex structure, which will be investigated further in a forthcoming paper. Here, we just note that an energy maximum is already present at depths of 1000-1300 m at the equator in the Eastern part of the Gulf of Guinea, and we focus on the propagation of this signal to the location of BIOZAIRE.

Coastal trapped waves generally have a signature at the surface (in the sea surface height field) so that their propagation has been studied using satellite altimetric data (e.g.,*Lazar et al.* [2006] in the tropical Atlantic). However this is possible only for periods long compared with the periodicity of the satellite orbit (about 1 week for TOPEX), so that it is not possible to study the propagation of biweekly waves from observations. A time-latitude diagram of the meridional velocity along the 1100 m isobath in the GUINEA model shows clearly a propagation of intra-seasonal waves away from the equator (Fig. 11). The propagation to the south can be observed beyond the latitude of BIOZAIRE. The phase velocity computed from this diagram varies from $c = 0.4$ m.s^{-1} between the equator and 3°S to greater values between 0.6 m.s^{-1} and 1.5 m.s^{-1} south of 3°S. Furthermore, the same figure drawn at several depths shows that the phase speed varies with depth (not shown). *Vangriesheim et al.* [2005] demonstrated that the 3^{rd} and the 5^{th} mode of CTW were compatible with the 14-day oscillations observed on the continental slope at BIOZAIRE. Here, the phase velocities computed with the model results indicate that those biweekly oscillations have complex characteristics and are probably due to a sum of several mode. The propagation and spatial distribution of those biweekly oscillations will be discussed in a forthcoming paper. Here we simply note that the signal propagation confirms our sensitivity experiments in pointing out the equatorial origin of the deep current variability at BIOZAIRE.

The remaining question is why the 14-day variability dominates over the other periods at BIOZAIRE, while the 35-day period dominates at the equator. Let us first consider the relationship between equatorial currents and equatorial winds. A kinetic energy spectrum has been computed for the daily QUIKSCAT winds over the latitude band 5°N -5°S (Fig. 12). Three peaks can be distinguished at 35, 14 and 9 days, corresponding to the dominant periods of the equatorial currents (Fig. 9). This is consistent with a linear response of the equatorial ocean to the winds, with the ocean acting as a low-pass filter (in the ocean the 35-day period is more energetic relative to the 14-day period, contrary to the atmosphere where spectral amplitudes in both bands are similar). Why then is the biweekly period so dominant at the BIOZAIRE site, with no large peaks corresponding the 9-day and 35-day maxima found along the equator? The most likely explanation is the one suggested by *Shaffer et al.* [1997], who have pointed out that for some combinations of frequency and wavelength, there is no wave propagating energy to the west along the equator. So for those combinations, all the energy reaching an eastern boundary propagates as coastal waves (no energy can be reflected westward).

We have drawn the dispersion diagram of equatorial waves with parameters appropriate to the tropical Atlantic (Fig. 13; baroclinic mode velocities have been computed using the mean stratification between 5°S and 5°N). The dispersion curves have been drawn for the first *meridional* mode of equatorial waves but for the first three *vertical* modes. Note that this is different from dispersion diagrams appearing in *Enfield et al.* [1987], *Shaffer* *et al.* [1997]. Only inertia-gravity waves and Rossby waves can propagate energy to the west; their dispersion curves are found at the top and bottom of the diagram respectively. There are no Rossby waves with period smaller than 30 days which is the cut-off period of the first baroclinic mode. The cut-off period corresponding to inertia-gravity waves is 5 days for the first baroclinic mode but note that it increases for higher vertical modes (Fig. 13). It reaches 11 days for the fifth mode. For the first five baroclinic modes together, there is a window between the periods of 11 days and 30 days where there is no Rossby nor inertia-gravity wave, so that all the energy propagates eastward on the equatorial waveguide and then poleward as coastal trapped waves. We believe that these properties of equatorial waves explain why there is a single energy peak around 14 days at BIOZAIRE, while there are three peaks in the signal at 0° along the equator.

7. Discussion

In this study we have used a numerical model to show that the biweekly oscillations observed on the African continental slope at 1300 m depth by *Vangriesheim et al.* [2005] are remotely forced by equatorial winds. The scenario demonstrated in the model is a direct forcing of Yanai waves along the equator at all longitudes, followed by poleward propagation as coastal trapped waves. We believe that this scenario explains the observed variability, because of the good agreement between the model reference experiment and the observations at the BIOZAIRE site. We find that the winds in a large equatorial band (5°N to 5°S) contribute to the forced response; another experiment with daily winds restricted to 2°N-2°S reproduced only half the energy (*Guiavarc'h* [2007]). This agrees with the Yanai wave structure of the equatorial response: Yanai waves have a maximum of meridional velocity at the equator, but antisymmetric extrema of zonal velocity on each side of the equator close to 2°N and 2°S for baroclinic modes 3 to 5.

Remote forcing of such coastal-trapped oscillations is not surprising. Propagation of coastal trapped waves or Kelvin waves away from the equator at intra-seasonal frequency (around 60 days) appears clearly in satellite altimetry data in the Gulf of Guinea (*Lazar et al.* [2006]). Similar propagation has been demonstrated in the eastern Pacific Ocean from current meters, altimetry and tide gauges at periods between 10 and 60 days by *Enfield et al.* [1987] and *Shaffer et al.* [1997], among others. In fact, one may wonder why such an explanation has not been proposed for the biweekly frequency along the continental shelf of the Gulf of Guinea, and why the generation by tides has been preferred in previous studies (*Picaut and Verstraete* [1979], *Clarke and Battisti* [1983]). One explanation is probably the small number of measurements (moorings and tide gauges) along the African coast compared with the south American coast, which makes it difficult to observe poleward propagation from the equator. Another explanation is probably the lower interannual variability in the Atlantic compared with the Pacific ocean. Observations of high frequency variability along the south American coast have generally followed El Nino events, and the authors have been able to relate the increased variability along the coast to equatorial perturbations. Obviously, the large interannual variability of the signal in the Pacific ocean makes a tidal origin much less likely. In the Atlantic, although interannual variability is also present in the biweekly oscillations at the BIOZAIRE site, the relationship with interannual variability at the equator is not straightforward. In a forthcoming paper, we try to link the seasonal and interannual variability of the biweekly oscillations to the variability of equatorial winds, and show that the oscillations are more complex than a simple linear response.

The good performance of the GUINEA model in reproducing the major characteristics of the observed variability on the continental slope is very encouraging, and perhaps unprecedented at such a large depth (1300 m). We have shown that the horizontal and vertical resolution of the GUINEA model are important to capture the bottom intensification and the energy of the signal. We anticipate that three-dimensional ocean general circulation models will contribute more and more to the study of such coastal trapped oscillations, because basin scale or even global models with comparable mesh size (1/12°) are becoming readily available.

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Data	**Year**	$\overline{u}$ (cm.s^{-1})	$\overline{v}$ (cm.s^{-1})	KE (cm^2.s^{-2})
Ifremer				
890 m	2001	-0.2	-0.4	17
(410 mab)	2002	-0.1	-0.4	21
1270m	2000	1.7	-2.7	43
(30 mab)	2001	0.5	-1.4	28
	2002	0.6	-1.9	21
	2003	0.4	-1.6	24
Total				
385 m	1998	0.3	-0.4	19
585 m	1998	-0.1	-0.4	14
785 m	1998	-0.5	0.2	13
985 m	1998	0.6	-0.4	19
1185 m	1998	0.4	0.1	23
1370 m	1998	0.9	-1.1	23

Table 1. Current Statistics at the BIOZAIRE site A. Ifremer data for years 2000-2002 are reproduced from *Vangriesheim et al.* [2005]; data from year 2003 and TOTAL have not been published before. The measurement depth are indicated in meters above bottom (mab) for the Ifremer mooring (total depth is 1300 m). The mean velocities are indicated in the zonal ($\overline{u}$) and the meridional ($\overline{v}$) directions. The eddy kinetic energy (KE) is calculated from the filtered time series, using a Lanczos filter with cut-off period of 6 days.

	Model			Data		
Year	14-day KE	total KE	Ratio	14-day KE	total KE	Ratio
1998	6.2	14.8	42	9.7	23	42
2000	11.0	17.6	63	19.5	44	44
2001	10.8	18.8	57	10.0	25	40
2002	5.7	11.7	49	8.4	22	39
2003	7.1	12.0	59	12.2	26	47

Table 2. Kinetic energy (KE, $cm^2.s^{-2}$) in the frequency band 12-17 days (14-day KE) and for subinertial frequencies (total KE), in the GUINEA model and in observations. For the model the KE is calculated at the level above the model bottom layer (135 mab). For the observations,the KE is calculated at 30 meters obave the bottom except in 1998 (15 mab). The ratio represents the percentage of the 14-day kinetic energy compared to the total kinetic enery.

Experiment	Wind forcing	Open boundaries
REF	daily	daily
EXP1	daily, 10°E-14°E, 2°S-15°S	monthly
EXP2	daily, 5°S-5°N	daily, 5°S-5°N
EXP3	monthly	daily
EXP4	daily	monthly
EXP5	monthly	daily from NATLM
EXP6	6-hourly NCEP winds	daily

Table 3. Sensitivity experiments carried out with the GUINEA model. All experiments cover years 2000-2004 following a common spin-up. Open boundary conditions come from a NATL experiment using the same daily forcing as REF, excepted for EXP5 which uses the NATLM experiment forced by daily heat and freshwater fluxes but monthly wind stress.

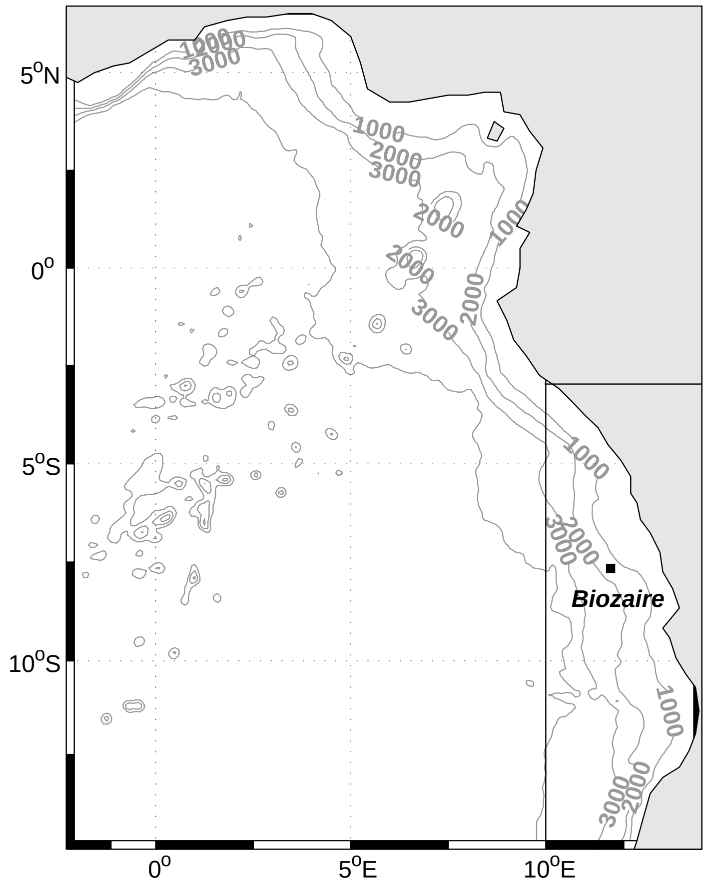

Figure 1. Bathymetry of the Gulf of Guinea and position of the BIOZAIRE mooring (Site A: 7°20'S,11°30'E). The TOTAL mooring (not shown on this map) is located at 7°40'S,11°40'E, 40 km SSW of the BIOZAIRE mooring at similar depth. The region shown is the domain covered by the GUINEA model. The box corresponds to the local box for daily wind forcing used in experiment EXP1 (Table 3).

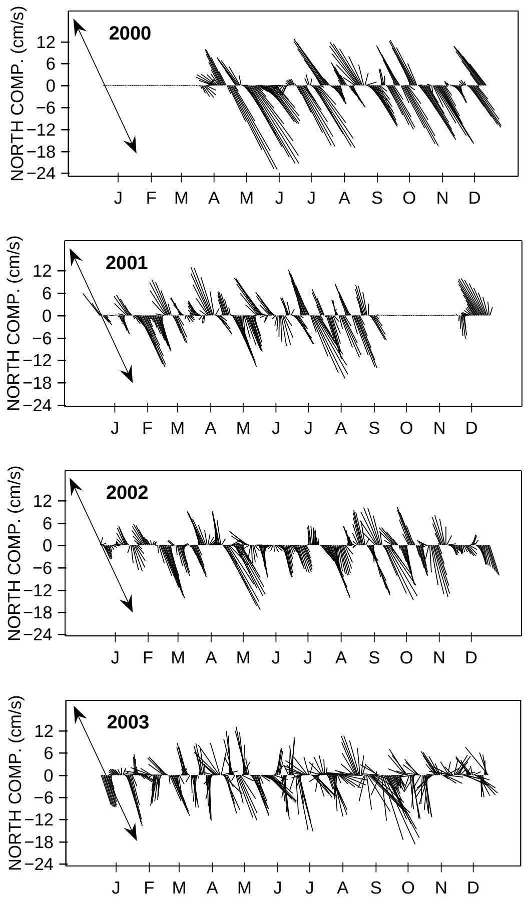

Figure 2. Stick plots of velocities at the BIOZAIRE mooring at 30 meters above the bottom (1270 m depth). The arrow indicates the direction of the local isobaths. Data are filtered using a Lanczos filter with a cut-off period of 6 days.

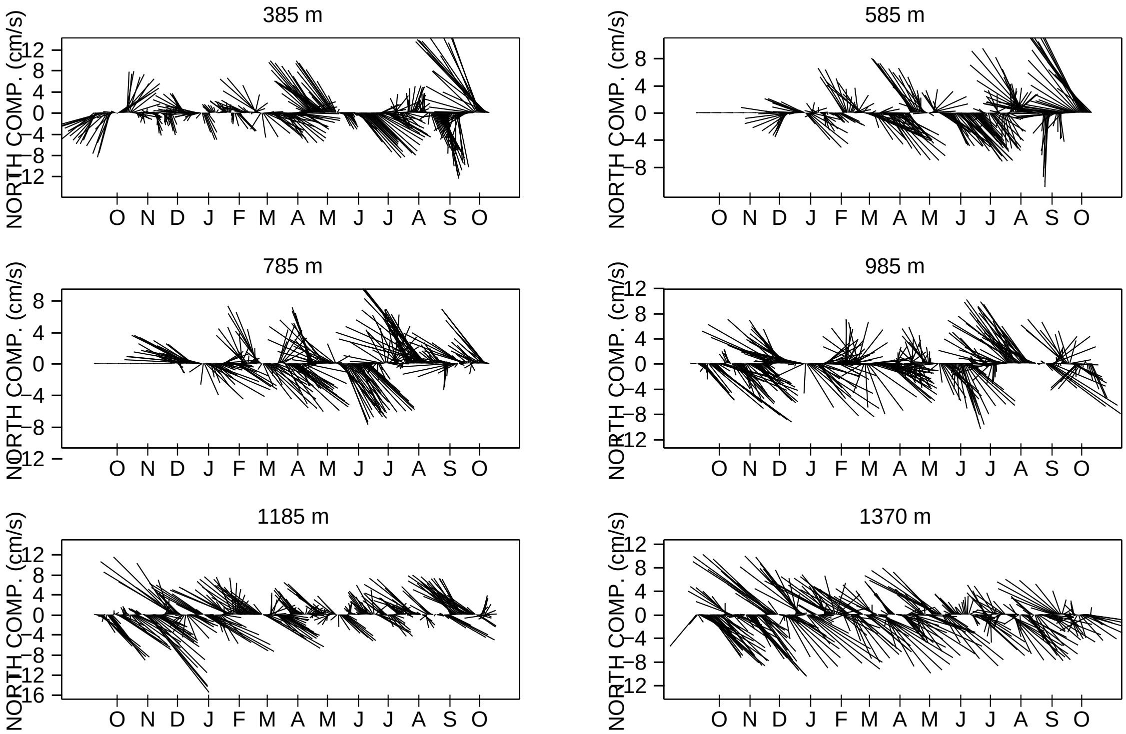

Figure 3. Stick plots of velocities at the TOTAL mooring at different depths. Data are filtered using a Lanczos filter with a cut-off period of 6 days.

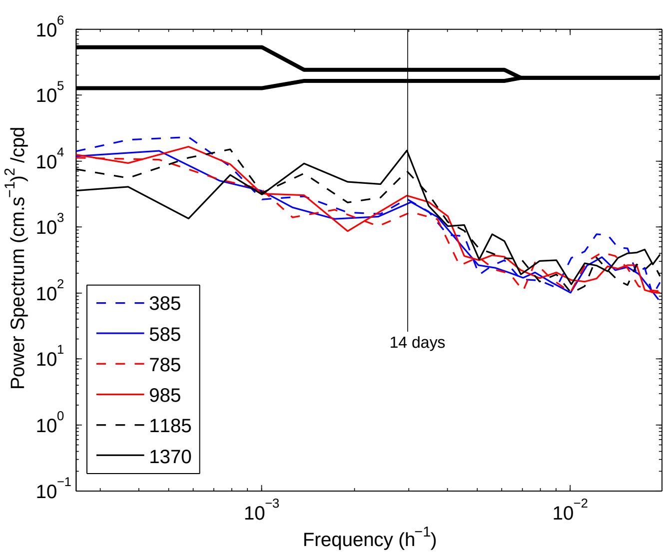

Figure 4. Kinetic energy spectra at different depths for the TOTAL mooring. The vertical spacing between the bold lines corresponds to 95% confidence interval.

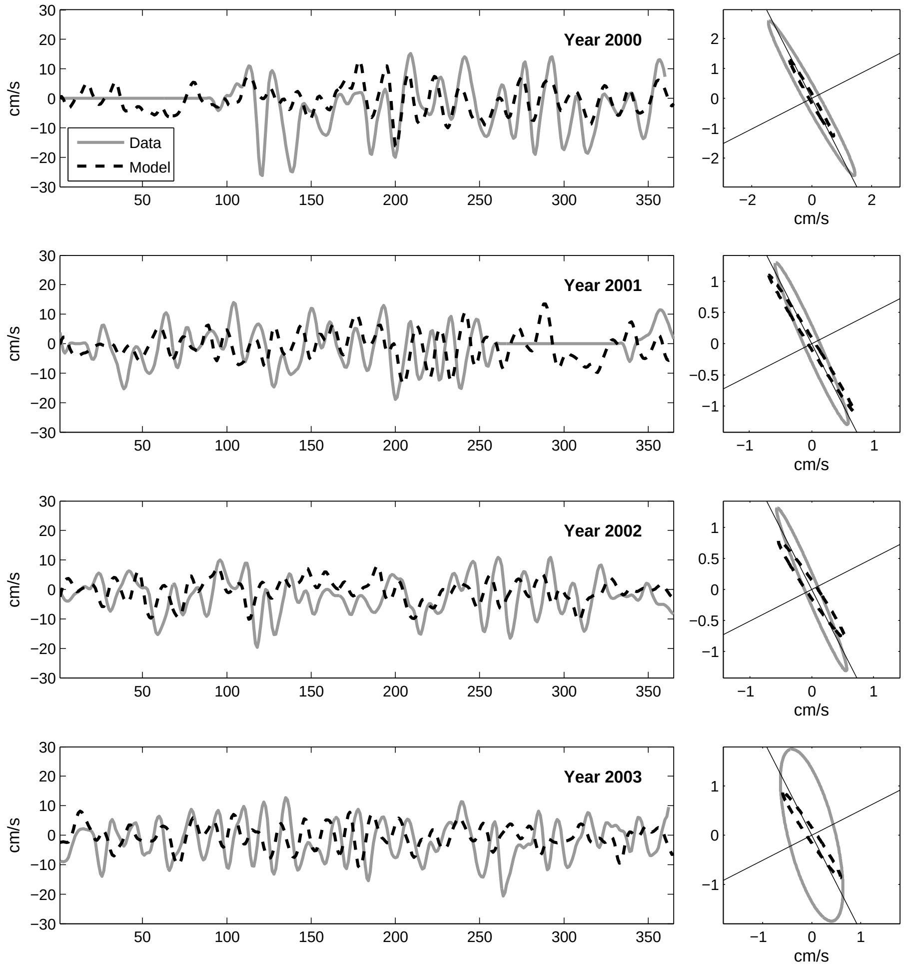

Figure 5. Left: Filtered velocity along the bathymetry on the site BIOZAIRE at 30 mab for the data, and at the level above the model bottom layer. Right: Variance ellipses for filtered series in the frequency band around 14 days. The directions parallel and perpendicular to the topography are indicated by thin lines. Model and observed velocities are filtered using a Lanczos filter with a cut-off period of 6 days.

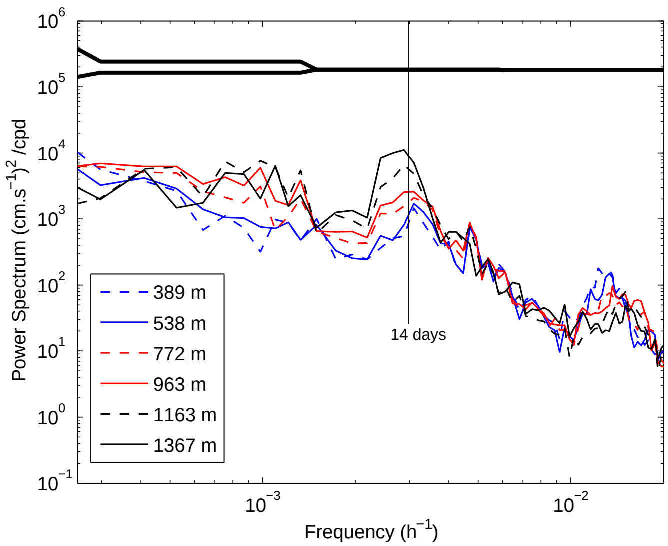

Figure 6. Kinetic energy spectra at the BIOZAIRE location in the reference experiment of the GUINEA model at model levels close to the depths sampled by the TOTAL mooring. The vertical spacing between the bold lines corresponds to 95% confidence interval.

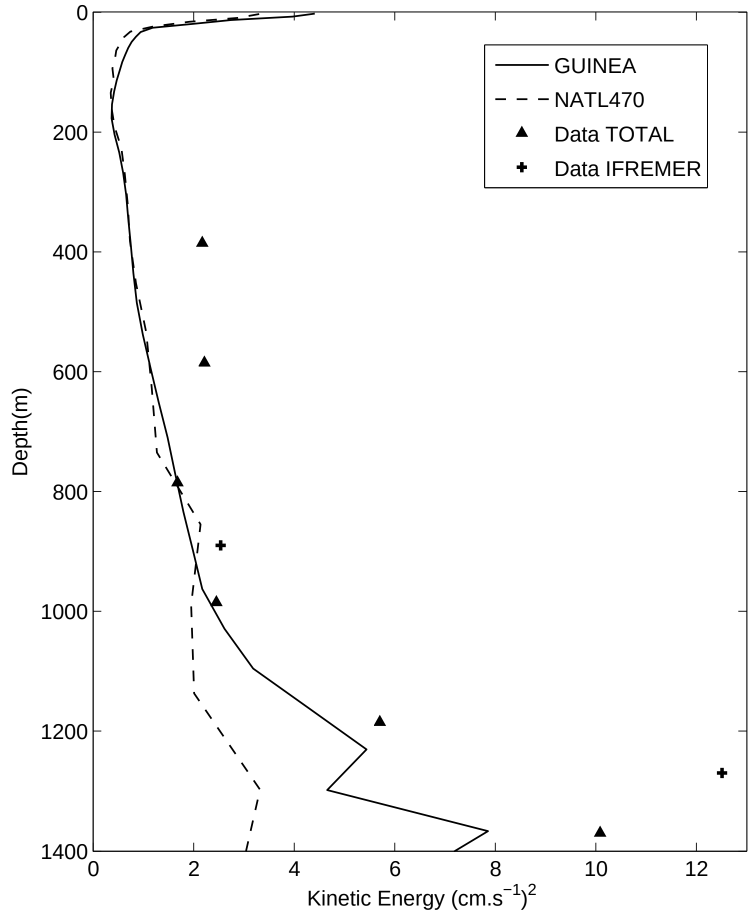

Figure 7. Kinetic energy at period between 12 and 17 days at BIOZAIRE site for the TOTAL and Ifremer data, for the REF experiment of GUINEA and for the NATL model.

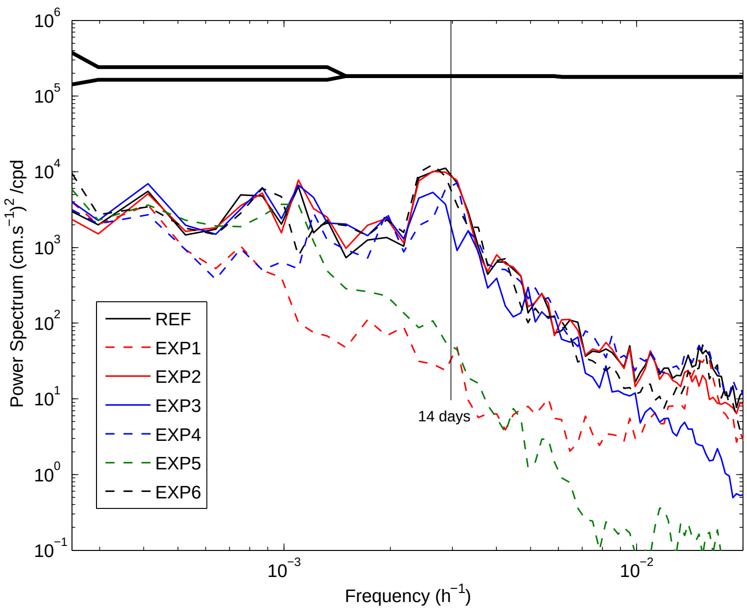

Figure 8. Kinetic energy spectra at the BIOZAIRE location in the GUINEA model (deepest model level) in the experiments described in table 3. REF: daily winds OBCs (Open Boundary Conditions); EXP1: daily winds between 10°E - 14°E, 2°S - 15°S and monthly OBCs; EXP2: daily winds and OBCs between 5°S - 5°N; EXP3: monthly winds and daily OBCs; EXP4: daily winds and monthly OBCs; EXP5: monthly winds and daily OBCs from NATLM; EXP6: 6-hourly CORE winds and daily OBCs.

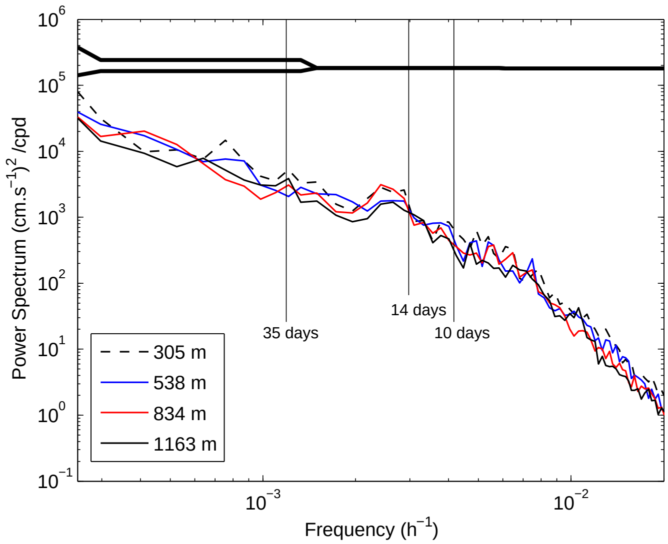

Figure 9. Kinetic energy spectra at the equator at 0°W in the reference experiment of the GUINEA model at several levels. The vertical spacing between the bold lines corresponds to 95% confidence interval.

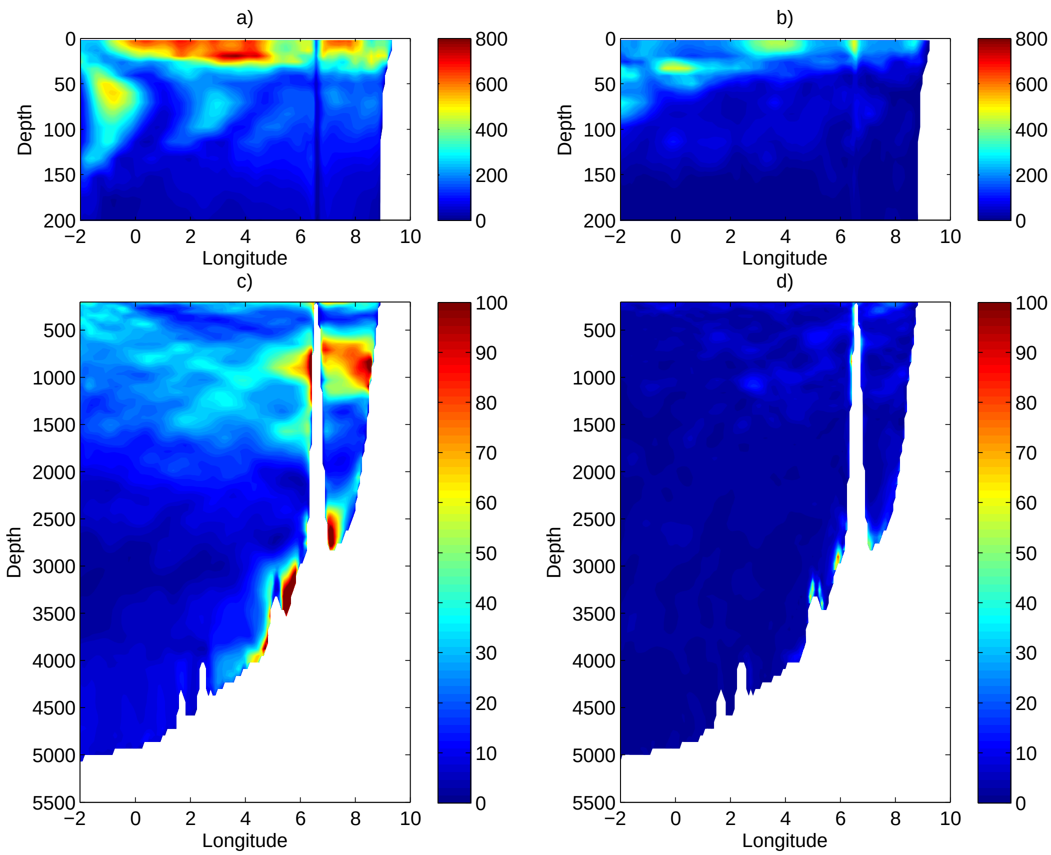

Figure 10. Kinetic energy ($cm^2.s^{-2}$) at periods between 13 and 16 days at the equator in the reference experiment. a) and b): upper layers above 200 m, for the meridional and for the zonal component. c) and d): below 200 m for the meridional and for the zonal component, respectively.

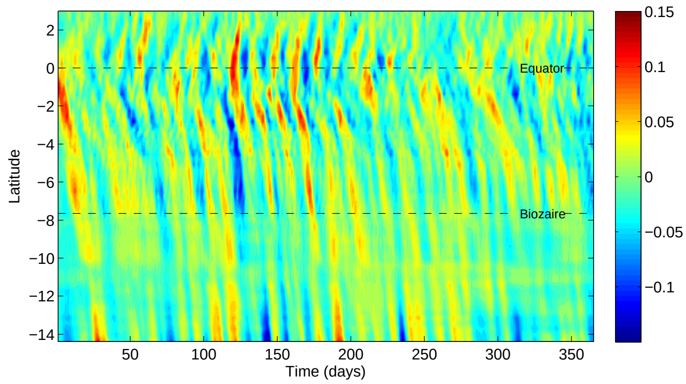

Figure 11. Time-latitude plot of the meridional velocity along the isobath 1100 m in the REF experiment of the GUINEA model.

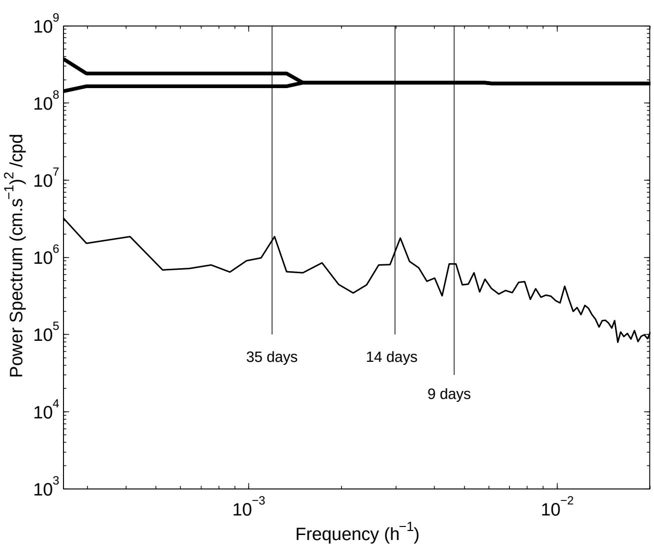

Figure 12. Kinetic energy spectra for the QUIKSCAT winds averaged over the GUINEA domain between 5°S and 5°N. The vertical spacing between the bold lines corresponds to 95% confidence interval.

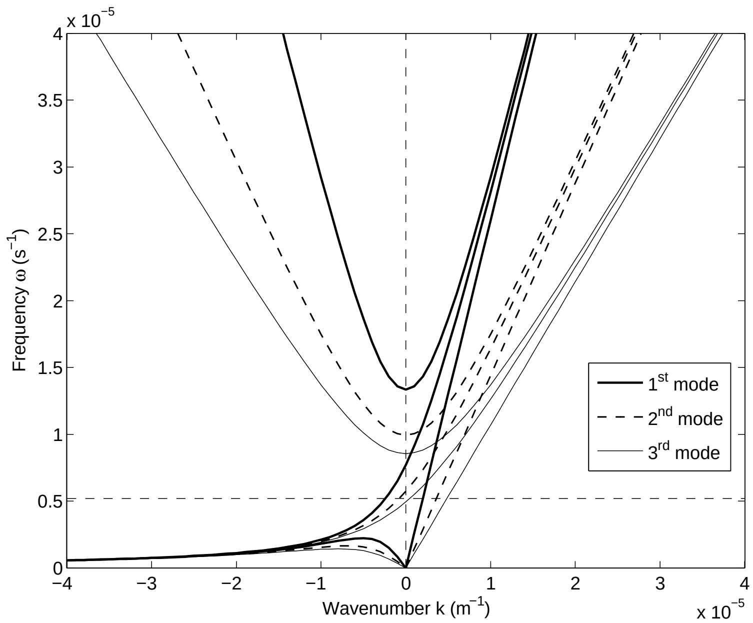

Figure 13. Dispersion relations for the first meridional mode equatorial trapped waves in the Atlantic ocean. Curves are drawn for the first three baroclinic modes. Baroclinic mode velocities have been computed using the mean stratification in the Atlantic ocean between 5°N and 5°S. The velocities are equal to 2.35 m/s, 1.35 m/s and 0.92 m/s for the 1^{st}, 2^{nd} and 3^{rd} baroclinic mode, respectively. The horizontal dashed line indicates the 14-day period.