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Modes of tropical Atlantic climate variability observed by PIRATA

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[1] The geography of the Pilot moored Research Array in the Tropical Atlantic (PIRATA) was especially designed to observe the two main modes of climate variability in the tropical Atlantic: the equatorial mode (equivalent to the warm events in the Pacific Ocean), and the meridional mode, also known as the dipole mode. This paper is an attempt, using the first available PIRATA data, to evaluate the presence of the two modes, as well as their relationship with the current array configuration. *INDEX TERMS:* 4215 Oceanography: General: Climate and interannual variability (3309); 4231 Oceanography: General: Equatorial oceanography; 4504 Oceanography: Physical: Air/sea interactions (0312). **Citation:** Servain, J., G. Clauzet, and I. C. Wainer, Modes of tropical Atlantic climate variability observed by PIRATA, *Geophys. Res. Lett.*, *30*(5), 8003, doi:10.1029/2002GL015124, 2003.

1. Introduction

[2] Within the last decades, numerous studies of climate variability in the tropical Atlantic have identified two main modes at interannual time scales [e.g., *Servain and Merle*, 1993; *Xie et al.*, 1999]. One mode of variability is similar to the Pacific El Niño - Southern Oscillation (ENSO) in the sense that it relates the ocean's equatorial adjustment to changes in the trade winds. However the Atlantic "El Niño-like" mode is much weaker than its Pacific counterpart. With the intensification (or weakening of the winds) in the western Atlantic one will find that the equatorial ocean responds with negative (or positive) sea surface temperature (SST) anomalies, particularly in the Gulf of Guinea. This mode is evident every 2 to 4 years not only at the surface (e.g., SST) but at the subsurface (as represented by the depth of the thermocline) as well. A good example is the warm event of 1984 [*Philander*, 1986; *Servain and Séva*, 1987; *Reverdin et al.*, 1991], where the monthly anomalies of SST reached 3–4°C close to the African coast while the equatorial thermocline slope became unusually flat.

[3] The second mode of interannual variability, also known as the Atlantic "dipole-mode", is characterized by a north-south oscillation of basin scale SST separated by the intertropical convergence zone (ITCZ) [*Moura and Shukla*, 1981; *Servain*, 1991]. This mode seems unique to the Atlantic ocean with no similar counterpart in the Pacific. Its time-scale of evolution ranges from interannual to decadal. So far, it has been observed mainly in SST fields as well as in the atmospheric surface winds, in particular with respect to the variations in the mean latitudinal position of the ITCZ.

[4] The initial PIRATA array consists of 12 Autonomous Temperature Line Acquisition System (ATLAS) moorings [*Mangum et al.*, 1994], four spanning the equator (from 35°W to 0°E) and eight spanning two meridional lines (at 38°W from 4°N to 15°N, and at 10°W from 2°N to 10°S). Based on the historical understanding of climate variability in the region (see above) this specific configuration has been chosen to provide measurements related to the two main modes of climatic variability in the tropical Atlantic basin. Along the equator, the array extends from the western Atlantic warm pool where the wind forcing is strong and the oceanic thermocline is deep, to the cold tongue region in the eastern basin (Gulf of Guinea) where the upwelling is strong and the thermocline is shallow. The two meridional lines of the PIRATA array cover the regions of high SST variability associated with the SST dipole mode, with the northwestern meridional line cutting across the ITCZ during most the year.

[5] With the very first PIRATA data set available during the period 1997–2001, the aim of this study is to verify how these measurements allow for an adequate description of the two principal modes of climate variability in the tropical Atlantic, and how they can be used to define an equatorial and a meridional index. A second purpose of this study is to check how these two PIRATA indices of variability are related, and if they confirm the results provided recently from longer time series [*Servain et al.*, 1999, 2000, hereafter noted *S*99-00; *Murtugudde et al.*, 2001].

2. Data

[6] The study period corresponds to the pilot phase of the PIRATA program (1997–2001). Unfortunately, as noted in a companion paper [*Wainer et al.*, 2002], the PIRATA time series presents several gaps during that period. These gaps are due to various catastrophic mechanical failures or, more commonly, due to vandalism associated with fishing activities [*Servain et al.*, 1998]. Furthermore, the availability of the PIRATA raw data is slightly different according to whether one uses the satellite daily transmissions of the data, or the in-situ yearly acquisition of the data at the 10-minute rate. Here, in order to carry out our analyses on the longest possible time series we chose to use the more adequate version of the raw data. Thus, the PIRATA oceanic temperatures (SST and the 10 subsurface levels) used here consist of the 10-minute data delivery. These data are available on the official PIRATA Web site at the following address: www.pmel.noaa.gov/pirata.

[7] The time series of the variables measured by PIRATA during the pilot phase of the program are obviously not large enough to compute seasonal climatologies. Here, two historical data sets of SST and subsurface temperature serve

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as references. These data references are (i) the 1964–2000 SST (and wind) file obtained from an analysis of the merchant ships' observations [*Servain and Lukas*, 1990, hereafter noted *SL*90], and (ii) the climatic atlas of subsurface temperature from *Levitus* [1982, hereafter noted *L*82]. The original time steps of these various data sources being different (10-minutes for the PIRATA data and 1-month for the climatologies) the PIRATA data were averaged, and the climatologies were interpolated in time to a daily interval. Furthermore, in order to facilitate the comparisons between the different variables (SST and thermocline depth) we standardized their anomalies.

[8] The meridional and equatorial indices discussed hereafter are only related to the existence of the common periods of the PIRATA measurements from which these indices were calculated. Furthermore, in order to obtain a better description in the discussed events, equatorial wind derived from the *SL*90 data set, and altimetric data delivered by the satellite Topex/Poseidon (T/P) [*Cheney et al.*, 1994] are also used for the period January 1998 to July 2001.

3. Results

[9] A PIRATA SST *dipole* index is calculated as follows. Using the two most poleward ATLAS sites at 15°N–38°W and 10°S–10°W, a daily time series is constructed by subtracting, for periods of common available data, the SST from the buoy south of the equator from the SST measured north of it. In order to remove the seasonal signal, the *SL*90 SST climatology at the same locations was daily interpolated and subtracted from the PIRATA data. Figure 1a shows the PIRATA dipole index (green line) computed according to this process. One sees two periods where the PIRATA dipole index is available: a shorter one in February–March 1998, and a longer one from November 1998 to February 2000. Slow fluctuations at about a 5-month time scale, with standardized values approaching or exceeding 1 unit, are noted within the periods. The two largest values with opposite signs are noted during the second period, a positive one in January 1999 and a negative one in June–July 1999. Superimposed on Figure 1a are the monthly time series of the dipole index as proposed by *Servain* [1991]. This dipole index is defined as being the arithmetical difference between the standardized SST anomalies averaged over the northern domain (28°N–5°N) and the similar calculation over the southern domain (5°N–20°S). Although long-term fluctuations are of the same order (basically a few months period) for the two time series, it seems that the dipole index computed using data for the whole tropical Atlantic is approximately 2 months ahead of the dipole index obtained from PIRATA. This can be explained by the fact that the *Servain*'s [1991] dipole index integrates the equatorial domain where the dynamics are faster, in contrast with the PIRATA index which only encompasses two tropical locations.

[10] The observed temperature profiles provided at each PIRATA site allows the assessment of the evolution of the thermocline depth at these specific locations. In the tropics, the thermocline depth can be estimated by the depth of the 20°C isotherm, called hereafter Z20. Available Z20 times series during the period January 1998 to June 2001 for the three equatorial PIRATA sites located at 35°W, 23°W and

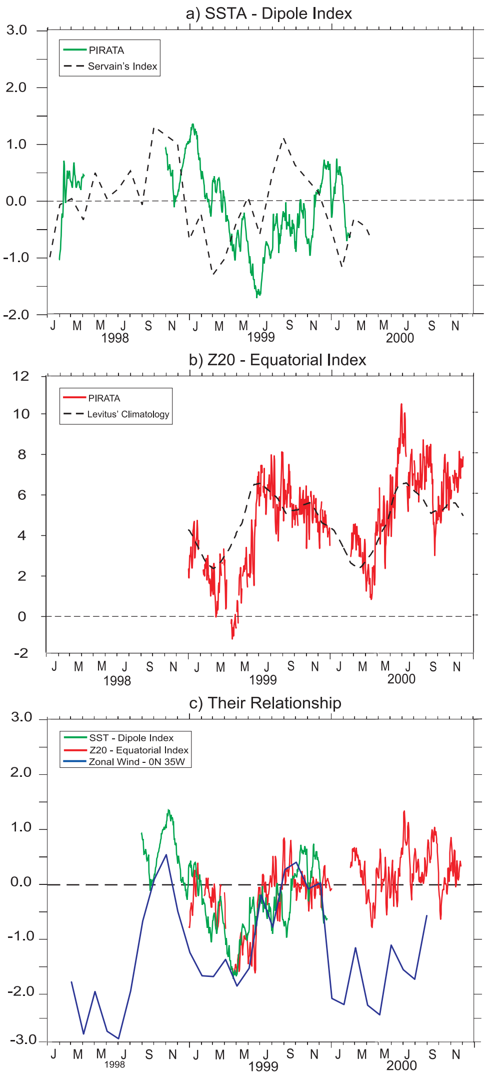

Figure 1. (a) Daily time series of the PIRATA SST dipole index (green line) superimposed to the *Servain*'s [1991] dipole index (black dashed line); (b) Daily time series of the PIRATA Z20 equatorial slope (red line) superimposed to the monthly slope deduced from L82 climatology (black dashed line); (c) PIRATA SST dipole index (green line) and Z20 equatorial index (red line), superimposed to the zonal wind (Wx) monthly anomaly at 0°N–35°W (blue line) deduced SL90 data. The time axis on (c) is related to the Z20 index; the SST dipole index is shifted backward by 2-month, whereas Wx is shifted forward by 2-month.

10°W are shown on Figure 2a. It is evident that the thermocline is deeper in the western equatorial basin (up to 80 meters for the site 0°N–35°W) and shallower in the eastern basin (less than 80 meters for the site 0°N–10°W). Also evident is the large seasonal signal of Z20 for the three equatorial PIRATA sites, in particular for the two most distant locations. Indeed the seasonal range of the observed Z20 during the years 1999–2001 reaches 60 meters in the west (23°W), 70 meters in the east (10°W), and only 50 meters in the center of the basin (23°W). In agreement with previous studies [e.g., *Merle*, 1980], the Z20 equatorial slope is most pronounced in July–September (about 60 meters between the deepest Z20 at 35°W and the shallowest

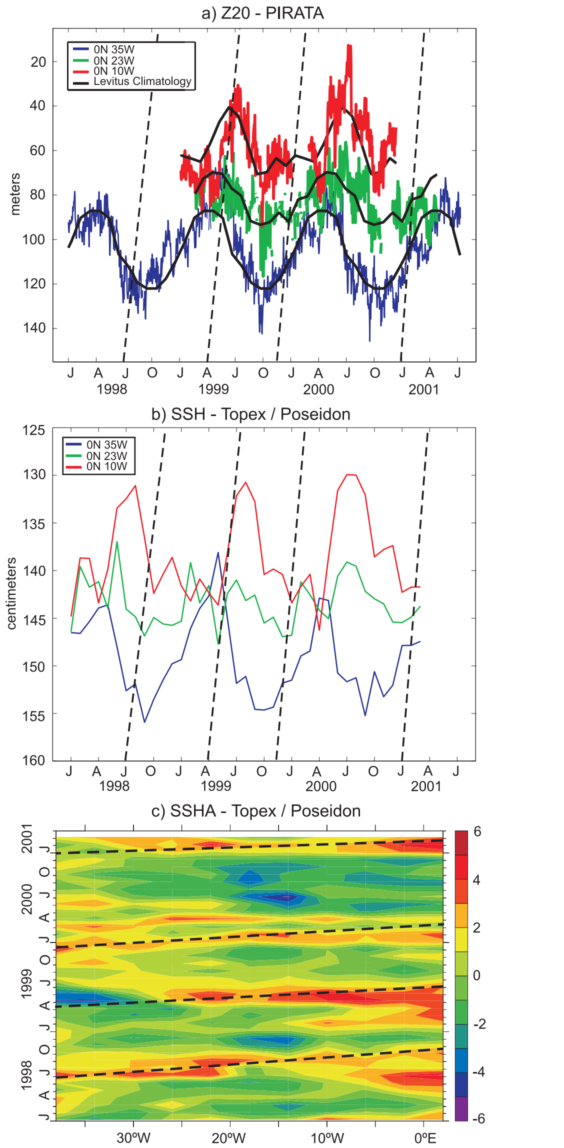

Figure 2. (a) Daily time series of Z20 provided by the PIRATA data at 0°N–35°W (blue), 0°N–23°W (green) and 0°N–10°W (red) superimposed to the monthly climatic values deduced from L82 (black lines); (b) Monthly times series of SSH as in (a) but from the T/P altimetry data set; (c) time-longitude diagram of SSH anomaly (humps in blue, hollows in red) along the equator during January 1998 to July 2001, as provided by the T/P altimetry data set. Eastward propagating events are identified in (c) by four dashed lines, also represented on (a) and (b).

Z20 at 10°W), whereas it is observed to flatten considerably in April–June (a difference less than 25 meters between the two sites). Superimposed on Figure 2a are the three climatological monthly averages of Z20 obtained from *L*82. As shown by these mean seasonal signals, Z20 is the shallowest (40 meters) at the beginning of austral winter (June–July) at 10°W and the deepest (120 meters) during the winter and beginning of fall (July to October) at 35°W.

[11] Time series of the sea surface height (SSH) are presented on Figure 2b for the same period, January 1998 to June 2001 for the same three equatorial positions. SSH is obtained from the T/P altimetry data set [*Cheney et al.*, 1994]. One notes a symmetrical seasonal evolution of SSH associated to that of Z20: when Z20 is the deepest, SSH is the highest, and vice versa. Interannual variability of the oceanic structures along the equator is evident (Figure 2a) in spite of the short duration of the series, albeit a weak signature on the monthly SSH time series (Figure 2b). One should note for example, the extreme shallowing of Z20 at 10°W in July 2000 and the abnormal deepening of Z20 at 35°W in October 1999 and October 2000. Compared to the *L*82 seasonal climatology, the PIRATA Z20 time series shows significant abnormal episodes with inverse signatures between the western and eastern equatorial locations: for instance an abnormal elevation (drop) at 35°W (10°W) in late 1998 (first half of 1999), and an abnormal drop (elevation) at 35°W (10°W) during the second half of 2000 (middle of 2000). These both events appear on Figure 1b where the observed difference of Z20 at 35°W minus Z20 at 10°W is plotted (red line) during their common period. The repeated seasonal climatic difference, obtained in the same manner from *L*82, is superimposed on this figure (black dotted line). By comparing the two time series, one can notice that a neutral equatorial Z20 slope is especially marked during the first half of 1999 (with a negative peak in April–May), whereas a strongly inclined thermocline is prominent during the second half of 2000 (with a highest positive value in June 2000). A simple arithmetical subtraction between the two time series of Figure 1b (after a daily interpolation of the monthly climatic series) yields a daily record of the interannual variability of the Z20 slope along the equator. This index can be used as a proxy for an equatorial index, according to that proposed by *S*99-00 which is shown on Figure 1c (red line), as well as the SST dipole index (green line). The time series of the SST dipole index on Figure 1c is delayed by 2 months compared to the time series of the Z20 equatorial index (the time axis of Figure 1c is related to the time of the Z20 time series).

[12] Because of the significant gaps in the data, it is not possible to check the quality of the relationship between the two indices throughout the entire pilot phase of the program PIRATA. The only common period between the time series of the two indices comprises the period from January 1999 to January 2000. This approximate 1-year duration is obviously too much a reduced period to expect any statistical significance at the interannual time scale. In spite of this short period one can however notice that the two indices change in a similar way all along 1999, thus confirming the results of *S*99-00. It is particularly remarkable to verify that the significant interannual event which mainly occurred during the second quarter of 1999 is related in Figure 1c by simultaneous (i.e., Z20 2-month in advance versus SST) maximum negative values for both indices. These peaks indicate a negative dipole index (cold north of the equator, warm to the south) and a flat equatorial slope from Z20. Indeed it is known that the tropical Atlantic experimented a strong negative SST dipole around that period exceeding one standard deviation in March–April 1999 (Figure 1a; see also *Climate Diagnostic Bulletin*, January 2002 issue, p. 47).

[13] The monthly time series of the zonal wind (easterly) anomaly (Wx) obtained from the *SL*90 data set at 0°N–

35°W is superimposed on Figure 1c (the blue line), with the time reference shifted forward by 2 months compared to that of Z20. One notes a remarkable agreement between the three curves (SST dipole index, Z20 equatorial index, Wx easterly index) throughout 1999, especially during the large abnormal event of the second quarter of that year. Taking into account the various temporal shifts used between the three curves it can be seen that a drastic relaxation of Wx (negative easterlies) in the western equatorial Atlantic occurred two months before the flattening of the equatorial slope, and four months before the negative value of the SST dipole.

4. Discussion and Conclusion

[14] There is very good potential to describe in real time (thanks to the day to day availability of the data on the Web) the two principal modes of climate variability in the tropical Atlantic, which was one of the objectives of the PIRATA program. The time series associated to the PIRATA data set are still very short, mainly because of the several data gaps, therefore the results presented are only preliminary. This analysis of the in-situ data validates at a higher frequency time sampling the good relationship between the two modes, as presented previously by *S*99-00 and *Murtugudde et al.* [2001]. Like in *S*99-00 both modes estimated using PIRATA data are related to delayed dynamical forcing off South America through fluctuations of the zonal wind in the western equatorial basin.

[15] However no in-situ observing system alone, can describe real time fast fluctuations of the coupled atmosphere-ocean and oceanic dynamics. Any program of in-situ observations, like PIRATA, must be combined with other observing networks so that it is possible to check spatio-temporal continuity in the measurements, as well as to allow mutual validations between different data sources. Figure 2c shows the time-longitude diagram of the SSH anomaly along the equator (from 40°W to 3°E) from the January 1998 to June 2001 (T/P altimetry data set). Several episodes of humps and hollows are noted along the studied period. Four eastward propagating events are identified on Figure 2c by dashed lines, also represented on Figures 2a and 2b. These events are all related to positive elevations of the SSH, corresponding to downwelling and warming events. They propagate eastward at a velocity ranging between 0.2 and 0.8 m/s crossing the basin in approximately 2–3 months. This velocity is in agreement with the theoretical value of the equatorial Kelvin wave speed. Due to the lack in some PIRATA data in 1998 and 2000, only the second of these pulses, noticed from April to July 1999 on Figure 2c, can be associated with the occurrence of the PIRATA observed neutral equatorial thermocline slope-Z20/negative-SST-dipole event discussed earlier (Figure 1c).

[16] Obviously, there is much to be learned from the PIRATA data. For instance, forthcoming analyses should be undertaken to test hypothesis that off-equatorial SST variability is caused mostly by equatorial dynamics (as related here) or by wind-induced latent heat fluxes [*Carton et al.*, 1996; *Chang et al.*, 1997]. Furthermore, usage of the data when the time-series will get longer should allow to test if the correlation between the dipole and equatorial modes is intermittent, as recently shown by *Murtugudde et al.* [2001] for the past 50 years.

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