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Key Points:

- Interannual Equatorial Kelvin waves in the tropical Atlantic are linked to major warm and cold events in the Angola Benguela Current system
- Interannual Equatorial Kelvin waves at the origin of warm and cold events are well monitored by PIRATA moorings and altimetry
- An interannual Equatorial Kelvin wave index is a skillful proxy to forecast warm and cold events by about 1 month

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Role of interannual Kelvin wave propagations in the equatorial Atlantic on the Angola Benguela Current system

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Abstract The link between equatorial Atlantic Ocean variability and the coastal region of Angola-Namibia is investigated at interannual time scales from 1998 to 2012. An index of equatorial Kelvin wave activity is defined based on Prediction and Research Moored Array in the Tropical Atlantic (PIRATA). Along the equator, results show a significant correlation between interannual PIRATA monthly dynamic height anomalies, altimetric monthly Sea Surface Height Anomalies (SSHA), and SSHA calculated with an Ocean Linear Model. This allows us to interpret PIRATA records in terms of equatorial Kelvin waves. Estimated phase speed of eastward propagations from PIRATA equatorial mooring remains in agreement with the linear theory, emphasizing the dominance of the second baroclinic mode. Systematic analysis of all strong interannual equatorial SSHA shows that they precede by 1–2 months extreme interannual Sea Surface Temperature Anomalies along the African coast, which confirms the hypothesis that major warm and cold events in the Angola-Benguela current system are remotely forced by ocean atmosphere interactions in the equatorial Atlantic. Equatorial wave dynamics is at the origin of their developments. Wind anomalies in the Western Equatorial Atlantic force equatorial downwelling and upwelling Kelvin waves that propagate eastward along the equator and then poleward along the African coast triggering extreme warm and cold events, respectively. A proxy index based on linear ocean dynamics appears to be significantly more correlated with coastal variability than an index based on wind variability. Results show a seasonal phasing, with significantly higher correlations between our equatorial index and coastal SSTA in October–April season.

1. Introduction

In the tropical Atlantic, the annual cycle is the most dominant driver, when compared to interannual variability [Xie and Carton, 2004]. The annual cycle has distinct annual and semiannual components comprised of eastward and westward propagating Sea Surface Height (SSH) and thermocline depth at the equator [Ding et al., 2009]. At interannual timescales, the tropical Atlantic upper ocean temperature, especially along the equator and at its eastern border, is primarily controlled by equatorial wave dynamics [Illig et al., 2004]. Indeed, the sudden relaxation or intensification of easterly Trade winds in the western equatorial Atlantic leads, respectively, to the generation of downwelling or upwelling Interannual Equatorial Kelvin Waves (IEKW) which propagate eastward up to the African coast. Part of the IEKW energy bounces back westward as equatorial Rossby waves, while a substantial amount of their energy is transmitted poleward along the coast of Africa as coastal trapped waves [Bachèlery et al., 2015]. Such wave dynamics is thought to be at the origin of major warm and cold events in the Angola-Benguela current system also called Benguela Niños and Niñas [Florenchie et al., 2004; Rouault et al., 2007; Ostrowski et al., 2009; Lübbecke et al., 2010; Rouault, 2012]. However, using a global ocean atmosphere coupled model, Richter et al. [2010] proposed that local wind forcing is an important mechanism to generate Benguela Niños, including the 1994/1995 Benguela Niños, one of the stronger on record.

Among other objectives, the Prediction and Research Moored Array in the Tropical Atlantic (PIRATA) program has been established since 1997 [Servain et al., 1998; Boulès et al., 2008] in order to monitor Kelvin and Rossby waves along the equatorial waveguide. Recently, based on the experimentation with a regional ocean model, Bachèlery et al. [2015] showed that 89% of the coastal interannual SSH variability is associated with oceanic remote equatorial forcing. Some major Kelvin wave propagations along the equator were

mentioned in the literature system [Hormann and Brandt, 2009; Marin et al., 2009], but these authors did not systematically study their link with Angola Benguela Current warm and cold events. To our knowledge, no systematic study of equatorial Kelvin and Rossby waves has been yet conducted in the equatorial Atlantic. Our study is unique by the fact that we use 15 years of observations, in particular the equatorial PIRATA in situ data to detect Equatorial Kelvin wave propagations. This provides an opportunity to link equatorial wave dynamics to warm and cold upper ocean abnormal events along the Angolan and Namibian Atlantic coastlines (from 10°S to 24°S). The prediction of these coastal extreme events is important because of their significant impacts on regional marine primary productions [Bachèlery et al., 2016], fisheries [Ostrowski et al., 2009; Blamey et al., 2015], and rainfall [Rouault et al., 2003, 2009]. According to modeling study by Bachèlery et al. [2015, 2016], oceanic equatorial remote forcing explains more than 80% of the variability of coastal SSH and Sea Surface Temperature (SST), but also of biogeochemical tracer (nitrate, oxygen) variability along the West African coast at interannual timescales, while local forcing plays a dominant role on at submonthly and intraseasonal frequencies (in agreement with Goubanova et al. [2013]).

In this paper, using PIRATA array in situ measurements, altimetric SSH and outputs from an Ocean Linear Model (OLM) [Illig et al., 2004, 2006], we demonstrate that major IEKW propagations along the equator are indeed linked to major warm and cold events in the Angola Benguela Current system. We show that IEKW signature leads the development of most coastal interannual events by about 1 month. The paper is organized as follows. Section 2 describes the data and model as well as the methodology used in this study. Section 3 is focused on defining an index of the equatorial Kelvin wave activity and show the link between abnormal propagation of SSH along the equator and Benguela Niño and Niña. Our results are discussed in section 4, which will also include our conclusions and perspectives.

2. Data, Model, and Methodology

In this study, we are using a simple approach to provide an indication of the equatorial variability at interannual time scales using Dynamic Height (DYNH) anomalies and thermocline depth fluctuations inferred from PIRATA buoys and Sea Surface Height Anomalies (SSHA) derived from altimetry over the 1998–2012 period (see section 2.4 for period restriction due to data availability). We then compare these local data from mooring lines with the outputs of an ocean linear model, which allow us to have access to the equatorial dynamics signature and to interpret the data in terms of linear propagations. The use of PIRATA data is crucial here to establish a criterion in order to define abnormally strong equatorial propagation episodes that are subsequently linked to warm and cold events in the Angola Benguela current system. When there is a gap into PIRATA records, we are using altimetry time series at PIRATA mooring positions as a proxy for defining abnormal propagation episodes. In the following, we describe the data and detail the characteristics of the linear equatorial model.

2.1. PIRATA Observations

We use in situ PIRATA array records [Servain et al., 1998; Boulès et al., 2008] over the 1998–2012 period. Noteworthy, one core objective of this program is to detect and monitor the propagation of Kelvin and Rossby waves along the equator. PIRATA has been implemented in the tropical Atlantic since September 1997. PIRATA moorings record and sample the water column with five temperature/conductivity sensors deployed at depths of 1, 10, 20, 40, and 120 m, five temperature sensors positioned at depths of 60, 80, 100, 140, and 180 m, and two temperature/pressure sensors at 300 and 500 m along the equatorial Atlantic. Data, gridding procedure, and climatology estimations are available on the website <http://www.pmel.noaa.gov/tao/disdel/>.

In order to detect strong Kelvin wave propagations along the equatorial wave guide, we use monthly dynamic height interannual anomalies and anomalous depth of the thermocline (identified by the position of the 20°C isotherm, Z20, positive downward) from 3 PIRATA's buoys located along the equator at 23°W, 10°W, and 0°E. It is worth noting that even at monthly scales gaps occur in PIRATA records at various locations due to vandalism or data failure. Indeed, over the 180 months sampled by PIRATA sensors over the study period, we encountered 35%, 41%, and 50% of missing values in the dynamics height interannual anomalies estimation at [23°W; 0°N], [10°W; 0°N], and [0°E; 0°N], respectively. Note that from 2006 to 2012, gaps are more infrequent with only 22%, 15% and, 16% of missing data at the same equatorial mooring locations. We also use 5 day means from PIRATA buoys data interpolated between different mooring

locations along the equator to illustrate some particular eastward propagations (over the July 2003 to May 2004 and August 2011 to December 2012 periods) using Hovmöller diagram of interannual anomalies of the depth of the thermocline along the equatorial Atlantic. This allows calculating the speed of identified Kelvin waves.

2.2. Altimetry

In order to document the interannual equatorial variability and fill gaps in PIRATA records, we also use the reference altimetric SSH gridded product distributed by AVISO, that combines data from TOPEX/Poseidon and Jason-1/2 altimeters. Data are distributed by CLS with a 7 day temporal resolution available on a $1/3^\circ$ by $1/3^\circ$ grid. Refer to *Le Traon et al.* [1998] and *Ducet et al.* [2000] for more details on data and gridding procedures.

2.3. Sea Surface Temperature Observations

In order to identify warm and cold interannual events along the Angolan and Namibian coastlines, we use monthly Optimum Interpolation Sea Surface Temperature (OI-SST) [*Reynolds et al.*, 2002] available at 1° by 1° horizontal resolution available since 1982. OI-SST data are a blend of remote sensed and in situ observations. We reduce our analysis of the coastal variability to three regions of interest where the monthly interannual SST anomalies are averaged over a 1° coastal fringe. The northern one is the Southern Angola region, where data are averaged from 10°S to 15°S , a tropical warm water region. In the middle, the Angola Benguela Frontal Zone (ABFZ) is a transition region, where coastal SST is averaged from 16.5°S to 17.5°S . The southern domain is in the Northern Benguela upwelling off Namibia domain where SST is averaged from 19°S to 24°S .

2.4. Linear Model Configuration

In order to interpret local observations measured by both PIRATA moorings and Altimeters into basin-scale IEKW dynamics, we carry out a simulation with the equatorial Atlantic Ocean Linear Model developed by *Illig et al.* [2004] and used in *Rouault et al.* [2007]. This model simulates the linear propagation of eastward and westward propagation along the equator, over the domain extending from 50°W to 10°E and from 28.875°S to 28.875°N , with a horizontal resolution of 2° in longitude and 0.25° in latitude. It includes six baroclinic modes with phase speed, wind-stress projection coefficient, and friction derived from a high-resolution Ocean General Circulation Model. Simulation is performed over the 1980–2012 period, during which OLM forcing is provided by 3 h DRAKKAR Forcing Set version 5 (DFS5) [*Dussin et al.*, 2016]. Note that in the tropical Atlantic, DFS is similar to ERA-Interim reanalysis with a horizontal resolution of $\sim 0.75^\circ$. OLM is forced by 2 day wind stress averages obtained by cubic interpolation of monthly means. Model forcing is first detrended and interannual anomalies are calculated over the 1980–2012 period. Note that DFS5 fields at our disposal were available up to the end of 2012. This, along with the start of the PIRATA program in September 1997, constrains our study to the 1998–2012 period.

2.5. Anomalies, Normalization, and Abnormal Episodes Criteria

2.5.1. Interannual Anomalies

To compute the interannual anomalies, we simply remove the monthly climatology (estimated over the 1998–2012 period) from the original monthly time series. Given the fact that we focus on interannual fluctuations and not on longer timescale variability, we first remove the linear trend before computing anomalies. To do so, we estimate the linear least square regression fit and remove it from the original time series.

Note that, when removing the monthly seasonal cycle from monthly time series, both intraseasonal and interannual cycles remain in the anomalous time series. Yet, *Bachèlery et al.* [2015] showed that only interannual variability is associated with remote equatorial forcing, while intraseasonal timescales are mostly triggered by local atmospheric forcing (in agreement with *Goubanova et al.* [2013]). This is why we will consider events for which the amplitude exceeds 1 standard deviation of the time series during at least two consecutive months along the equator and at least three consecutive months along the coast (cf., section 2.5.3). Indeed, this allows filtering out most of the intraseasonal variability (shortest periods) and ensure that the timescales of variability we analyze lie in the same frequency range as the one of *Bachèlery et al.*, [2015]. Also, we have verified that removing the trend just slightly impacts the different time series (not shown). However, for the definition of interannual abnormal equatorial propagation and coastal temperature events, not removing the trend can impact the identification of interannual abnormal coastal events and equatorial

propagations. Also, removing the trend allows a better comparison between the different products (in situ, satellite data, and model outputs).

2.5.2. Time Series Normalization

As in Rouault [2012], monthly interannual coastal OI-SST time series are normalized in order to account for a significant seasonal phasing of the variability (standard deviation) which is 1.5, 2.1, and 1.9 times more intense in austral fall than in austral spring in Southern Angola, ABFZ, and Northern Benguela regions, respectively. To do so, for each month individually, we estimate the standard deviation of the interannual anomalies. We then normalize the time series by the monthly varying standard deviation estimates.

Note that, due to the gaps in PIRATA records, it is not possible to quantify the seasonal phasing in the equatorial interannual variability in in situ data. Also, analysis of remote altimetric data and OLM outputs do not reveal a significant seasonal phasing of the interannual variability over the 1998–2012 period. Thus, interannual equatorial anomalies are normalized with respect to their mean standard deviation.

2.5.3. Criteria for Strong Equatorial Propagations and Coastal Events

Two criteria have been established in this study. The first criterion concerns the detection of abnormal propagations of SSHA along the equatorial wave guide. Given the fact that one of the goal of PIRATA program is to monitor equatorial wave propagation, the objective of this study is to document propagations in dynamic height anomalies and anomalous depth of the thermocline primarily based on PIRATA records. To do so, we first estimate the standard deviation of the PIRATA time series, DYNH and Z20, for each of the three equatorial moorings. We then detect DYNH and Z20 anomalies that exceed this threshold for at least 2 months in a row at [0°E; 0°N] and at one other equatorial mooring location. Also, we observe a very good linear agreement between PIRATA dynamic height anomalies and the altimetry signal, with 95% significant correlations larger than 0.68 at [0°E; 0°N]. This leads us to use monthly altimetry SSH anomalies at the PIRATA moorings location, when encountering missing values in monthly DYNH and Z20 PIRATA records, in order to be able to detect anomalous SSHA over the whole 1998–2012 period. Similarly, we search for 2 month abnormal SSHA at [0°E; 0°N] and at one other PIRATA mooring location. However, these local measurements also capture small-scale variability associated primarily with mesoscale activity, local variability, meridional dynamics, and tropical instability waves, as opposed to zonal basin-scale equatorial wave dynamics. In this context, the use of OLM outputs allows for filtering out this variability and for interpreting the data in terms of linear equatorial propagations. Thus, detected abnormal episodes are always expected to be concomitant with eastward Kelvin propagation estimated from the OLM, in order to interpret local anomalies into basin scale IEKW.

The second criterion is designed to detect positive and negative interannual coastal events along the Angola-Namibia coastlines. In order to identify these events, we use the same method based on simple time series analysis methodology and on the breaching of a predefined threshold. Our threshold is classically defined using the limit of ± 1 standard deviation. Thus, we define an extreme warm or cold event as when the normalized detrended SST anomalies exceed 1 for at least 3 months in a row, and for at least two of the three coastal SST time series (see section 2.3 for coastal SST time series definition). Also, when SSTA exceed one standard deviation for less than 3 months in a row within two of the three coastal domains, we distinguish the event as a moderate coastal event.

Note that, we search for 2 month lasting SSHA episodes along equator and 3 month lasting SSTA events along Angola-Namibia coastlines because coastal SST events here last longer (up to 6 months) than equatorial propagating episodes. This can be seen in the SSHA and SSTA Hovmöller (Figures 6 and 7).

As described previously, for both criteria, consistency in time is expected. This allows filtering out any high-frequency noise and increases the robustness of our indexes. Also, our methodology requires some consistency in space. Indeed, along the equator and in the coastal sector, two out of three observed time series have to fulfill the above defined criteria. This strengthens our analyses and consolidates the definition of our equatorial and coastal proxies. Noteworthy, confidence in our indexes is also provided by the fact the anomalies are detected in different parameters at the same time. For instance, along the equator SSH and Z20 are concomitantly captured by PIRATA and satellite observations, while along the southwestern African coast SSH and SST interannual anomalies are analyzed.

2.6. Wave Speed

IEKW speed, c , is estimated using the formula $c = dx/dt$, where dt is the propagation time across the equatorial basin wide dx . dt is estimated based on a lag correlation analysis using in situ PIRATA Z20 and the linear

model SSH outputs between 35°W and 0°E. This methodology is similar to the work of *Hormann and Brandt* [2009].

3. Results

3.1. Identification of Abnormal SSH Propagations Along the Equator

In order to document the link between equatorial Kelvin waves and the Angola-Benguela Current system, we present in Figure 1 the monthly normalized detrended interannual anomalies of dynamic height from PIRATA (blue line), along with monthly altimetry derived and OLM-derived SSH anomalies (black line and red line, respectively) from January 1998 to December 2012 at [0°E; 0°N] (top), [10°W; 0°N] (middle), and [23°W; 0°N] (bottom). The standard deviation of PIRATA-derived DYNH anomalies at [0°E; 0°N] is 2.83 cm, 2.76 cm at [10°W; 0°N], and 2.33 cm at [23°W; 0°N]. In Figure 1, abnormal positive and negative SSH anomalies episodes at the eastern equatorial Atlantic are highlighted by red and blue rectangular shadings, respectively, which width is function of the duration of the episode. These colored rectangles will constitute our equatorial variability index. This proxy will be used throughout this paper and rectangles will be reproduced in the subsequent figures. At a monthly resolution, there is good agreement between PIRATA-DYNH, AVISO SSH, and OLM SSH interannual anomalies (cf., Table 1). At [0°E; 0°N], there is a correlation of 0.68 between altimetry-derived SSH anomalies and PIRATA DYNH anomalies, while correlation between the OLM SSHA and PIRATA DYNH anomalies is 0.65, both being significant at 95% level [*Sciremammano*, 1979]. We also conducted the same analysis using the depth of the isotherm (Z20) from PIRATA moorings (not shown). Results show that, even if numerous gaps are presents in PIRATA Z20 data, correlation between PIRATA Z20 and PIRATA DYNH remains larger than 0.8 for the three equatorial moorings and 2 month length peaks identified in DYNH are also captured in the subsurface PIRATA Z20 measurements (cf., Table 2). Gaps occur occasionally in PIRATA at different locations (see section 2.1), so we are also using altimetry to verify the robustness of our results and

Figure 1. Monthly detrended normalized interannual anomalies of dynamic height (DYNH) from PIRATA in blue line, AVISO SSH monthly anomalies in black line, and OLM SSH monthly anomalies in red line; top, at [0°E; 0°N]; middle, at [10°W; 0°N], and bottom, at [23°W; 0°N]. Green horizontal lines indicate thresholds (± 1 standard deviation) to detect abnormal equatorial episodes. Abnormal positive and negative SSHA propagation episodes are represented by red and blue rectangles, respectively. Red and blue stars above the top plot highlight abnormal positive and negative SSHA propagation episodes associated with wind-forced IEKW (as opposed to IEKW triggered by Rossby wave reflection, see section 3.2 for further information).

Table 1. Correlation Between PIRATA DYNH, OLM SSH and AVISO SSH Monthly Detrended Interannual Anomalies at [23°W; 0°N], [10°W; 0°N], and at [0°E; 0°N] Over the 1998–2012 Period

Correlation	[23°W; 0°N]	[10°W; 0°N]	[0°E; 0°N]
PIRATA DYNH–OLM SSHA	0.59	0.53	0.65
PIRATA DYNH–AVISO SSHA	0.75	0.67	0.68
OLM SSHA–AVISO SSHA	0.51	0.59	0.62

extend our analysis to period where no PIRATA data are available. Interannual OLM SSH outputs compare well with equatorial observations emphasizing the dominance of the equatorial wave propagation signal on the equatorial variability over the 1998–2012 period, extending the results from Illig *et al.* [2004] over a more

recent period. Thus OLM outputs are used here to interpret local observations in terms of basin-scale variability associated with IEKW. A combined analysis of PIRATA, altimetry, and OLM time series allows us to identify numerous significant upwelling and downwelling IEKW over the 1998–2012 period (cf., section 2.5.3 for criterion definition). Our results are summarized in Table 2. According to our criterion, abnormal downwelling IEKW SSH signatures (positive SSH episodes) occurred in 1998 (May–September), 1999 (March–July), 2001 (January–March), 2002 (March–May), 2003 (August–December), 2004/2005 (December–February), 2007 (September–December), 2008 (April–July), 2008 (October–December), 2009 (April–June), 2010 (October–December), and 2012 (September–November). Negative SSH episodes (abnormal upwelling IEKW SSH signatures) occurred in 2001/2002 (October–January), 2004 (March–June), 2005 (April–July), 2009 (June–September), 2011 (May–August), and 2011/2012 (November–February). These anomalies are also clearly detected earlier in time in the other mooring locations (Figure 1 middle and bottom plots) at [10°W; 0°N] and [23°W; 0°N] confirming a propagation in SSH from West to East. Note that the linear model shows a significant eastward SSH propagation from February to June 2010, which is not captured by the observations (Figure 1). Thus, it is not taken into account in our equatorial index, whereas a Benguela Niña was observed along the western African coast afterward. Some of these episodes were described in the literature. For instance, the 2001 propagation episode was extensively reported in Rouault *et al.* [2007] and linked to a warm event in the Angola-Benguela Current system in late austral summer 2001. The propagation of positive SSH in 1999 described here corresponds to a coastal warm event at the Angola Benguela front reported by Mohrholz *et al.* [2001] and Doi *et al.* [2007]. Furthermore, the austral fall 2002 abnormal positive propagation episode SSH is described in the study of Hormann and Brandt [2009], who mentioned intense downwelling Kelvin wave activities in 2002 along the equator. Upwelling Kelvin waves were already identified along the Equator at the origin of the negative SSH propagation episode in 2005 presented here [Hormann and Brandt, 2009; Marin *et al.*, 2009]. More details are given in the following section concerning the 2009 abnormal negative SSH episode which has been documented by Foltz and McPhaden [2010b] and Burmeister *et al.*, [2016]. We note that during the 2001 downwelling propagation episode, no data are available from PIRATA equatorial dynamic height (DYNH). However, the 2001 event is well captured by PIRATA anomalous depth of the thermocline (Z20) at [23°W; 0°N]. Normalized Altimetry monthly SSHA also capture strong abnormal episode at [0°E; 0°N]. In Rouault *et al.* [2007], the PIRATA data (depth of the isotherm 20°C) was available at the time and allowed detecting the eastward propagation of higher than normal SSHA in early 2001. For our study, since the PIRATA data processing has changed, no DYNH data are now available for download to sample the 2001 downwelling propagation, and only time series of Z20 at [23°W; 0°N] is available.

3.2. Forcing and Propagation of Equatorial Kelvin Waves From 1998 to 2012

In order to interpret the local in situ signal from PIRATA records in terms of linear propagations, and better describe the propagating characteristics of the equatorial dynamics as sampled by PIRATA along the equator, we analyze now the equatorial wave propagation signature and the associated forcing. To do so, we have detrended and averaged the OLM key forcing parameter, viz., the zonal wind stress interannual anomalies over the ATL4 domain (i.e., [50°W–25°W; 3°S–3°N], cf., Illig and Dewitte [2006]). This time series is displayed on Figure 2 (top). Most of the SSH positive and negative propagations described earlier are associated with weaker and stronger than normal easterly wind stress anomalies, respectively. Following the decrease or the increase of the easterly wind stress in the western equatorial Atlantic, positive or negative events, respectively, propagate eastward through the PIRATA array of moorings (Figure 1). Close inspection of lag correlation between zonal wind stress anomalies and OLM SSH anomalies (not shown) reveals a 95% significant correlation of 0.6 when the western equatorial zonal wind stress anomalies in ATL4 lead the OLM SSH anomalies at [0°E; 0°N] by a month. This lag of 1 month corresponds to a propagation speed of 1.6 m/s which is consistent with the propagation phase speed of Kelvin wave mode 2, in agreement with the study of Illig *et al.* [2004]. This leads us to focus on IEKW and examine the outputs of the OLM in order

Table 2. List of Abnormal Downwelling and Upwelling Propagations as Detected in Detrended Interannual PIRATA Dynamics Height (DYNH), Depth of 20°C Isotherm (Z20), Altimetric Signal at [23°W; 0°N], [10°W; 0°N], and [0°E; 0°N], With Outputs From the Ocean Linear Model (OLM) Showing Concomitant Anomalous Propagations^a

downwelling episodes	PIRATA DYNH			PIRATA Z20			Altimetry			OLM	Literature
	23°W	10°W	0°E	23°W	10°W	0°E	23°W	10°W	0°E		
1998 (May-Sep)							✓	✓	✓	✓	
1999 (Mar-Jul)	✓			✓	✓		✓	✓	✓	✓	Doi2007
2001 (Jan-Mar)				✓			✓	✗	✓	✓	Rouault2007
2002 (Mar-May)	✗			✗			✓	✓	✓	✓	HB2009
2003 (Aug-Dec)		✓	✓		✓	✓	✓	✓	✓	✓	
2004/2005 (Dec-Feb)	✓			✓			✓	✓	✓	✓	
2007 (Sep-Dec)		✓	✓	✓	✓	✓	✗	✓	✓	✓	
2008 (Apr-Jul)		✓	✓	✓	✓		✓	✓	✗	✓	
2008 (Oct-Dec)	✓	✓	✓	✓	✓	✓	✗	✗	✓	✓	
2009 (Apr-Jun)	✓	✓	✗	✗	✗	✓	✓	✓	✓	✓	
2010 (Oct-Dec)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
2012 (Sep-No)	✗		✓	✓	✓	✓	✓	✗	✓	✓	
Upwelling episodes											
2001/2002 (Oct-Jan)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
2004 (Mar-Jun)	✗			✗			✓	✓	✓	✓	
2005 (Apr-Jul)				✗	✓		✗	✓	✓	✓	Marin2009+HB2009
2009 (Jun-Sep)	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	FM2010b+BUR2016
2011 (May-Aug)	✓	✓	✓	✗	✓	✓	✗	✓	✓	✓	
2011/2012 (Nov-Feb)	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓	

^aGrey cell shading corresponds to missing data in PIRATA records. Green check symbols correspond to 2 month abnormal episodes captured by time series analysis. Orange check symbols correspond to 1 month abnormal episodes. Red cross symbols depict anomalies that do not exceed our predefined threshold. In agreement with our methodology to depict strong equatorial propagations (priority to in situ PIRATA data over altimetry, and peaks detected concomitantly at [0°E; 0°N] and at one of the other mooring location, see section 2.5.3 for more details), green cell shading highlight the decisive information used to catalogue strong downwelling and upwelling episodes. The last column recapitulates the studies which mention these abnormal propagations: Foltz and McPhaden [2010b] (FM2010b), Doi et al. [2007] (Doi2007), Rouault et al. [2007] (Rouault2007), Hormann and Brandt [2009] (HB2009), Marin et al. [2009] (Marin2009), and Burmeister et al. [2016] (BUR2016).

to characterize the role of equatorial wave dynamics in the propagations of the SSH across the basin. Figure 2 (bottom) presents the first three gravest baroclinic modes of equatorial Kelvin wave contributions to SSH variation from 1998 to 2012. The summed-up contribution is averaged between 20°W and 0°E, at 0°N. The second baroclinic mode of IEKW is the most energetic mode, followed by the first one [Illig et al., 2004; Bachèlery et al., 2015]. As in Illig et al. [2004], the linear dynamics controls the equatorial variability as the correlation between OLM outputs and altimetric interannual anomalies remains significant at 95% level along the whole equatorial waveguide (not shown). The amplitude of IEKW averaged between 20°W and

Figure 2. (top) Detrended monthly anomalies of zonal wind stress (N.m^{-2}) averaged over ATL4 (50°W – 25°W , 3°S – 3°N). Black horizontal lines indicate ± 1 standard deviation. Bottom, OLM detrended anomalies of Kelvin wave monthly contribution to SSHA (cm): first baroclinic mode in blue, second baroclinic mode in red, and third baroclinic mode in black, averaged over (20°W – 0°E , at 0°N). Abnormal equatorial positive and negative SSHA propagation episodes identified in Figure 1 are represented by red and blue rectangles, respectively. Red and blue stars highlight abnormal positive and negative SSHA propagation episodes associated with wind-forced IEKW (as opposed to IEKW triggered by Rossby wave reflection, see section 3.2 for further information).

0°E , at 0°N (Figure 2, bottom) is compared with our equatorial index (Figure 1) and results show a good agreement. Thus, the OLM represents well the equatorial variability of IEKW propagations over the 1998–2012 period. Note that similar results are obtained when averaging baroclinic IEKW contributions from 20°W to 10°E , at 0°N (not shown). This suggests that the interannual signal of Kelvin waves do not vary considerably in the eastern equatorial Atlantic.

We observe that most of western zonal wind stress anomalies are related to propagation of downwelling or upwelling IEKW, respectively. These waves propagate eastward and are observed through positive or negative abnormal SSH in the eastern equatorial Atlantic (Figure 1, top). We note that, according to what is expected from Kelvin wave dynamics in connection with the modulation of the forcing, for some particular years, 1998 (from May to September), 2001/2002 (from October 2001 to January 2002), and 2009 (from June to September), the direction of zonal wind stress anomalies (Figure 2, top) does not match the sign of abnormal SSH propagations. In agreement with *Foltz and McPhaden* [2010a], the analysis of the wave sequence (not shown) reveals that for the year 1998, negative zonal wind stress interannual anomalies force preferentially westward propagating downwelling Rossby waves, rather than upwelling Kelvin waves. This is more likely due to the spatial pattern of the wind stress anomalies that is maximal off equator. At the Brazilian coast, these Rossby waves reflect into eastward propagating downwelling Kelvin waves. Symmetrically, for years 2001/2002 and 2009, decreased easterly winds in the western tropical Atlantic, through the propagation and reflection of upwelling Rossby waves, yield to upwelling IEKW signal in the Eastern Atlantic. According to *Foltz and McPhaden* [2010b] and *Burmeister et al.* [2016], the observed 2009 negative abnormal SSH anomalies results from a wave reflection process. The latter is related to anomalous North-westerly wind in the Equatorial Atlantic associated with strong negative Atlantic meridional mode in boreal spring 2009. This mechanism explains the apparent inconsistency between the sign of the wind stress anomalies in the western Atlantic and the equatorial SSHA in the Gulf of Guinea. This supports our idea of defining an index based on the IEKW activity in the eastern Atlantic as monitored by PIRATA, rather than using wind stress amplitude in the western Tropical Atlantic, in order to forecast SST anomalies along the coasts of Angola and Namibia, which will be done in the following. Indeed, over 1998–2012, when we compare OLM second mode of IEKW (averaged within $[20^{\circ}\text{W}$ – 0°E ; $0^{\circ}\text{N}]$) and wind index (averaged within ATL4 box), the 95% significant correlation between IEKW and SSH anomalies along the Southern Angola coastline (averaged between 10°S and 15°S and within 1°

Figure 3. (a) Correlation analysis between monthly Zonal Wind Stress Anomalies (ZWSA) averaged in ATL4 (50°W–25°W; 3°S–3°N), and monthly SSH anomalies along the African coast in Southern Angola (averaged between 10°S and 15°S and over 1° coastal fringe), in function of the Lag (in months). Negative lags indicate that ZWS leads. (b) Same but with correlation between monthly OLM IEKW second mode averaged between 20°W and 0°E at 0°N and monthly SSH anomalies along the African coast. Negative lags indicate that IEKW leads. The 95% significant correlation threshold is indicated by red lines. (c) Monthly OLM IEKW second mode in blue averaged between 20°W and 0°E at 0°N and 1 month lagged detrended normalized monthly SSH anomalies averaged between 10°S and 15°S and from the coast to 1° offshore according to the maximum of correlation that appears at lag -1 . Green horizontal lines represent the ± 1 standard deviation. Abnormal equatorial positive and negative SSHA propagation episodes identified in Figure 1 are represented by red and blue rectangles, respectively. Red and blue stars highlight abnormal positive and negative SSHA propagation episodes associated with wind-forced IEKW (as opposed to IEKW triggered by Rossby wave reflection, see section 3.2 for further information).

coastal band) is significantly higher (~ 0.5 , Figure 3a) than the one with the wind index (~ 0.25 , Figure 3b), when both equatorial indexes lead coastal SSH variability by 1 month. Noteworthy, when we remove periods during which the sign of the wind does not match (according to what is expected from the linear theory) with the sign of the OLM second mode IEKW SSH anomalies (i.e., May–September 1998, October 2001 to January 2002, and June–September 2009), the correlation between the wind index and coastal SSH anomalies increases to reach a value of 0.4. Also, we notice that in Figure 3b, the significant correlations with IEKW leading coastal SSH anomalies occur over a broad lag interval, ranging from 0 to 2 months, highlighting the duration of interannual events. It most likely also reflects the change in IEKW phase speed associated with each peculiar event and which depends on the South-Eastern Atlantic vertical structure variability and baroclinic mode contribution that will be discussed in detail at the end of section 3.4. Figure 3c presents the IEKW mode 2 time series (averaged within [20°W–0°E;0°N]) and the coastal SSHA time series (averaged between 10°S and 15°S and within 1° coastal band) shifted ahead in time by one month. It allows appreciating the dynamical coherence between equatorial and coastal domains, when the equatorial (IEKW mode 2) leads the Southern Angola coastal SSH by 1 month according to the maximum of correlation obtained in Figure 3b.

3.3. Propagations of Kelvin Waves in PIRATA Z20

Figure 4 further illustrates the signature of eastward propagations in PIRATA records. It presents some specific cases used to estimate the speed of abnormal propagations as observed by 5 day means of Z20 anomalies from PIRATA records and altimetry. This also allows us to calculate for some specific strong eastward propagations the time lags at different longitudes and compare estimated phase speed values to the speed of each baroclinic modes. We focus here on PIRATA Z20 interannual anomalies, because fluctuations of the thermocline depth ~ 15 m (deepening or shoaling) are also an important characteristic of the IEKW, which is also captured by altimetry (SSHA).

Figure 4. (top: from left to right, a) Longitude time Hovmöller diagram of 5 day means of Z20 anomalies (m) along the equator inferred from PIRATA moorings and interpolated between mooring locations, (b) SSH anomalies (cm) inferred from AVISO along the equator averaged between 1°S and 1°N, (c) latitude time Hovmöller diagram of SSH anomalies (cm) inferred from AVISO averaged within 1° coastal fringe, and (d) time series of SST anomalies (°C) averaged from 10°S to 15°S within 1° coastal fringe for the period July 2003 to May 2004. (bottom) The same plots are represented, but for the period August 2011 to December 2012. The red and black tick straight lines represent eastward phase speed estimates (m/s).

In Figure 4a, we observe from the 22 October 2003, a clear eastward displacement of the deepening of the thermocline starting at 35°W which takes 32 days to reach the eastern part of the equatorial Atlantic (0°E) on the 22 November 2003. The maximum deepening of thermocline is larger than 15 m, located between 15°W and 10°W. Thus, this propagation is in agreement with a free propagating second baroclinic mode downwelling Kelvin wave with a phase speed of 1.4 m/s, in agreement with the study of *Illig et al.* [2004]. The associated anomalies (SSH and Z20) last for about 3 months at 0°E, as illustrated on Figures 4b and 1 (top). The associated SSH anomalies are consequently captured by our equatorial criterion based on PIRATA DYNH and classified as a strong abnormal equatorial SSH episode (see red rectangle in Figure 1). The thermocline depth, (Z20) remains deeper than normal up to September 2003, when an upwelling negative propagation develops. Equatorial propagating anomalies are also captured by altimetry (Figure 4b). Similarly, in 2012 a clear eastward propagation of positive anomalies of Z20 larger than 10 m is observed basin wide from the 30 August to the 27 September 2012 with a maximum deepening larger than 15 m at 0°E in early October 2012 (Figure 4e). The thermocline remains deeper by about 15 m during the propagation of the IEKW along the equator. An eastward phase speed of 1.6 m/s is estimated using the above mentioned methodology. It suggests that a strong downwelling IEKW mode 2 was triggered in the west by a relaxation of the equatorial Trade wind (Figure 2 top plot).

In austral autumn 2004, from 35°W toward the African coast along the equatorial wave guide, we observe a rapid eastward propagation of negative anomalies of Z20 from around the 15 March 2004 and reaching 0°E

Figure 5. Monthly detrended normalized anomalies of SST in (top) Southern Angola averaged from 10°S to 15°S and from the coast to 1° offshore, (middle) Angola Benguela Front region averaged from 16.5°S to 17.5°S and from the coast to 1° offshore, and (bottom) Northern Namibia averaged from 19°S to 24°S and from the coast to 1° offshore. Blue horizontal lines represent the threshold (± 1 standard deviation) used to detect abnormal coastal SST events in the three domains. Dark red and blue triangles on the bottom plot represent extreme warm and cold events, respectively, along the Angolan-Namibian coastlines. Abnormal equatorial positive and negative SSHA propagation episodes identified in Figure 1 are highlighted with red and blue rectangles, respectively. Red and blue stars highlight abnormal positive and negative SSHA propagation episodes associated with wind-forced IEKW (as opposed to IEKW triggered by Rossby wave reflection, see section 3.2 for further information).

around the 6 April 2004, with a maximum shoaling located east of 10°W. Despite the lack of data in the eastern part of the equatorial Atlantic records by the PIRATA buoys in April and May 2004, this eastward propagation is well observed in the altimetric signal (Figure 4b). It suggests that shoaling of the thermocline takes ~ 15 days to travel eastward from 35°W to 0°E. The corresponding wave speed is around 2 m/s and corresponds to the first baroclinic mode. Similarly, around the 30 October 2011 from 35°W, an eastward propagation of negative anomalies of Z20 is observed in the PIRATA records along the equator. It reaches 0°E around the 2 December 2011, characterized by a maximum shoaling of the thermocline of ~ 15 m at 0°E. The eastward IEKW speed associated is ~ 1.4 m/s. This propagation corresponds to a second baroclinic mode of IEKW. This eastward propagation of Sea Surface Height anomalies is also observed in altimetry (Figure 4f). These observed phase speed and baroclinic mode remain in agreement with the study of Illig *et al.* [2004].

In Figures 4c and 4g, we observe that the anomalous equatorial propagations identified in Figures 4b and 4f are consistent with southward propagations along the African coast up to 25°S. However the coastal anomalies are less intense than the anomalies along the equator and decrease as they propagate further south, in agreement with the modeling results of Bachèlery *et al.* [2015]. Furthermore, Figures 4d and 4h which present the interannual coastal SST anomalies along the Southern Angola, highlight that the equatorial wave propagation identified in the observations (PIRATA and altimetry) are subsequently associated with extreme cold or warm SST events along the western coast of Africa. Indeed downwelling propagations in austral spring 2003 and 2012 are associated with warmer than usual SST in the coastal [10°S–15°S] box. Conversely, upwelling equatorial propagation are subsequently followed by negative anomalous SST larger than 2°C. These preliminary results suggest that the oceanic

Table 3. Correlation Between Monthly Detrended Interannual Equatorial Kelvin Wave Mode 2 Anomalies Averaged Between [20°W and 0°E] at 0°N and Monthly Detrended Normalized Anomalies of SST in Southern Angola ([10°S–15°S]; 1° Coastal Band), in the Angola Benguela Front region ([16.5°S–17.5°S]; 1° Coastal Band), and in the Northern Namibia Area ([19°S–24°S]; 1° Coastal Band)^a.

	Whole 15 Year Period	Strong Equatorial Propagation Periods
[10°S–15°S]	0.4	0.60
[16.5°S–17.5°S]	0.27	0.49
[19°S–24°S]	0.16	0.38

^aCorrelations are performed over the 1998–2012 period (first column) and only during identified strong equatorial propagation episodes (second column), with IEKW2 leading SST anomalies by 1 month.

series of the Southern Angola domain ([10°S–15°S]); in the middle, the Angola Benguela Frontal zone ([16.5°S–17.5°S]), and at the bottom, the Northern Namibia upwelling domain ([19°S–24°S]). Here, we define an extreme warm or cold event as a period during which the normalized detrended SST anomalies exceed 1 for at least 3 months in a row. Identified major SST events are denoted with dark red or blue triangles above the time axis on the bottom plot. Results show that most major warm and cold events along the African coast especially in Southern Angola and Angola Benguela front domains are linked to the equatorial variability index associated with IEKW propagations and western zonal wind stress anomalies. Based on our coastal SST criterion (see section 2.5.3), we have selected seven major warm events: in 1998 (August–November),

teleconnection with equatorial dynamics as observed by PIRATA moorings play an important part in the coastal interannual SST variability along West Africa. This will be addressed in more detail in the following section.

3.4. Link Between Equatorial Variability and the Angola Benguela System

In order to document the link between the equator and the Angola Benguela Current system, Figure 5 presents normalized coastal detrended OI SST along the Angola Benguela Current system. On top, we show the time

Figure 6. Longitude-time and latitude-time Hovmöller diagrams of monthly detrended SSH anomalies in cm, left plot averaged between 1°S and 1°N along the equator, and right plot along the African coast from 0°S to 30°S and averaged from the coast to 1° offshore.

Figure 7. (left; top) Standard deviation) and (bottom) Hovmöller diagram of monthly detrended OI-SST anomalies ($^{\circ}\text{C}$) along the equator and averaged between 1°S and 1°N , and for (top) the right plot standard deviation and (bottom) Hovmöller latitude-time diagram of monthly detrended but along the African coast from 0°S to 30°S and averaged from the coast to 1° offshore. The yearly mean latitude from 1998 to 2012 over the October to April season of the isotherm 22°C is represented by the black line and its averaged position by the straight line along the African coast.

1999 (March–August), 2001 (January–May), 2003 (July–December), 2008/2009 (November–January), 2010/2011 (November–April), and 2012 (October–December), and six cold events in 2001/2002 (October–March), 2002 (July–December), 2004 (January–April), 2005 (April–June), 2010 (February–May), and 2011/2012 (November–March). Major warm events 2003 and 2012 as well as major cold events 2004 and 2011 are clearly seen in Figures 4c, 4d, 4g, and 4h. Some of these warm events were identified previously by couple of authors [Rouault *et al.*, 2007; Ostrowski *et al.*, 2009; Lübbecke *et al.*, 2010; Rouault 2012]. There is little in the literature concerning cold events after 2002. The 1999 Benguela Niño at the Angola Benguela Front was described by Mohrholz *et al.* [2001] and Doi *et al.* [2007]. A 0.4 (0.27) lag correlation (cf., Table 3), statistically significant at 95%, is estimated when normalized detrended anomalies of IEKW mode 2 averaged between 20°W and 0°E at 0°N leads normalized

Figure 8. (a) Prediction score of the coastal warm and cold events using the equatorial variability index from 1998 to 2012. Red and blue rectangles represents abnormal positive and negative equatorial SSH propagation identified in Figure 1. Tick symbols (✓) inside rectangles mean that equatorial propagations precede coastal warm or cold events, while cross symbols (X) indicate a mismatch. Bold red and blue contours of rectangles stand for extreme coastal warm events (see section 2.5.3). (b) Seasonal cycle of 5 months running correlation between IEKW mode 2 anomalies averaged between (20°W and 0°E) at 0°N and monthly detrended normalized SSTA in the Southern Angola (red), Angola Benguela Front region (orange), and Northern Namibia (yellow). Correlations are performed only over the strong equatorial propagation periods (blue and red rectangles in top plot) with equatorial index leading coastal SSTA by 1 month. Green background shading indicates the best forecasting period from October to April.

guela (17°S) or further south. Hovmöller diagram shown in Figure 7 illustrates the propagation of monthly detrended SST and shows the connection between the equatorial domain and the African coastline but with less success than altimetry. The main altimetry-derived propagations along the coast (Figures 6 and 4c and 4g) correspond to the main IEKW identified previously. Recently, *Bachelery et al.* [2015] demonstrated that the propagations along the coast were due to Coastal Trapped Kelvin Waves (CTW), also mentioned in *Ostrowski et al.* [2009]. This suggests that the main IEKW and SSHA propagation episodes that we have identified propagate along the coast as CTW.

We summarize our equatorial variability index in relation with the major warm and cold events in Figure 8a. The red (blue) rectangles describe the positive (negative) equatorial propagation episodes and their duration identified in Figure 1. Tick symbols inside rectangles mean that equatorial propagations precede coastal warm or cold events in the Angola-Benguela Current system, while cross symbols indicate a mismatch. Results show that over the 1998–2012 period, 12 out of 18 IEKW identified episodes match coastal SSTA events. From October to April, 10 out of 12 equatorial SSHA episodes match coastal events, while

detrended anomalies of SST in the Southern Angola (ABF) domains by 1 month over the whole (15 years) period. There is no significant correlation with Northern Namibia domain. Significantly higher values of correlations are estimated when only considering periods of strong equatorial propagations (cf., Table 3). Indeed the lag correlation between OLM IEKW mode 2 and SSTA in Southern Angola and ABF region (with equatorial variability leading coastal SST signal by 1 month) is 0.6 and 0.49, respectively. Noteworthy, these values are dependent on the prescribed lag, with in particular higher correlations with Northern Namibia domain when a 2 month lag is used (not shown). We observe in Figure 5, slow propagations of SST anomalies as we move from Southern Angola to Northern Namibia. A sensitivity to the speed of propagation of coastal SSTA is observed, revealing that each coastal event develops differently. The persistence and slow propagation of SST anomalies from Southern Angola to Northern Namibia in these domains, already mentioned in *Rouault* [2012], were attributed to advection of warm tropical waters in the Northern Benguela upwelling domain. He found a significant lag correlation between the two domains when Southern Angola SST anomalies lead Northern Namibia SST anomalies by 1–4 months. Also local effect could modulate the SSTA magnitude of these events south of the ABF [*Richter et al.*, 2010]. Most of the abnormal positive and negative propagation episodes described above in Figure 1 are clearly observed in Figure 6. Figure 6 is a Hovmöller diagram of monthly detrended altimetry derived SSH anomalies along the equator and along the African coast all the way to the Angola Ben-

from May to September 4 out of 6 equatorial propagations are not followed by coastal events along western Africa. Furthermore, we note that all 11 extreme coastal events (identified with contours on Figure 8a) are associated with preceding equatorial propagating signal. Also particular IEKW propagation episodes in 1998, 2001/2002, and 2009 associated with Rossby wave reflection, show a good match with coastal SST events, which, as pointed out previously, give more credit to an IEKW index, rather than wind stress amplitude in the western Tropical Atlantic. In addition, as illustrated on Figures 3c and 5, periods with no strong interannual equatorial Kelvin wave episode (from July 1999 to February 2001 and from July 2005 to September 2007 for instance) also correspond with periods without extreme coastal SSH and SST event. However, the cold coastal events in August 2002 and May 2010 (Figure 5) are not preceded by strong upwelling equatorial waves as depicted by our criterion. Noteworthy, the linear model shows strong anomalous negative SSHA at 0°E and 10°W preceding the cold coastal event in May 2010. For the cold coastal event in August 2002, only PIRATA buoy located at 23°W shows strong negative SSHA, no data are available at the others moorings locations and altimetric SSHA peaks do not fulfill the criterion. Following our methodology, both SSH signals are not catalogued as a strong equatorial propagations.

To better appreciate the link between the interannual equatorial and coastal variability, we computed a 5 months running correlation between IEKW mode 2 anomalies averaged between [20°W and 0°E; 0°N] and monthly detrended normalized anomalies of coastal SSTA in the three regions. We only selected period of strong equatorial propagations when the equatorial index is leading coastal SSTA by 1 month. The seasonal cycle of the corresponding correlation is presented in Figure 8b. We observe that the maximum lag-correlation (statistically significant at 95%) occurs during austral summer. The peak is observed in February, when values of the lag correlation between equatorial variability and SSTA in the Southern Angola (red line) and in the Angola Benguela Front region (orange line) reach 0.75. A sensitivity to the value of the prescribed lag is observed, with, in particular, larger correlation values (>0.7) for the southern domain (Northern Namibia) when a lag of 2 month is considered (not shown). Over the mid-October to April period (green shading in Figure 8), the correlation in the northern domain is significantly higher than in the other regions. In general, October to April seems the best season for the successful prediction of the warm and cold events in the Angola Benguela current system. Noteworthy, this good correlation highlighted in Figures 8a and 8b does not take into account the local effects (local upwelling induced by alongshore wind stress variability, vertical density stratification efficiency, cloud cover fluctuations, and turbulent heat flux forcing), which can modulate the signature of the remote equatorial forcing along the western coast of Africa. Our study is thus consistent with the modeling study of *Bachelery et al.* [2015], who observed that at interannual timescales, remote equatorial forcing is more efficient to modulate coastal SSH and SST than local forcing along the Angola Benguela coasts. But the alongshore wind forcing, with unfavorable or favorable local upwelling wind, is not negligible, since their effects on temperature interannual anomalies can superimpose on the remotely forced CTW. Also, of particular interest is the vertical stratification of the water column which can modulate the signature in SST of CTW propagations. In agreement with our results, vertical stratification will modulate the efficiency of vertical current anomalies to imprint the SST [*Goubanova et al.*, 2013], and thus austral summer stratified surface layer will be more prone to SST anomalies than mixed winter conditions. Also *Polo et al.* [2008a] studied the intraseasonal EKW and highlighted two dominant periods for the emergence of Kelvin Waves (KW): Austral Spring (September–December) for downwelling KW and Austral summer (November–January) for upwelling KW. The favorable season when a potential propagation of the Second baroclinic mode IEKW could trigger a warm or a cold event 1 month later would be mostly between October and April.

4. Summary, Discussion, and Conclusions

In this paper, we use a simple methodology, based on monthly anomaly time series at particular locations along the equator in the Atlantic Ocean where real-time in situ data from PIRATA moorings are available, along with satellite SST along the southwestern coast of Africa over the 1998–2012 period. From PIRATA DYNH and Z20, we highlight the connection between strong interannual equatorial Kelvin wave signals and Benguela Niño or Benguela Niña events in the Angola Benguela current system zone. To our knowledge, PIRATA data had never been systematically exploited for the detection of equatorial Kelvin waves over such a long period (15 years). Local PIRATA in situ data at [23°W, 10°W, and 0°E; 0°N] are used concomitantly with altimetric data and outputs of an Ocean Linear Model sampling the equatorial wave guide. Interannual

OLM SSH outputs compare well with the equatorial observations, confirming the dominance of the equatorial wave propagation signal on the equatorial variability over this period. This allows us to interpret PIRATA records in terms of equatorial Kelvin waves. Thus, the OLM outputs along with a methodology based on temporal and spatial coherence allows depicting strong downwelling and upwelling Kelvin wave signatures in local PIRATA data and altimetric observations. This equatorial time series and the emergence of strong Kelvin wave propagations are systematically compared to interannual SST anomalies indexes in the Southern Angola, ABF, and Northern Namibia coastal sectors commonly used for the study of Benguela Niño/Niña events [Rouault, 2012].

Our results confirm that interannual warm and cold events in the Angola Benguela Current system are remotely forced by Kelvin wave propagations in the equatorial Atlantic. IEKW phase speed estimations suggest that these events are predominantly forced by second baroclinic IEKW which in turn trigger poleward propagating CTW. Correlation of 0.4 (0.27) is estimated when IEKW mode 2 leads SST in the Southern Angola (ABF) domains by 1 month. Although these correlations are modest, they remain statistically significant at 95%. This has to be attributed to the fact these statistics are performed over the whole 15 years period which encompasses long periods of weak interannual equatorial activity (for instance 1999/2000; 2005/2006, 2006/2007, see Figure 8a), uncorrelated with coastal variability. Furthermore, our results reveal a seasonal phasing of the connection between equatorial and coastal variability, with a very good agreement within the October to April season (see Figure 8c, green-shaded area), when correlation are significantly higher. They peak up to 0.75 when estimated exclusively in February for the Southern Angola and Angola Benguela Front domains (see Figure 8b). This period is the most crucial for Benguela Niños according to the literature. This most likely due to the favorable coastal stratification in this season, which acts as an efficiency coefficient of the impact of wave-induced vertical upwelling on SST.

Noteworthy, we observe that early 2001, there is a lack of DYNH data from PIRATA moorings along the equator (cf., Table 2). However, the strong eastward propagation in 2001 is well captured by PIRATA anomalous depth of the thermocline (Z20) at [23°W; 0°N]. For some reasons, in Rouault *et al.* [2007], PIRATA data were then available (depth of the isotherm 20°C), and easily allowed detecting the eastward propagation of higher than normal SSHA in early 2001. Thus, for our study, because PIRATA data processing has changed, only Z20 PIRATA at [23°W; 0°N] data are now available to sample the 2001 downwelling propagation. Fortunately, we also rely in this study on altimetry data to fulfil our criterion in order to detect the 2001 positive propagation of SSHA although there are difference between PIRATA and altimetry. In 2001, SSHA anomalies are clearly linked to Kelvin wave propagation and are associated with a warm SST event along the African coast (Figures 5–7) [Rouault *et al.*, 2007]).

Our results show that an index based on oceanic variability along the equatorial wave guide (for instance PIRATA data and OLM outputs at [0°E; 0°N]) is more skilful than an index based on wind stress anomalies in the Western Tropical Atlantic. Altimetry-derived SSH, links the equatorial propagations to the coastal region. This is particularly true for the 2009 strong equatorial SSH episode which has been studied by Foltz and McPhaden [2010a, 2010b] and Burmeister *et al.* [2016]. They suggested that 2009 negative SSHA episode is mainly triggered by westward Rossby wave propagation which in turn reflects into upwelling eastward IEKW. This wave reflection process is linked to anomalous North-westerly wind in the Equatorial Atlantic associated with strong negative Atlantic meridional mode (AMM) in boreal spring 2009. Our finding is consistent with Foltz and McPhaden [2010a, 2010b] and Burmeister *et al.* [2016] even if we do not investigate equatorial North-westerly wind associated with AMM, but just equatorial wind stress forcing that generates waves in our Ocean Linear Model. This mechanism explains the apparent inconsistency between the sign of the wind stress anomalies in the western Atlantic and the equatorial SSHA in the Gulf of Guinea. This supports our idea of defining an index based preferentially on the IEKW activity in the eastern Atlantic, rather than using wind stress amplitude in the western tropical Atlantic.

We observe that 12 out of 18 identified coastal events matches with strong interannual equatorial episodes. Also, periods with no strong interannual equatorial Kelvin wave correspond with periods without extreme coastal SSH and SST event, except for two cold SST events. These observations have been estimated without taking into account the local effects (alongshore wind, density stratification, net heat budget due to turbulent fluxes and radiative) that are therefore secondary to the development of major cold and warm events, especially from October to April. This finding is consistent with the study of Bachélery *et al.* [2015]

who observed from their regional ocean model that at interannual timescales remote equatorial forcing drives SSH coastal variability. The remaining six mismatches ($1/3^{\text{rd}}$ of the identified strong equatorial episodes) mainly occur during the May–September season. They might be attributed to the local coastal stratification, which is weaker in austral winter and makes wave-induced vertical upwelling inefficient to imprint the temperature in the mixed layer. This mismatch cases can also be attributed to the effect of local atmospheric forcing which is not negligible since we have not quantified its contribution. However, we also acknowledge the fact that even if we use monthly mean and search for the strong equatorial episodes (coastal events) with SSHA (SSTA) exceeding the threshold for at least 2 (3) months, we may have not entirely removed the intraseasonal variability contribution to the coastal SSHA, which is driven by the local forcing according to *Bachèlery et al.* [2015]. However, along the African coast, Benguela Niños have been known to occur in the region in spite of above normal upwelling favorable wind (local forcing) for instance in 1984 [Shannon et al., 1986] or in 2001 [Rouault et al., 2007]. Also, the contribution of the local surface forcing through latent and sensible fluxes, important drivers of the net heat budget at the surface, tends to damp the mixed-layer interannual temperature anomalies, decreasing the temperature of warm events and increasing the temperature of cold events [Florenchie et al., 2004; Bachèlery et al., 2015]. As for vertical velocity due to wind-driven upwelling, it is important to note that this effect only apply southward of the Angola Benguela front in the Benguela upwelling. In agreement with *Bachèlery et al.* [2015], our results suggest that at interannual time scales, wind-induced upwelling can certainly modulate SST, but it is not the dominant mechanism.

We have also performed sensitivity tests to the lag between equatorial and coastal variability. Indeed, Figure 3b shows that correlation between IEKW mode 2 and coastal Southern Angola SSHA peaks when equatorial variability leads coastal one by one month, but significant correlations occur for a broader range of lag extending from 0 to 2 months. More than highlighting the time scales of the variability, this lag-correlation analysis reveals that each event develops differently. Indeed, the equatorial variability is the results of the superposition of numerous baroclinic modes, with the second baroclinic mode contribution mostly dominating the eastward equatorial propagating signal. However, we have observed the contribution of the first baroclinic mode (three times more rapid than the second baroclinic mode) [Illig et al., 2004] for the abnormal negative propagation in 2004. In that case the signature is more noticeable through the shoaling of the thermocline. Major variations in thermocline depth at the origin of these events are observed by PIRATA and altimetry and are simulated by the Ocean Linear Model forced by wind stress only. It is also important to note that all our estimations of equatorial wave phase speed from observations remain consistent with the study of Illig et al. [2004]. However, another caveat is that the advection of water masses can modify the estimated propagation velocity if the latter is computed based on tracer's properties [Bachèlery et al., 2016]. Indeed, the propagation speed associated with tracers spreading can be different from the wave propagation phase speed. Indeed, the estimation of the phase speed differs in function of the parameter used for the estimation: tracer (temperature, salinity) or dynamical field (thermocline depth, sea level). Nevertheless, the estimation of coastal propagation speed of the spreading at interannual timescales due solely to advection is not straightforward, while we can rely on the linear theory to have an estimation of the theoretical phase speeds associated with the CTW but, it would be difficult to speculate in that study on the importance of the advection of anomalous gradient by the anomalous meridional currents.

A conclusion of this study is that an Ocean Linear Model can be implemented in real time relatively easily using real time satellite wind estimates or atmospheric model outputs. Equally important is the equatorial DYNH and thermocline depth (Z20 provided by PIRATA moorings which are available in real time). PIRATA data and altimetry data, also available in real time, can be used concomitantly in an early warning system for Benguela Niños and Niñas or abnormal events along the Equator such as Atlantic Niño. This could lead the way to a bulletin on the state of the Tropical Atlantic similar to bulletin done for El Niño and La Niña in the Pacific. Such a bulletin for the Tropical Atlantic does not exist yet. The PIRATA array of moorings is crucial for the observation of these Kelvin waves and must be maintained.

At monthly scales, local atmospheric forcing has little impact on the generation of most major cold and warm coastal events, although it could modulate their intensity. The limited surface signature of these events in temperature anomalies along the Angola and Namibia coasts seen in Figure 7, could be due to the fact that the temperature is not a dynamic parameter, as warm and cold events are associated with

deepening or shoaling of the thermocline [Florenchie et al., 2004], change in the net heat budget at the air sea interface [Florenchie et al., 2004] or advection [Rouault, 2012].

At last, this study opens the possibility to forecast Benguela Niños and Niñas, especially from October to April, using an Ocean Linear Model forced by wind speed, and altimetry and PIRATA data. Tide gauge and current meter available in real time in Angola and Namibia would complete the system and are much needed. Further work will involve study of the peculiar events for which our equatorial index failed to explain the coastal interannual variability, although some answers can already be found in the literature. We should better ascertain the relation between the Southern Angola and Northern Namibia domains. Also we need to better ascertain the role of local variability (strength of stratification, wind forced upwelling, cloud cover, and turbulent fluxes) for each Benguela Niño and Benguela Niña event over 1958–2015. We will use for that matter an Ocean General Circulation Model (OGCM) that allows calculating each term of the heat budget in the subsurface as a continuation of this study.

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