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SEASONAL SEA LEVEL VARIABILITY IN THE GULF OF GUINEA FROM ALTIMETRY AND TIDE GAUGE

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ABSTRACT

Sea level from the Topex/Poseïdon (T/P) radar altimetry measurements and tide gauges records are used to perform an intercomparison at Sao Tomé, Pointe Noire and San Pedro sites. A Gaussian low-filter is applied to both data sets which suppresses high frequency fluctuations on periods of less than 2 months. The results obtained show the capability of the altimeter data to reproduce the sea level time series with an rms difference of 3.4 cm at Pointe Noire and San Pedro, and 2.3 cm at Sao Tomé.

The correlation coefficients are 0.93, 0.86 and 0.92 respectively at Pointe Noire, San Pedro and Sao Tomé. This result confirms the necessity to maintain a tide gauge network in the Gulf of Guinea that could be used for satellite altimetry signal calibration.

The second part of this paper focuses on the upwelling signal itself and its space distribution along the northern and southern coasts of the Gulf of Guinea. The altimetry data reproduce clearly the seasonal signal in the Gulf of Guinea. The upwelling signal propagates westward along the Côte d'Ivoire, Ghana and Benin coasts.

Keywords : *Tide gauge; altimetry; upwelling; sea level; Gulf of Guinea.*

RÉSUMÉ

Variabilité saisonnière du niveau de la mer dans le golfe de guinée à l'aide d'observation altimétrique et marégraphique

Les données issues du satellite altimétrique Topex/Poseïdon (T/P) et des marégraphes de Sao Tomé, Pointe Noire et de San Pedro sont utilisées pour réaliser une intercomparaison des anomalies du niveau de la mer. Un filtre gaussien passe bas est pour cela appliqué aux deux types de données permettant ainsi de supprimer les fluctuations aux hautes fréquences de moins de deux mois. Les données altimétriques de T/P permettent de reproduire la variation du niveau de la mer avec erreur moyenne de l'ordre 3.4 cm à Pointe Noire, 2.3 cm à San Pedro et à Sao Tomé.

Les coefficients de corrélation obtenus entre les anomalies du niveau de la mer mesurées à partir de T/P et des marégraphes sont de 0.93, 0.86 et 0.92 respectivement à Pointe Noire, San Pedro et de Sao Tomé. Ce résultat est intéressant car les données fournies par ces marégraphes pourraient servir à la calibration des mesures altimétriques.
La seconde partie de cet article montre à partir des données altimétriques que le signal d'upwelling se propage d'Est en Ouest le long des côtes du Bénin, du Ghana et de la Côte d'Ivoire. Le signal altimétrique reproduit distinctement le cycle saisonnier de l'upwelling côtier du Golfe de Guinée.

Mots-clés : *Marégraphe, altimétrie, upwelling, niveau de la mer, Golfe de Guinée*

I - INTRODUCTION

The extensive studies of the Gulf of Guinea since 1960s (EQUALANT: 1963-1965 then 1999-2000, GATE: 1974, CIPREA: 1978-1980, FOCAL/SEQUAL : 1982-1984, EGEE : 2005-2006) have considerably increased the knowledge of general hydrology, circulation and seasonal variations in this area [1-4]. Understanding the dynamic of this region is of great interest:
First, the Gulf of Guinea is the principal source of the water vapour which can constitute most of the precipitation on the continent. Recent studies have clearly confirmed that this area may play a key role on West African Monsoon [5]. The linkage of the ocean and atmosphere parameters with climate of neighbouring regions is still poorly known. They are ones of the main objectives of the African Monsoon Multidisciplinary Analyses (AMMA) programme.
Second, the Gulf of Guinea is the region of the tropical Atlantic with the largest SST seasonal amplitude (5-8°C). A coastal upwelling is observed

each year along the northern coast of the Gulf of Guinea. The upwellings which occur in this area, especially off Côte d'Ivoire and Ghana have been actively studied [6-8]. Coolings are observed during the boreal winter and summer; the main one occurs from May through September. *Colin* [9] showed that the cooling is first induced by the large scale structure of the Guinea current off the continental and shelf which tilts the thermocline towards the coast and then amplified by increase of the zonal component of the wind at the coast. *Picaut* [3], from a long time series available at different coastal stations along the northern coast of the Gulf of Guinea showed the presence of many low-frequency oscillations.

A wave with a period of about 15 days exists throughout the year and is revealed by the mean sea level. This oscillation clearly appears during the upwelling season. *Verstraete et al.* [10] used SST and hourly analogue sea level records to show an annual cycle in mean sea level amplitude of about 20 cm at Tema, Takoradi and Abidjan. The mechanisms causing the upwelling are not well understood, thus complex interactions among several processes are thought to contribute to the observed coolings and the related upwelling [1,3].

Since the launch of Topex/Poseïdon (T/P) in 1992, satellite altimetry has proven to be a significant enhancement to our ability to measure sea level from space. In contraste to the sparse network of coastal and mid-ocean island tide gauges, measurements of sea level from space by satellite radar altimetry provide near global and homogeneous coverage of the world's oceans, thereby allowing the determination of regional sea level change. Both the altimeter and orbit errors were only a few centimetres, giving sea level measurements accurate to 3-4 cm. There have been numerous papers describing the global sea level variations observed by T/P (e.g. [11]).

However, in spite of their accuracy, satellite observations must be carefully processed and supported by in situ measurements. Tide gauge sea levels have been found to be an effective means of validation of altimetric measurements [12]. Unfortunately, there is a lack of suitable sites in Africa. If one considers the Gulf of Guinea as an example, during the last two decades most coastal tide gauges have been abandoned or have provided poor quality records. Reliable conventional float gauges were operated in the 1980's at Lomé (Togo), Cotonou (Benin), Takoradi and Tema (Ghana), Abidjan and San Pedro (Cote d'Ivoire) and Pointe Noire (Congo). The only tide gauges maintained adequately into recent times and found to be useful for comparison to T/P data in the Gulf of Guinea are those of Sao Tomé Island, Pointe Noire and San Pedro.

The aim of this paper is based on intercomparison between radar altimetry measurements and tide gauges records at Sao Tomé, Pointe Noire and San

Pedro sites. This study follows up those of *Arnault and Cheney* [13], *Arnault and Le Provost* [14] and *Verstraete and Park* [15].
In the second part of this paper, we will discuss results with a special attention to the seasonal sea level variability and the propagation of the upwelling signal in the Gulf of Guinea. Up to now, the full description of the waves and their propagation from all along the northern coast of the Gulf of Guinea is missing.

II - SEA LEVEL DATA AND PROCESSING

For most regions of the world, sea level is increasing at a rate of only a few millimetres per year. Over the last century, long-term sea level change has been estimated from tide gauges in spite of their poor spatial distribution. The modern epoch of sea level measurement began 170 years ago with the use of recording tide gauge at Sheerness in United Kingdom. Since the launch of T/P (1992), satellite altimetry has proven to be a significant enhancement to our ability to measure sea level from space. Sea level data recorded from tide gauges and satellite altimetry are used in this study.

II-1. Sea level from tide gauges

The San Pedro and Pointe tide gauges are conventional float instruments with continuous analogue records. Measurements are available from January 1989 to October 1997 for Pointe Noire and from January 1991 to December 1995 for San Pedro. There is one year gap (1993-1994) in the Pointe Noire records and two 6-month gaps in 1993 and 1995 in the San Pedro record. Sao Tomé has a bottom pressure tide gauge as part of GLOSS network and it is maintained by IRD (Institut de Recherche pour le Développement).

Sea level from this tide gauge has a five year gaps between 1996 and 2000. All series were detided using the classical Demerliac filter. Useful tide gauge measurements for comparison to altimetry are from January 1995 to October 1997, from May 1993 to October 1995 and from October 2000 to October 2002 respectively for Pointe Noire, San Pedro and Sao Tomé.
The tide gauges are not connected to a benchmark, so only relative sea levels about their time mean over the observation period are useful for our purpose of intercomparison with the altimeter data.

II-2. Sea level from T/P

The first point to make about satellite altimeter data is that they are not simply the product of an instrument measurement, but come from a measurement system. The altimeter observes the sea surface elevation in the same way as a classical tide gauge with a float, the reference being the Earth's center rather than the benchmark. The bottom pressure-derived sea level data are equivalent to those from classical tide gauge after the latter has been corrected from atmospheric pressure variation. This does not raise any problem for the comparison with T/P data, since apply "inverse barometer" correction supplied by Archiving, Validation, and Interpretation of Satellite Data in Oceanography (AVISO) to the altimetric sea surface height to obtain the adjusted sea level, i.e., which can be directly compared to sea level derived from tide gauge [15].

We compute the sea level anomaly for all available T/P cycles using corrections given by AVISO. Small parts of these tracks were isolated near the coast and the tide gauges, and a polynomial fit of the along track profile was subtracted in order to reference each profile to one mean profile. These detided sea level anomalies time series were filtered using a Gaussian recursive filter with 60 days half pass period. Details about this filter can be found in *Park and Gamberoni* [16]. The same filter has also been applied to the tide gauge data. This low-passed at 2 month filter is necessary to remove the effect of the tidal aliasing leaving the seasonal and longer signals well-preserved.

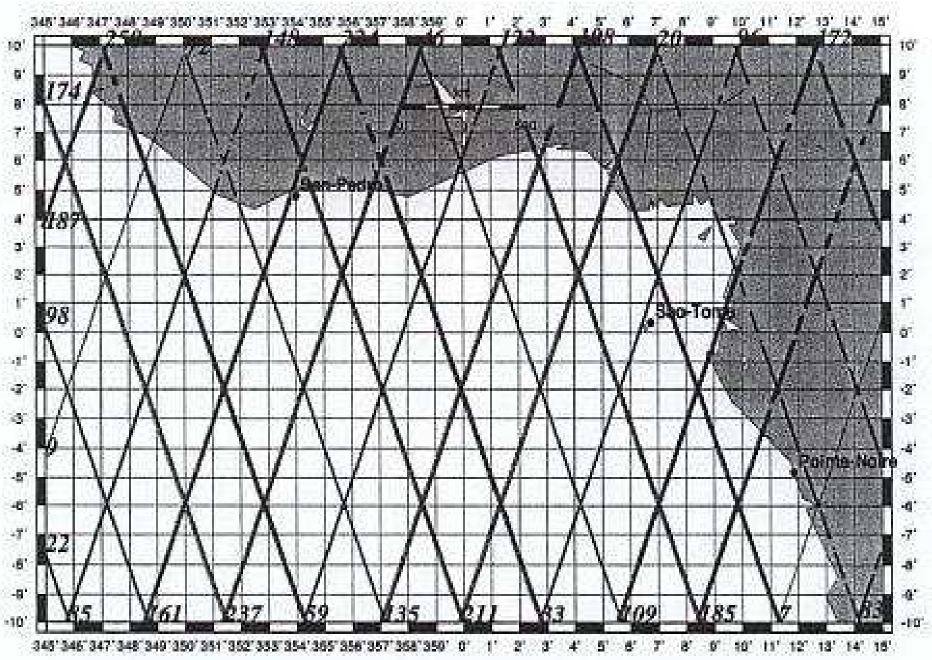

Figure 1 : *Location of the studied sites along T/P ground tracks*

III - RESULTS

III-1. Comparison of altimetric and tide gauge records Pointe Noire

A first attempt to compare altimetric and in situ sea levels at Pointe Noire was made by *Ménard* [17] and *Arnault et al*. [14,18].They showed that the ocean signal derived from the GEOSAT altimeter product was significantly smaller than that indicated by in situ historical data. With a new processing of GEOSAT data, *Arnault and Cheney* [13] reported on a monthly basis a 5.4 cm rms difference (instead of 7.1 cm with previous altimetric data) with a correlation coefficient of 0.66 (instead of 0.51), enhancing by this way the crucial role of the processing of data. The present study at Pointe Noire complements these earlier studies with recent tide gauge data and high quality T/P altimetric data.

Comparison has been performed over October/1994-October/1997 period. The sea level extracted from T/P track n° 185 ***(Figure 1)*** : i.e. one degree north of Pointe Noire along coast is found to be highly correlated with the tide gauge sea level. The correlation coefficient is 0.85 with a 4.8 cm rms difference. But one can see on ***Figure 2*** that the 1997 major upwelling from tide gauge is clearly stronger than the one observed from altimetry. From different altimetric tracks located around Pointe Noire, we are able to check that such a strong upwelling in 1997 is not present in the altimetric data. Thus, this anomaly is probably due to an anomaly of the tide gauge or to an error when digitizing the data from analogical records. Restricting the comparison over the October/1994 –December/1996 period gives a correlation of 0.93 and a rms difference of 3.45 cm.

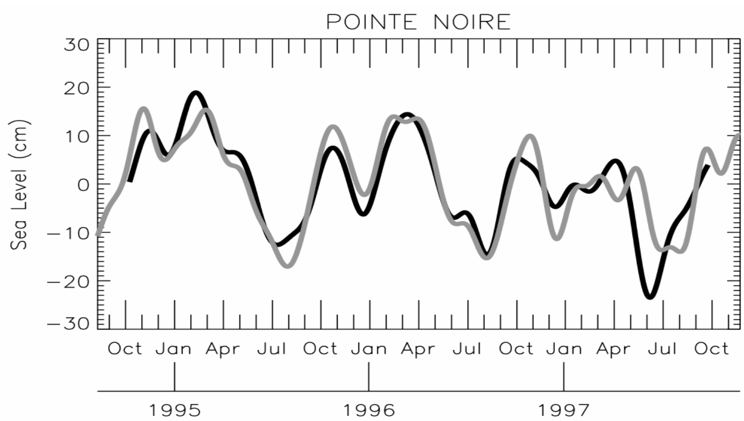

Figure 2 : *Sea level anomaly at Pointe Noire from T/P (grey) and from tide gauge (black).*

Sao Tomé

A bottom pressure gauge operates at Sao Tomé Island, just under T/P northward pass and two southward passes 185 and 7 ***(Figure 1)***.
Sao Tomé is at present the only operational coastal tide gauge in the whole Gulf of Guinea which transmits its data in real time. For the last 15 months of T/P with the same methodology used in this paper, *Verstraete and Park* [15] found a high correlation of 0.88 with 2.2 cm rms difference. We confirm here their result over the period October/2000-August/2002 with a correlation coefficient of 0.92 and 2.3 cm rms difference.

The sea level minimum corresponding to the major upwelling is observed in July and the minor one is well observed in December (2001 and 2002). During the major upwelling event, the sea level minimum computed from the tide gauge data is lower than that detected by T/P ***(Figure 3)***. The sea level minimum observed by the tide gauge is comparable for both years (2001-2002) but lasted two months in 2001 compared with one month in 2002. The year to year variation of the sea level is also detected by T/P altimetry but the minimum is always observed in July for both 2001 and 2002.

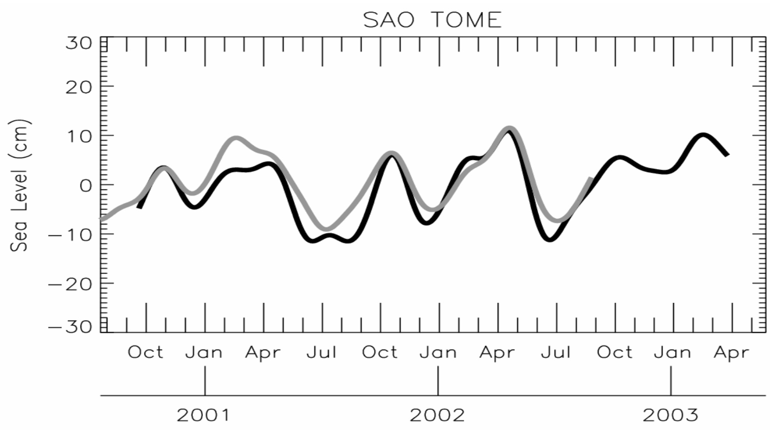

Figure 3 : *Sea level anomaly at Sao Tomé from T/P (grey) and from tide gauge (black).*

San Pedro

According to our knowledge, this is the first time that San Pedro in situ sea level records are used together with altimetric data ***(Figure 4)***. Comparison is made with track n° 161 over the June/1994-Septembre/1995 period. This comparison gives a correlation of 0.86 and a rms difference of 3.4 cm.

According to the tide gauge and altimetric signal, the maximum and the minimum of sea level are respectively observed in November and July-August. A drop of 10-15 cm in sea level occurs during the upwelling season and the altimetric signal is observed one month early. According to the 60-day low passed tide gauge data, the sea level minimum is observed in August (1993) and in July (1994). The minor upwelling intensity is weak and is revealed in February and March 1994 when using T/P data.

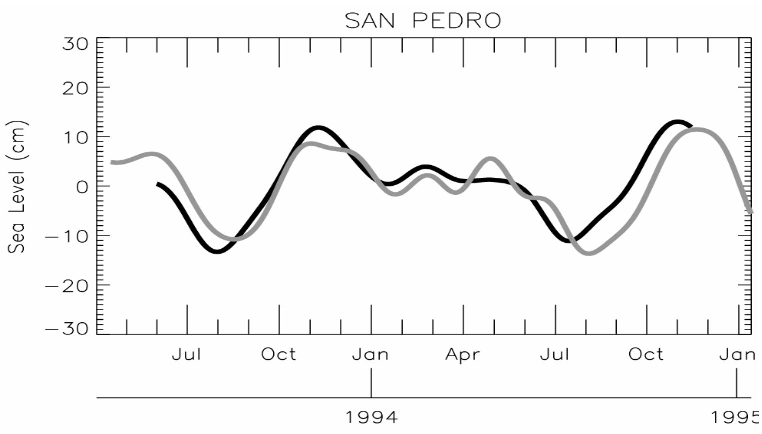

Figure 4 : *Sea level anomaly at san Pedro from T/P (grey) and from tide gauge (black)*

III-2. Horizontal propagation of the seasonal upwelling signal along the northern coast of the Gulf of Guinea observed with T/P

Here, we can focus on the upwelling signal itself and its space-time distribution along the northern and southern coasts. The analysis of 9 years data derived from T/P shows a year to year fluctuation of the seasonal upwelling signal (***Figure 5***, upper panel). The altimetry data reproduce clearly the seasonal signal in the Gulf of Guinea. At Sao Tomé (along the equator), a drop in sea level is detected between June and July (major upwelling) while the minor upwelling occurs in December with a weak amplitude.

The analysis of two tracks (n°185 and 7) north and south of Pointe Noire shows that a strong coastal upwelling takes place along the southern coast of Africa (Gabon, Congo, Angola). A major upwelling event is also observed roughly between July and the end of August along the northern coastlines of Benin (Cotonou), Ghana (Tema) and Côte d'Ivoire (Abidjan, San Pedro).

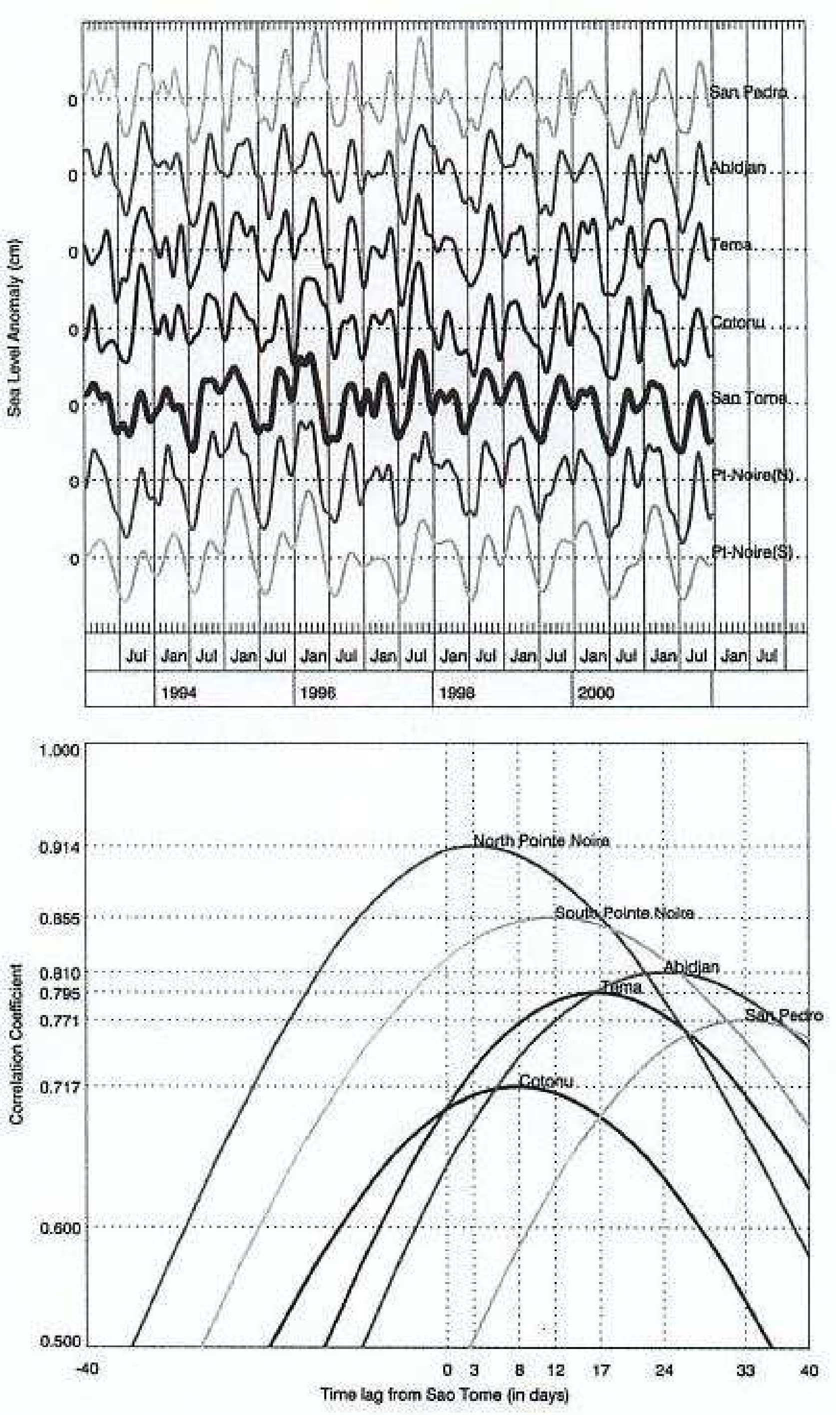

Figure 5 : *The upper panel represents the 9 years of altimetric sea level anomalies derived from T/P on both part of the equator along the northern and western coasts of the Gulf of Guinea.*

The cross correlation of 60-days filtered time series referenced to Sao Tomé sea level, shows a clear propagation of the seasonal upwelling signal on both part of the equator. From Sao Tomé, it takes respectively 8, 17, 24, 33 days for the upwelling signal to reach Cotonou, Tema, Abidjan and San Pedro. Similarly, the upwelling at Sao Tomé is observed 3 days later northward of Pointe Noire and 12 days southward (***Figure 5***, lower panel).

This study shows clearly that for each year (1993-2001), the upwelling signal propagates from east to west. The lower panel represents the cross-correlation coefficient curve of each sea level time series in function of the lag time between the time series and the Sao Tomé sea level which is taken as a reference.

IV - DISCUSSION

Here, the comparison of Sao Tomé sea level derived from a bottom pressure and T/P data confirmed the previous results by *Verstraete and Park* [15]. In the cases of Pointe Noire and San Pedro, our study constitutes the first attempt to validate tide gauge measurements with T/P data. The result obtained at Pointe Noire is an improvement of those obtained by *Arnault and Cheney* [13]. The correlation coefficient and the rms difference reported especially at Pointe Noire and Sao Tomé are consistent with others comparisons in the Pacific and Indian Oceans [21,22]. At San Pedro, this is the first time that a comparison is reported between tide gauge and T/P measurements. We confirm the capacity of the T/P altimetry in detecting sea level changes, within about 2 cm rms accuracy. This study demonstrates also the necessity to maintain a tide gauge network in the Gulf of Guinea as they could be used to calibrate signal derived from satellite altimetry.

In the second part of this study, the precision of T/P time series sea level has allowed the description of the seasonal upwelling signal from Sao Tomé (equator) to the northern and southern coastlines of the Gulf of Guinea. We found a shift in time of the upwelling signal from east to west. However, the phase lag between the equator and the northern coast varies from year to year. *Picaut* [3] found that the upwelling signal propagates westward along Côte d'Ivoire, Ghana, Togo and Benin coasts when using daily SST coastal and historical merchant ship SST observations. The cross correlation analysis of the reconstituted time series showed that the propagation of the upwelling signal was only evident between the cape Palmas front and the Togo-Benin front.

The driving mechanisms of the upwelling in the western Gulf of Guinea are not well understood. The appearance of the upwelling event is detected by a drop of mean sea level starting in May. This occurs about one month prior to the drop of the sea surface temperature. The acceleration of the Guinea Current which starts in May, simultaneously with the fall of the mean in sea level cannot by itself account for either this drop or this lag [23].

This study based only on altimetric data shows clearly that the upwelling event propagates from east to west along the northern coast of the Gulf of Guinea and this result confirms those obtained by *Verstraete and Picaut* [23]. Satellite radar altimetry has proven to be a significant enhancement to our ability to describe the seasonal upwelling variability in the Gulf of Guinea.
In spite of these multiple questions, the Gulf of Guinea is poorly instrumented and needs to be better equipped with monitoring stations to obtain a more precise understanding of the regional climate variability.
The occurrence of tsunami in Indian Ocean on 26 December 2004, and its aftermath demonstrated the urgent need to have an operational network of sea level stations which would form the core element on a tsunami early system particularly in East Africa. Ocean Data and Information Network for Africa (ODINAFRICA) in collaboration with the Global Sea Level Observing System (GLOSS), the Indian Ocean Tsunami Early and Mitigation System (IOTWS), the University of Hawaii Sea Level Centre (UHSLC), and the Proudman Oceanography Laboratory (Liverpool, UK) to develop a Pan African network of sea level stations, consisting of tide gauges eventually spaced along the African coast, providing data near real time, and addressing the key oceanographic phenomena [24,25].

These stations and those planned by other programmes will ensure optimal coverage of the African coastline. The reactivation of the tide gauges along the Gulf of Guinea coastline could be very effective way for ODINAFRICA to contribute significantly to the efforts of World Ocean Circulation Experiment (WOCE) community in Tropical Atlantic. The altimetric signal and the sea level data collected by the tide gauges network could offer an interesting way for scientists involved in Tropical Atlantic CLIVAR (Climate Variability) and AMMA programmes to get a better understanding on the futures of the Gulf of Guinea.

V - CONCLUSION

Over the last century, long-term sea level change has been estimated from tide gauges in spite of their poor spatial distribution. Since the launch of Topex-Poseidon in 1992, altimetry is used to measure sea level from space. However, tide gauge data remains nowadays the main means of calibrating sea level information from satellite radar altimeters. In this study, an intercomparaison is carried out based on sea level anomalies observed from Topex/Poseïdon and tide gauges located at San Pedro, Pointe Noire and Sao Tomé in the Gulf of Guinea. The correlation coefficients are 0.93, 0.86 and 0.92 respectively at Pointe Noire, San Pedro and Sao Tomé.

The rms difference obtained (3.4 cm at Pointe and San Pedro, and 2.3 cm at Sao Tomé) are comparable to those reported in the Pacific Ocean. This result shows the capability of the altimeter and the tide gauges data to reproduce the seasonal sea level variability in the Gulf of Guinea. Moreover, the precision of Topex/Poseïdon series sea level allowed the description of the coastal seasonal upwelling signal from Sao Tomé (equator) to the northern coastline of the Gulf of Guinea. The detailed analysis of T/P measurements reveals a westward propagation of the upwelling signal along the northern coast.

Acknowledgments

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