ABSTRACT

Title of Scholarly Paper: CHARACTERIZATION OF EQUATORIAL AND SOUTHEASTERN TROPICAL ATLANTIC WARM EVENTS FROM 1982 TO 2003

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The tropical Atlantic Ocean shows warm and cool sea surface temperature (SST) anomalous events. Some warm episodes have been referred to as Atlantic Niños while others have been referred to as Benguela Niños. The differences and relation between them have not been addressed and a clear distinction or categorization has not been presented. The objectives of this study was to characterize similar Atlantic warm events based on SST, low-level winds and precipitation anomalies and study the differences and relation between the warm events. Two area indices were analyzed: a central-equatorial (3°S-3°N, 25°W-5°W) index and a southeastern tropical (10°S-23°S, 8°E-coast) index representing the Benguela region. Positive SST anomalies were identified during the boreal spring from 1982 to 2003, the period common to the data sets. For the central-equatorial area index the warm anomalies of 1988, 1998 and 1999 met the criterion and were averaged into composites while for the southeastern tropical area index the anomalies of 1984, 1996 and 2001 were composited. The peak month of the southeastern tropical warm event (Benguela Niño) is April and has a greater SST anomaly than the peak month of the equatorial warm event, June. Since they are distinguishable from each other we suggest the

terms Benguela Niño and Equatorial Atlantic Niño for the warm events in the respective areas. The precipitation anomalies corresponding to the Equatorial Atlantic Niño show a zonal shift away from the continents while those corresponding to the Benguela Niño show positive anomalies over the continents. The northern subtropical region is consistently warm during an Equatorial Atlantic Niño in association with a weakening of the northeasterlies while for a Benguela Niño the northern subtropics are consistently normal.

CHARACTERIZATION OF EQUATORIAL AND SOUTHEASTERN TROPICAL ATLANTIC WARM EVENTS FROM 1982 TO 2003

By

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1. Introduction and Background

1.1. Introduction and Significance of Study

Even though the tropical Atlantic Ocean has a fairly regular annual cycle, there are deviations from the mean of sea surface temperature (SST) that constitute warm or cold events especially in the equatorial and coastal upwelling regions. Associated with these warm events there is anomalous behavior of rainfall and low-level winds. Two of the land regions sensitive to interannual variability of the Atlantic Ocean are the northeast region of Brazil and the western region of Africa [*Nobre and Shukla* 1996; *Gianinni et al.,* 2003; *Rouault et al*., 2003]. Rainfall anomalies of the intertropical convergence zone (ITCZ) in these regions affect the physical environment as well as the life of people residing in these areas. Hence, the anomalous oceanic warm or cool episodes have the potential for inducing changes in weather and climate patterns that may affect the economies and human health of South American and African societies.

1.2. Interannual Variability

1.2.1. Interhemispheric Mode

The tropical Atlantic shows different modes of variability [*Servain et al.*, 1990; *Carton et al.*, 1996; *Chang et al*., 1997; *Servain et al*., 1998]. The two main modes of variability are the equatorial mode and the interhemispheric mode [*Servain et al.,* 1998; *Ruiz-Barradas et al*., 2000]. The interhemispheric mode has also been called the Atlantic dipole or the meridional gradient mode and its better observed during boreal spring [*Nobre and Shukla,* 1996; *Ruiz-Barradas et al.,* 2000; *Chang et al.,* 2001; *Tanimoto and Xie*, 2002]. The meridional gradient mode is characterized by a meridional gradient of SST anomalies from one subtropical region to its counterpart in the other hemisphere, a pattern of wind anomalies from colder subtropics to warmer subtropics and a shift of the Atlantic Marine Intertropical Convergence Zone (AMI) to the warmer subtropics [*Nobre and Shukla,* 1996; *Ruiz-Barradas et al.,* 2000]. Although the causes of the formation of this meridional pattern of temperature anomalies and winds are poorly understood, it has been observed that the north subtropical Atlantic is remotely forced by the Pacific El Niño-Southern Oscillation (ENSO) and by the North Atlantic Oscillation (NAO) [*Enfield and Mayer,* 1997; *Saravanan and Chang*, 2000; *Czaja et al.*, 2002].

1.2.2. Equatorial Mode

The equatorial mode is characterized by the manifestation of positive (warm) or negative (cool) sea surface temperature anomalies (SSTA) along the equator and in the cold tongue region (central and eastern equatorial regions to the southeastern tropical region) especially during boreal summer. Related to the warm events are anomalies of the precipitation band which shift to the warm region as well as anomalies of low-level winds towards the warm center. Previous studies have analyzed these events in several ways by studying different regions of the tropical Atlantic [*Zebiak*, 1993; *Carton and Huang*, 1994; *Wang,* 2002; *Florenchie et al.,* 2004]. Two main regions that have been studied, albeit separately, are the equatorial region and the southeastern tropical region. The warm events that manifest along the equator have been dubbed Atlantic Niños [*Merle*, 1980] while the warm events that manifest in the southeastern tropical region have been dubbed Benguela Niños [*Florenchie et al*., 2004]. However, previous studies have addressed either the equatorial Atlantic Niño or the Benguela Niño and no comparison between them has been presented so far. In some studies, especially the older articles, the term Atlantic Niño is used to refer to any warming in the tropical region akin to the Pacific Niño. Hence the use of the terms might be ambiguous some times and a study of the differences and similarities of the tropical Atlantic warm events is mandatory to quantify the relation of the anomalous events of the equatorial and Benguela regions.

1.3. Objectives

One objective of this work was to study the differences between the tropical Atlantic warm events after grouping or compositing them based on spatial and temporal similarities. Another objective of this study was to characterize the tropical Atlantic warm events by SST, low-level winds and precipitation patterns from 1982 through 2003. The period of study was the common period of coverage of available data sets that include satellite observations.

1.4. Previous Characterization of Warm Events

1.4.1. Previous Characterization of the Atlantic Niño

As stated above, the equatorial Atlantic Niño is one of the modes of interannual variability of the tropical Atlantic. The anomalous warming of the eastern equatorial and southeastern tropical Atlantic regions observed during the 1963 expedition of the EQUALANT Program was named by *Hisard* [1980] and *Merle* [1980] an 'Atlantic Niño' after the similarity to the Pacific Niño. They observed that positive SSTs were concurrent with shifts in convection and relaxation of the trade winds. Just as *Hisard* [1980] and *Merle* [1980] called the 1963 event an Atlantic Niño, *Shannon et al*., [1986] called the same event a Benguela Niño.

During a later expedition of SEQUAL/FOCAL in 1984, another warm event was observed. This event has been documented by *Philander* [1986], *Shannon et al.* [1986] and *Carton and Huang* [1994] among others. *Philander* [1986] observed that the mixed layer warmed and that the thermocline showed an anomalous deepening in the eastern basin. *Shannon et al.* [1986] studied the 1984 event and called it a Benguela Niño. *Carton and Huang* [1994], studying observations and numerical simulations, presented a comprehensive discussion of the warm events of 1984 and 1988 and their differences. They observed that the causes of the 1984 were somewhat different than the ones of the 1988 event. They indicated that the 1988 event is explained by changes in the winds during spring of the same year while the cause of the 1984 event goes back to the anomalous intense trade winds during the summer and fall of 1983 and a massive buildup of anomalous heat in the western Atlantic [*Carton and Huang*, 1994].

Zebiak [1993] based on coupled modeling studies made distinctions between the Pacific ENSO and the Atlantic equatorial mode and attributed the differences to the dissimilarities of the atmospheric and oceanic phenomena between the basins. He observed that the warm and cold events in the Atlantic last shorter than in the Pacific and that the SSTA reached largest amplitudes during boreal summer for the Atlantic as opposed to boreal winter for the Pacific. *Zebiak* [1993] attributed the differences to the zonal structure of the winds, the upwelling, the SST and the thermocline depth between the two basins. He stated that, even though the Pacific and Atlantic equatorial modes are similar, the total climate variability explained by the equatorial coupled mode in the Atlantic is less than in the Pacific.

A more in-depth study of the variability of the tropical Atlantic was done by *Ruiz-Barradas et al*. [2000] through a 5-variable rotated principal component analyses. *Ruiz-Barradas et al*. [2000] confirmed that the Atlantic Niño (the equatorial mode) has a principal component that varies at interannual timescales with maximum amplitude in northern summer. Since this is the season when an equatorial cold tongue of water appears in the east, the positive phase of the mode results in an absence of the cold tongue in the eastern tropical Atlantic [*Ruiz-Barradas et al*., 2000]. They observed that the trade winds along the equator weaken west of 20°W and warm thermocline water is shifted eastward.

1.4.2. Previous Characterization of the Benguela Niño

According to *Shannon et al.,* [1986] during the 1968 equatorial Atlantic warm event there was no indication of any particularly abnormal situation in the northern Benguela region (off southwestern Africa). Also, the 1988 warm event in the equatorial Atlantic did not show a correspondent warm event in the Benguela region. In fact, several studies have stressed that some of the differences obtained in similar studies is due to focusing on different regions of the tropical Atlantic [*Hirst and Hastenrath*, 1984]. That is, the tropical Atlantic warm events seem to manifest either along the central and eastern equatorial region, in the southeastern tropical Atlantic region or in both regions; and a warm event in one region does not always have a correspondent event in the other region (Figure 6).

Shannon et al. [1986] discussed the warm events of 1963 and 1984 in the Benguela region and coined the term "Benguela Niños" for these warm events akin to the Pacific Niños. They studied the northern Benguela region, (i.e., south of 15°S and north of 25°S), a region where significant upwelling occurs. At the time of their publication three major warm water intrusions into the Benguela region were known: 1934, 1963 and 1984. Using mainly coastal data they studied these events and discussed connections with processes in the equatorial Atlantic. Their account of the 1984 Benguela Niño is as follows:

> "very warm and highly saline water from the north or northwest penetrated about 5 degrees of latitude farther south than normal during the late summer and autumn of 1984 and effectively suppressed upwelling of cool nutrient rich water in the northern Benguela, in spite of the strong equatorward winds" [*Shannon et al.,* 1986].

They concluded that the major northern Benguela events are not related to changes in local wind stress but have their origin to the north or northwest of the system.

Then, *Florenchie et al.* [2003, 2004] revised the Benguela Niño phenomenon by using more recent observations and an ocean general circulation model. The model realistically simulated the Benguela Niños of 1984 and 1995 and *Florenchie et al.* [2003, 2004] observed that wind stress changes of between 25 to 50% over the western equatorial Atlantic induce thermocline displacements locally. This anomalous displacement follows the thermocline as an internal Kelvin wave propagating toward the east but does not outcrop when it reaches the eastern boundary though it becomes a coastal Kelvin wave propagating southward and outcrops further south as a Benguela Niño [*Florenchie et al.,* 2003, 2004].

1.5. *The Response of the Eastern Tropical Atlantic to Forcing from the Western Equatorial Atlantic*

One of the earliest numerical studies of the remote forcing through Kelvin waves in the upwelling of eastern Atlantic was that of *Adamec and O'Brien* [1978]. Though it was the study of the seasonal phenomenon (and not interannual) they were able to show that an upwelling equatorial Kelvin wave is excited at the western Atlantic and travels eastward to the eastern Atlantic. This was confirmed by *Katz* [1987]. *Adamec and O'Brien* [1978] concluded that "the increase of wind stress in the western basin is a remote forcing mechanism capable of producing upwelling in the Gulf of Guinea" [*Adamec and O'Brien,* 1978]. That is, an increase of wind stress excites an upwelling equatorial Kelvin wave related to the shoaling of the thermocline and induces upwelling in Gulf of Guinea.

Servain et al. [1982] showed by statistical methods (correlation with lags, power spectra, etc.) that remote forcing by wind stress also explains the SST anomalies observed in the Gulf of Guinea. They discussed that the interannual variability of SST in the eastern equatorial Atlantic (Gulf of Guinea) is highly correlated with the interannual variability of the zonal wind stress in the western equatorial Atlantic. They observed that a westerly anomaly of zonal wind stress near the north Brazilian coast is followed by a warm SST anomaly in the Gulf of Guinea about one month later and they indicate that the lag is related to the speed of Kelvin waves. The fact that the western Atlantic region (northern Brazil) has high interannual variability of wind stress along the Equator was shown by *Picaut et al.* [1984], later. Based on model results, *Carton et al*. [1996] demonstrated that most of the SST variability in the eastern Atlantic results from wind anomalies within 7.5 degrees to the north or south of the equator.

Complementing the study by *Servain et al*. [1982] is the study by *Hirst and Hastenrath* [1983] who tried to elucidate the cause of rainfall anomalies on the Angola coast (south of the Gulf of Guinea). They studied the atmosphere-ocean mechanisms from effect to cause and concluded that the anomalies of wind stress in western Atlantic explain 23% of the SSTA on the eastern Atlantic while the local anomalies of wind stress explain 9% of the SSTA. They emphasized that the seasonal relaxation of wind stress (i.e., wind stress in Sept-Nov minus that in Feb-April) is more relevant than the wind stress itself in explaining the SSTA. They pointed out that *Servain et al.* [1982] made no distinction of seasons and only studied the wind stress and not the seasonal relaxation of wind stress. Also very interesting, is another statement they made regarding the region of the SSTA studied, that is, that *Servain et al.* [1982] studied the Guinea Gulf region while *Hirst and Hastenrath* [1983] studied the waters off Angola (Benguela region). As this work shows, they indicated a significant difference between the studies, i.e. the regions of study.

2. Data and Methods

2.1. Data of SST, Precipitation Rate and Low-level Winds

To achieve the aforementioned objectives, data of SST, precipitation rate and low-level winds from 1982-2003 were used. The period from 1982 to 2003 was studied since this is the period of available common data. The SST data set used was the NOAA Optimum Interpolation SST v.2 (OI-SST v.2) and is described in *Reynolds et al.* [2002]. The SST data are monthly averages in °C with 1° x 1° spatial resolution. The precipitation rate data set used was the Global Precipitation Climatology Project (GPCP) Version 2 Combined Precipitation Data Set described in *Adler et al.* [2003]. The NCEP/NCAR Reanalysis [*Kalnay et al.*, 1996] 2-meter zonal and meridional wind components were used to compute pseudo wind stress. Monthly climatologies, anomalies and standard deviations were calculated for the period 1982-2003. The monthly anomalies are the departure of each month of the record from the monthly climatology.

2.2. Area Indices

Two area indices were analyzed to identify warm events from 1982 to 2003. One area index corresponds to the central equatorial Atlantic; the other area index corresponds to the southeastern tropical Atlantic or Benguela oceanic region. The central equatorial area index was chosen after dividing the deep tropical Atlantic into three regions from 3°S to 3°N. The three regions were: western (from 45°W to 25°W), central (from 25°W to 5°W) and eastern (from 5°W to eastern boundary) equatorial Atlantic regions. The southeastern tropical Atlantic region or the Benguela oceanic region was delimited after the region with highest standard deviation of SST from 23°S to 10°S and from 8°E to the eastern boundary.

2.3. Selection of Warm Events and Compositing

The composites were computed based on SST anomalies during the warmest months of the annual cycle for each region separately. The annual cycle of the central equatorial region (Figure 2) shows the warmer months to be February, March, April and May. The monthly time series of anomalies were low-pass filtered with a 3-month running mean to capture the slow variations of the anomalous events. Then, the anomalies of the central-equatorial region were area averaged. From the central-equatorial area index those years that had SST anomalies greater than the monthly standard deviation for at least one of the months mentioned above were identified as years with equatorial warm events. The anomalies for these years were averaged to create the composite of the equatorial warm event. The same procedure was done to create the composite of the Benguela warm event from the Benguela area index but focusing on February, March and April (i.e. the warmer months in the Benguela area as in Figure 2). The composites were done for anomalies of SST, precipitation rate and 2-m pseudo wind stress.

3. Climatologies and Variability

3.1. April and July Climatologies

In the tropical Atlantic the SST and precipitation rate show significant changes from April to July. The SST for the month of April and July are shown in Figure 1 and the annual cycle for the central equatorial and Benguela regions is shown in Figure 2. During April there is a band of water warmer than 28°C crossing the deep tropics from west to east. The precipitation rate during April is concentrated over the western Atlantic and over the northern region of Brazil (Figure 3). Also, there is precipitation greater than 6 mm/day over the African region east of the Gulf of Guinea. During July the precipitation band has shifted to the northeast of the tropical ocean with greater precipitation over the African region north and northwest of the Gulf of Guinea. The SST during July is very different from that of April (Figure 1). The July SST shows a cold tongue in the central and eastern equatorial regions with water cooler than 24°C. This is in part a response to the regional upwelling by the equatorial and coastal Kelvin waves [*Adamec and O'Brien,* 1978].

3.2. Interannual Variability

The standard deviation of monthly SST anomalies shows a region of high variability on the southeastern tropical Atlantic close to the coast (Figure 4). The region of high standard deviation extends to the equatorial region encompassing the region of the summer cold tongue. These are areas of equatorial and coastal upwelling. Based on the figures of standard deviation the southeastern tropical Atlantic was studied separately from the central equatorial region. After analyzing the standard deviation for each month separately, the month that showed highest standard deviation in the Benguela region was April and the month that showed the highest standard deviation in the central equatorial region was June (Figure 5).

Figure 6 shows the time series of SST anomalies for the Benguela and central equatorial indices. The highest correlation, ρ=0.61, is obtained when the Benguela index leads the central equatorial index by 1 month (Figure 7). This however is not so different from the correlation when there is no lead or when the Benguela index leads by 2 months which is 0.59 and 0.60 respectively.

An autocorrelation analysis was done to determine the duration of both the anomalous warm and cold events in each region. Given that the central equatorial region showed highest variability during June and the Benguela region during April (Figure 5) the area indices were autocorrelated with June and April as the central month respectively. The whole time series was separated into 12 time series corresponding to each month of the calendar year. Hence, the time series of June had 23 templates each corresponding to a year of the period 1982-2003. For the central equatorial area index the time series for June was correlated with the same area index of the other 11 months (of the calendar year) for the period 1983-2003 (Figure 8). The year 1982 was used to do the correlation with the year before. That is, to get the autocorrelation with the December of the year before (i.e., December(Y-1)) the time series of December(Y-1) was from 1982 to 2002 while the June time series was from 1983 to 2003. This whole procedure was also done for the Benguela region index but autocorrelating the months with April since April was the month of highest variability in the Benguela region (Figure 5). Considering the correlations greater than 0.5

(Figure 8), the anomalous events in the equatorial region that peak in June have a duration of about 6 months from March to August. The anomalous events in the Benguela region that peak in April have duration of about 7 months from January to July.

4. Composites of Warm Events

4.1. SSTA Composites

For the equatorial index, the years 1988, 1995, 1998 and 1999 showed SSTA higher than the monthly standard deviation for at least 1 month (after 3-month running mean) out of February, March, April and May (Figure 9). For the Benguela index the warm years were 1984, 1995, 1996 and 2001 (Figure 9). The Benguela years coincide with the analyses by *Florenchie et al*. [2004]. Even though the SSTAs of 1996 are below the monthly standard deviation, the anomalies are greater than 0.5°C. Given that 1995 is in both lists it was not included in either composite to better appreciate the differences between composited warm events.

In space, the equatorial composite warm event shows positive SSTA in the equatorial region and also along the coast down to about 20°S. For the equatorial warm composite Figures 10 and 12a show the spatial pattern and the time series, respectively. The peak month of the equatorial warm event is June with anomalies greater than 0.8°C along the central and eastern equatorial regions and along the western coast of Africa to the southeastern tropical Atlantic. Positive SSTAs greater than 0.3°C along the deep tropics are observed before February through September. The peak in June is preceded by several months of positive SST anomalies.

The Benguela composite warm event manifests as a pattern of positive SSTA very close to coast, from the equator to about 20°S (Figure 11). The anomaly is distinguishable in February and continues to increase during the following months in both magnitude and extent reaching a peak in intensity in the month of April (Figures 11 and 12d).

Figure 12b (12c) shows the SSTAs for the central equatorial (Benguela) region for the years when the Benguela (central equatorial) region was warm. For the years when the Benguela region was warm the central equatorial region shows a very modest warming of less than 0.3°C for any given month. For the years when the equatorial region was warm the Benguela region shows a warming with a peak of about 0.5°C in June. Hence, during an equatorial warm event the Benguela region shows a correspondent warming while the equatorial region does not show a correspondent warming during a Benguela warm event.

The subtropical Atlantic regions and the tropical Pacific region show differences in SSTA between the two composites. During the life of the equatorial warm event the Atlantic subtropics are warm especially the northern subtropics (Figure 10). Also, the global SSTAs show that from October of the previous year to March there is a Pacific warm event in the eastern tropical region of the Pacific basin. This Pacific warm event evolves into a cool event (Figure 13). This is in contrast to the anomalies in the subtropics and tropical Pacific for the Benguela event. The subtropics for the Benguela Niño are normal to cold with the exception of the southern subtropics in February (Figure 11). From the October preceding the Benguela Niño the tropical Pacific shows a cool event that persists throughout the life of the Benguela Niño (Figure 14).

4.2. Pseudo Wind Stress Anomalies Composite

The wind stress composites show some basic similarities (Figures 15 and 16). For both composites there is a weakening of the equatorial easterlies in the western region since February. Later in June both composites show anomalies toward the central-eastern equatorial region, i.e., the warm center. One difference is that during February, while the Benguela composite shows weakening of the southeasterlies, the equatorial composite shows weakening of the northeasterlies.

4.3. Precipitation Anomalies Composite

The composites of precipitation anomalies corresponding to the years of equatorial and Benguela events show differences (Figures 17 and 18) in spatial pattern and temporal intensity. The season with the peak anomalies in precipitation rate are different between composites. Over the tropical ocean, the Benguela composite shows stronger or more intense precipitation rate anomalies during spring while the equatorial composite shows them during summer.

There are also differences in the zonal extension of the precipitation band along the tropics. One of the months in which these differences are most evident is in March. During March the Benguela precipitation composite shows positive precipitation anomalies not only over the ocean, but also over the coastal countries of western Africa and the northeast region of Brazil. These regions have high precipitation rate normally (Figure 3) and positive anomalies are added becoming an extreme event in those regions. On the other hand, the correspondent month for the equatorial composite shows negative anomalies over the same regions of western

Africa and the northeast region of Brazil. These negative anomalies of the equatorial composite constitute a zonal shift of the precipitation band away from the continents with the positive precipitation anomalies concentrated merely over the ocean. Hence, while the western African countries such as Angola, Congo, Gabon and Cameroon might be more likely to experience positive anomalies in precipitation during March for Benguela Niños the same countries might be more likely to experience negative anomalies during March of equatorial Atlantic Niños.

In addition to the anomalies extending away from or into the continents there is a meridional shift of the precipitation band mainly for the equatorial composite. The equatorial composite shows a meridional shift of precipitation to the south during spring while the Benguela composite shows a slight shift during summer.

5. Discussion and Conclusions

Tropical Atlantic warm events for the period from 1982 through 2003 have been characterized by studying the SST anomalies for specific regions of the tropical Atlantic that show high variability on interannual timescales. The tropical Atlantic Ocean shows warm events centered on the Benguela region and on the central-eastern equatorial region with different life cycles. Their respective peak month is only two months apart, one being the Benguela Niño, with a peak in April, and the Equatorial Atlantic Niño with a peak in June. To clarify the ambiguity in the use of the term Atlantic Niño, the terms Equatorial Atlantic Niño or Deep Tropical Atlantic Niño are suggested to distinguish from the Benguela Atlantic Niño.

In previous studies the Atlantic Niño has been identified during the months of June, July and August. However, the autocorrelation analysis presented in this study suggests that the central-equatorial Atlantic SST anomalies that peak in June have an incipient stage during March since the autocorrelation monotonically increases from $\rho > 0.5$ in March to $\rho = 1.0$ in June. In fact, even though the criterion for the equatorial warm event was defined as SSTAs > standard deviation from February through May, the peak month of the composite event ended up being June. This indicates that the peak anomalies in June of an Equatorial Atlantic Niño can be traced back to March of the same year. Also, even though the area index analyzed was the central-equatorial region the Equatorial Atlantic Niño composite show warming along the central and eastern equatorial regions justifying the term Equatorial Atlantic Niño or Deep Tropical Atlantic Niño.

Along with the differences in spatial extent and timing of the SSTA between the equatorial and Benguela regions there are also differences in spatial pattern and timing of the precipitation rate anomalies and wind stress anomalies associated with the different composites. This is important when studying the implications or consequences of Atlantic warm events. The composite of precipitation rate anomalies corresponding to the Equatorial Atlantic Niño shows a zonal shift away from the continents from March through May (only April shown here) while the Benguela Niño precipitation composite shows positive anomalies over the continents. Hence, Equatorial Atlantic Niños and Benguela Niños have different consequences in precipitation rate over inhabited regions of western equatorial Africa and northeastern Brazil both regions being wetter during Benguela Niños and drier during Equatorial Atlantic Niños.

The weakening of the equatorial easterlies for both composites is consistent with previous studies. However, when comparing the subtropical regions it is observed that the Benguela Niño is associated with a weakening of the southeasterlies while the Equatorial Atlantic Niño is associated with a weakening of the northeasterlies. The weakening of the northeasterlies for the Equatorial Atlantic Niño is concurrent with a warming of the northern subtropics providing an indication of a thermodynamic (wind-evaporation-SST) feedback between SST and winds. In fact, the wind-evaporation-SST feedback has been observed to explain the Atlantic interhemispheric mode of variability. The differences of the subtropical SSTs and wind anomalies between the composites put into question the relation between the interhemispheric mode and equatorial mode of variability during an Equatorial Atlantic Niño and a

Benguela Niño. Previous studies by *Servain et al*., [1998, 1999] and *Murtugudde et al*., [2001] have studied the relation between the two modes of variability. However, the relation between the two modes of tropical Atlantic variability within the context of Benguela Niños or Equatorial Atlantic Niños needs further work.

The subtropical SSTAs for the two different composites (Benguela and central-equatorial) behave differently, i.e., they are consistently warm for the Equatorial Atlantic Niño composite and consistently normal for the Benguela Niño composite. For the Equatorial Atlantic Niño the northern subtropical warming is associated with the weakening of the northeasterlies. In fact, the northern subtropical Atlantic region has been observed to warm several months after a Pacific ENSO [*Czaja et al.,* 2002; *Wang,* 2002]. From the results it is observed that the tropical Pacific shows a warm event several months prior to the Equatorial Atlantic Niño composite. However, several months prior to a Benguela Niño the tropical Pacific shows a cool event that is sustained throughout the life of the Benguela Niño and the northern subtropical Atlantic is normal throughout the life of the Benguela Niño. This might be an indication that the different manifestation between the Equatorial Atlantic Niño and the Benguela Niño relies to some extent on the SST anomalies in the eastern tropical Pacific and their impact on the tropical-subtropical Atlantic through teleconnections. Further work is needed to study the remote influences of the Pacific on Atlantic warm events.

The surface SSTAs of the subtropical regions could also have correspondent subsurface temperature anomalies or heat content anomalies bringing up the necessity to do oceanic model simulations. *Huang et al*., [1995] and *Ruiz-Barradas et al*.,

[2001] observed that associated with tropical Atlantic warm events there was a shift of heat content anomalies from the subtropical regions to the equatorial region. This motivates the creation of composites of the subsurface variability (of heat content and thermocline displacement) after numerical simulations with an ocean model as future work.

In the past, the term Atlantic Niño has been used to refer broadly to warm events in the tropical Atlantic Ocean; its use has conflicted at times with the term Benguela Niño. This nomenclature issue has turned the term Atlantic Niño into an ambiguous one. In this paper we have shown that the equatorial Atlantic and southeastern tropical Atlantic warm events have distinctive anomalies of SST, 2-meter winds and precipitation. We have also shown that these two classes of warm events are associated with distinctive anomalies of SST and 2-m winds in the subtropical Atlantic and with distinctive anomalies of SST in the eastern tropical Pacific. Further work is needed to explain the cause or mechanism, the relation between the tropical and subtropical regions, and any remote influence from the tropical Pacific of the tropical Atlantic warm events.

Bibliography

Adamec, D., and J. J. O'Brien (1978), The seasonal upwelling in the Gulf of Guinea due to remote forcing, *J. Phys. Oceanogr.*, *8*, 1050-1060.

Adler, R. F., G. J. Huffman, A. C. Chang, R. Ferraro, P. P. Xie, J. Janowiak, B. Rudolf, U. Schneider, S. Curtis, D. Bolvin, A. Gruber, J. Susskind, P. Arkin and E. Nelkin (2003), The Version-2 Global Precipitation Climatology Project (GPCP) monthly precipitation analysis (1979-present), *J. Hydrometeor.*, *4*, 1147-1167.

Carton, J. A., and B. Huang (1994), Warm events in the Tropical Atlantic, *J. Phys. Oceanogr.*, *24*, 888-903.

Carton, J. A., X. Cao, B. S. Giese, and A. M. da Silva (1996), Decadal and interannual SST variability in the tropical Atlantic Ocean, *J. Phys. Oceanogr.*, *26*, 1165-1175.

Chang, P., L. Ji and H. Li (1997), A decadal climate variation in the tropical Atlantic Ocean from thermodynamic air-sea interactions, *Nature*, *385*, 516-518.

Chang, P., L. Ji and R. Saravanan (2001), A hybrid coupled model study of tropical Atlantic variability. *J. Climate*, *14*, 361-390.

Czaja, A., P. van der Vaart, and J. Marshall (2002), A diagnostic study of the role of remote forcing in tropical Atlantic variability, *J. Climate*, *15*, 3280-3290.

Enfield, D.B. and D.A. Mayer (1997), Tropical Atlantic SST variability and its relation to El Nino-Southern Oscillation, *J. Geophys. Res., 102*, 929-945.

Florenchie, P., J. R. E. Lutjeharms, and C. J. C. Reason (2003), The source of Benguela Niños in the south Atlantic Ocean, *Geophys. Res. Lett.*, *30*(10), 1505, doi:10.1029/2003GL017172.

Florenchie, P., C.J.C. Reason, J.R.E. Lutjeharms, M. Rouault and C. Roy (2004), Evolution of interannual warm and cold events in the southeast Atlantic Ocean, *J. Climate*, *17*, 2318-2334.

Giannini, A., R. Saravanan, and P. Chang (2003), Oceanic forcing of Sahel rainfall on interannual to interdecadal time scales, *Science express*, Oct, 10.1126.

Huang, B., J. A. Carton, and J. Shukla (1995), A numerical simulation of the variability in the tropical Atlantic Ocean, 1980-88, *J. Phys. Oceanogr.*, *25*, 835-854.

Hirst, C., and S. Hastenrath (1983), Atmosphere-ocean mechanisms of climate anomalies in the Angola-tropical Atlantic sector, *J. Phys. Oceanogr.*, *13*, 1146-1157.

Hisard, P. (1980), Observation de reponses de type « El Niño » dans l'Atlantique tropical oriental, Golfe de Guineé, *Oceanol. Act*, 3, 1, 69-78.

Kalnay, E., and coauthors (1996), The NCEP/NCAR 40-year reanalysis project, *Bull. Amer. Meteor. Soc.*, *77*(3).

Katz, E. J. (1987), Equatorial Kelvin waves in the Atlantic, *J. Geophys. Res.*, *92*(2), 1894-1898.

Meeuwis, J. M., and J. R. E. Lutjeharms (1990), Surface thermal characteristic of the Angola-Benguela front, *S. Afr. J. Mar. Sci.*, *9*, 261-279.

Merle, J. (1980), Variabilité thermique annuelle et interannuelle de l'océan Atlantique équatorial Est. L'hypothèse d'un « El Niño » Atlantique, *Oceanol. Acta,* 3, 2, 209-220.

Murtugudde, R. G., J. Ballabrera-Poy, J. Beauchamp, A. J. Busalacchi (2001), Relationship between zonal and meridional modes in the tropical Atlantic, *Geophys. Res. Lett*., *28*(23), 4463-4466.

Nobre P. and J. Shukla (1996), Variations of sea surface temperature, wind stress, and rainfall over the tropical Atlantic and South America, *J. Climate*, *9*, 2464-2479.

Philander, S. G. H. (1986), Unusual conditions in the tropical Atlantic Ocean in 1984, *Nature*, *322*(6076), 236-238.

Picaut, J., J. Servain, A. J. Busalacchi, and M. Seva (1984), Interannual variability versus seasonal variability in the Tropical Atlantic, *Geophys. Res. Lett*., *11*(8).

Reynolds, R.W., N. A. Rayner, T. M. Smith, D. C. Stokes and W. Wang (2002), An improved in situ and satellite SST analysis for climate, *J. Climate*, *15*, 1609-1625.

Rouault, M., P. Florenchie, N. Fauchereau, and C. J. C. Reason (2003), South east tropical Atlantic warm events and southern African rainfall, *Geophys. Res. Lett*., *30*(5), 8009, doi:10.1029/2002GL014840.

Ruiz-Barradas, A., J. A. Carton, and S. Nigam (2000), Structure of interannual-to-decadal climate variability in the tropical Atlantic sector, *J. Climate*, *13*(18).

Saravanan, R., and P. Chang (2000), Interaction between tropical Atlantic variability and El Nino-Southern Oscillation, *J. Climate*, *13*, 2177-2194.

Servain, J. (1991), Simple climatic indices for the tropical Atlantic Ocean and some applications, *J. Geophys. Res*., *96*(C8), 15137-15146.

Servain, J., J. Picaut and J. Merle (1982), Evidence of remote forcing in the Equatorial Atlantic Ocean, *J. Phys. Oceanogr*., *12*, 457-463.

Servain, J., M. Seva, and P. Rual (1990), Climatology comparison and long-term variations of sea surface temperature over the tropical Atlantic Ocean, *J. Geophys. Res*., *95*(C6), 9421-9431.

Servain, J., A. J. Busalacchi, M. J. McPhaden, A. D. Moura, G. Reverdin, M. Vianna, and S. E. Zebiak (1998), A Pilot Research Moored Array in the Tropical Atlantic (PIRATA), *Bull. Amer. Meteor. Soc*., *79*(10), 2019-2031.

Servain, J., I. Wainer, J. P. McCreary Jr., and A. Dessier (1999), Relationship between the equatorial and meridional modes of climatic variability in the tropical Atlantic, *Geophys. Res. Lett*, *26*(4), 485-488.

Servain, J., G. Clauzet, and I. Wainer, Modes of tropical Atlantic climate variability observed by PIRATA (2003), *Geophys. Res. Lett*., *30*(5), 8003, doi:10.1029/2002GL015124.

Shannon, L. V., A. J. Boyd, G. B. Brundrit, and J. Taunton-Clark (1986), On the existence of an El Niño-type phenomenon in the Benguela system, *J. Mar. Res*., *44*, 495-520.

Tanimoto, Y. and S.-P. Xie (2002), Inter-hemispheric decadal variations in SST, surface wind, heat flux and cloud cover over the Atlantic Ocean, *J. Meteor. Soc. Japan*, *80*, 1199-1219.

Wang, C. (2002), Atlantic climate variability and its associated atmospheric circulation cells, *J. Climate*, *15*, 1516-1536.

Zebiak, S.E. (1993), Air-Sea interaction in the equatorial Atlantic region, *J. Climate.*, *6*, 1567-1586.

Figures

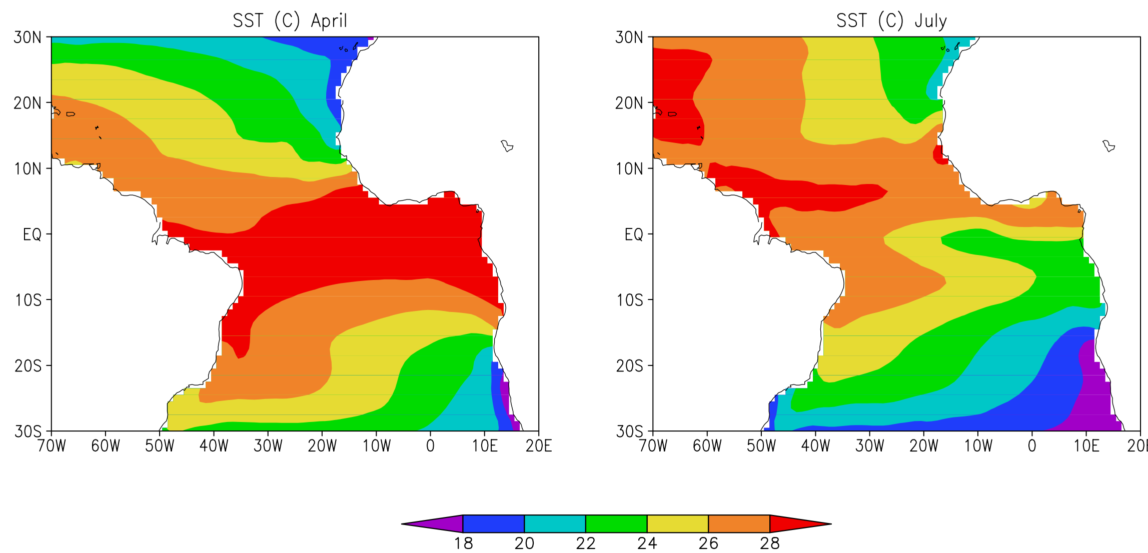

Figure 1. SST (in units of °C) of April (left) and of July (right).

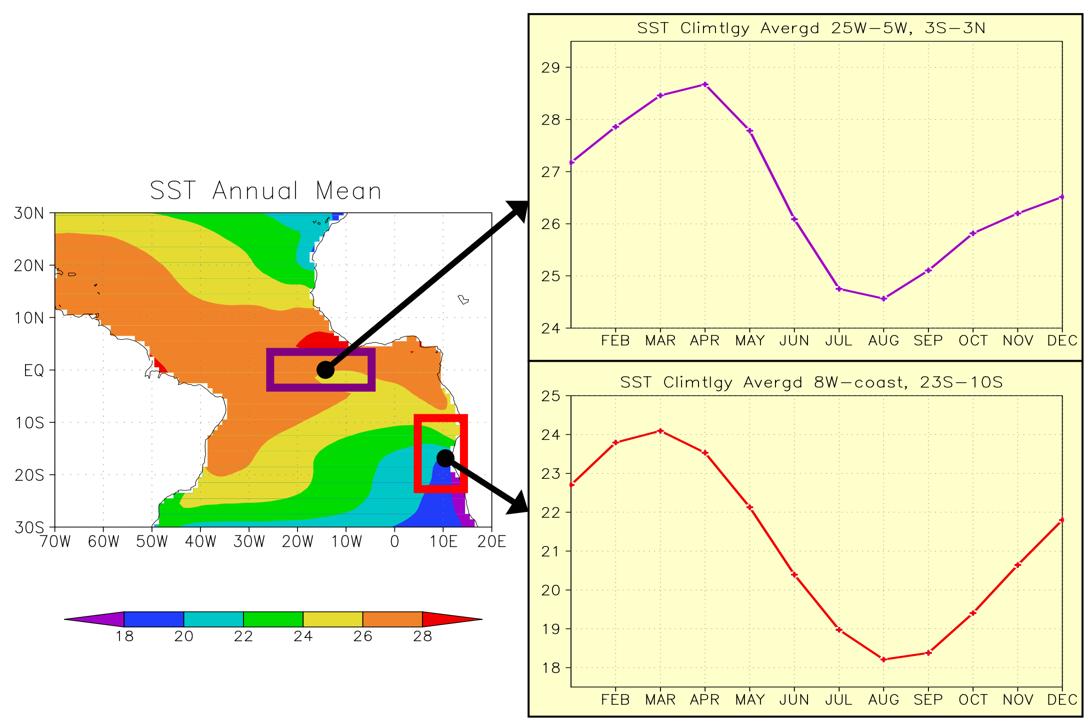

Figure 2. Annual mean SST (left) with delimitation of the equatorial area (purple) and the Benguela area (red) studied. Annual cycle of SST (right) for the equatorial area index (top) and the Benguela area index (bottom).

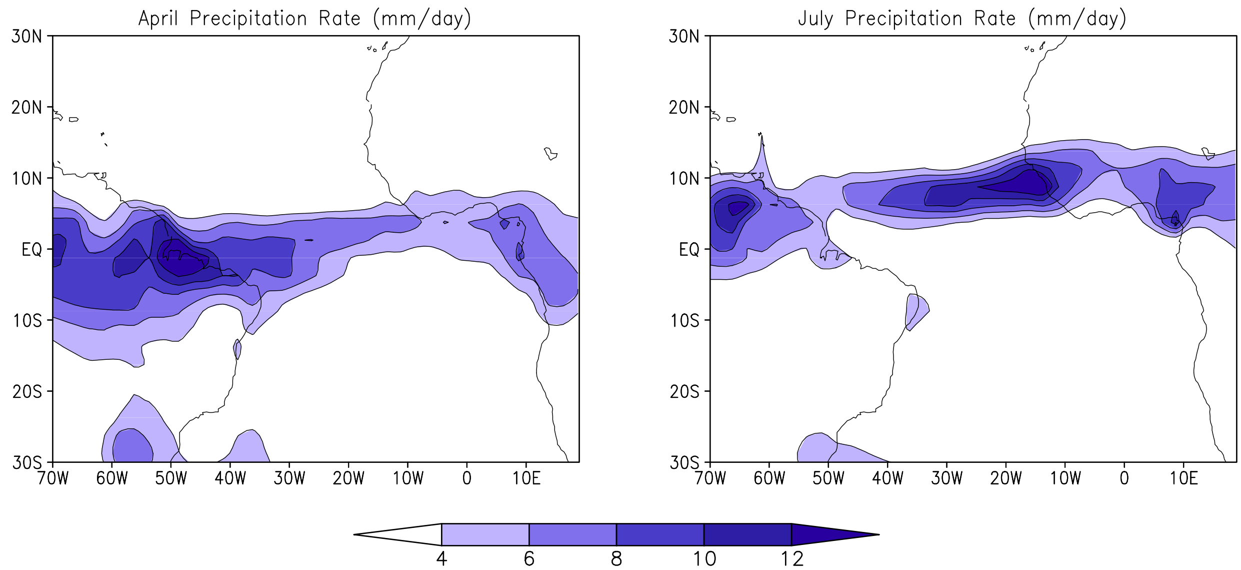

Figure 3. Precipitation rate (in units of mm/day) of April (left) and July (right).

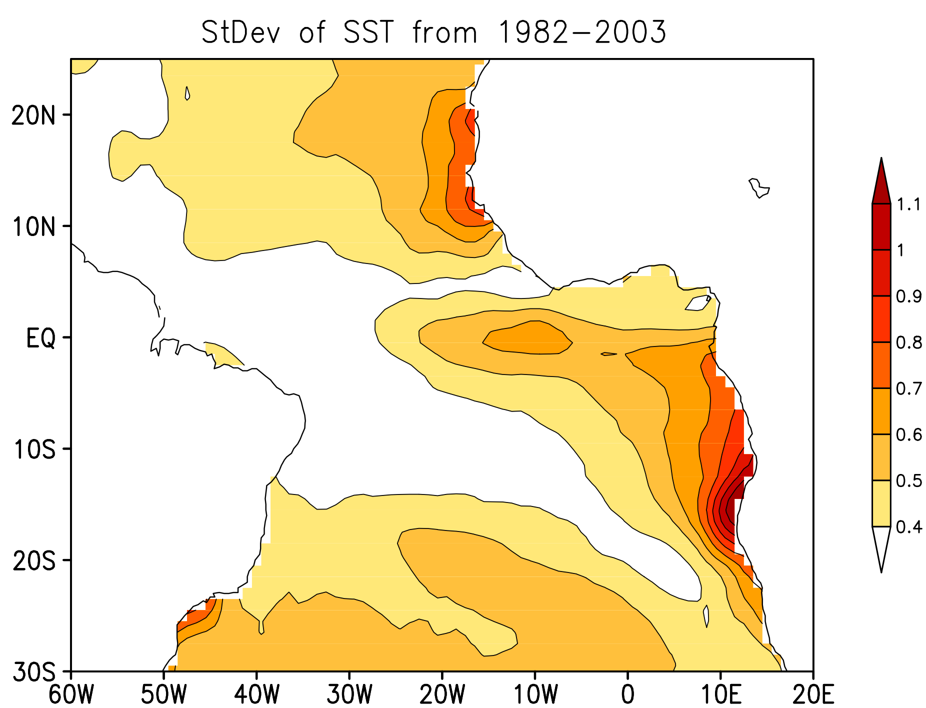

Figure 4. Standard deviation of the SST anomalies from 1982 to 2003.

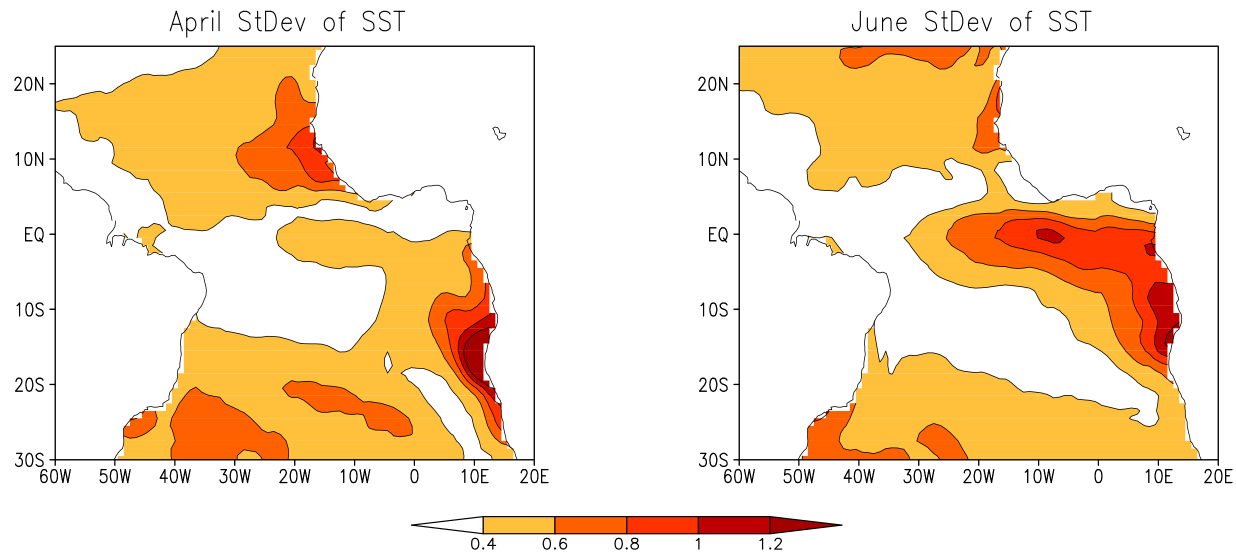

Figure 5. Standard deviation of the SST anomalies of the months of April (left) and of June (right).

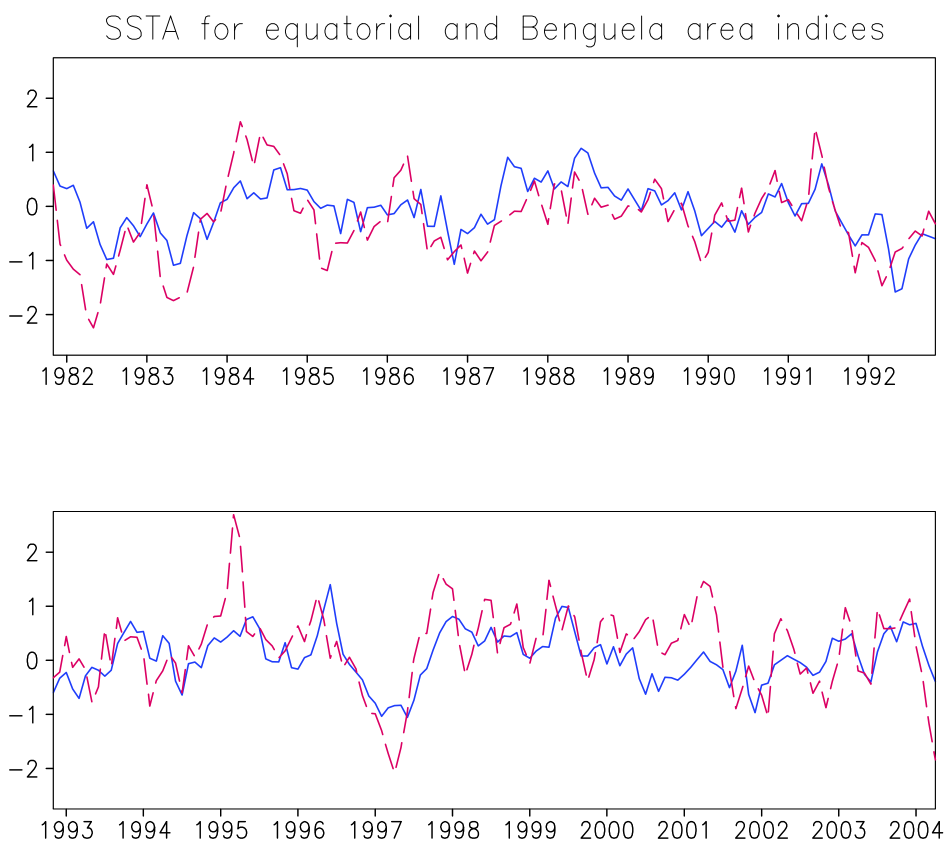

Figure 6. Time series of monthly anomalies of the equatorial area index (blue) and of the Benguela area index (magenta).

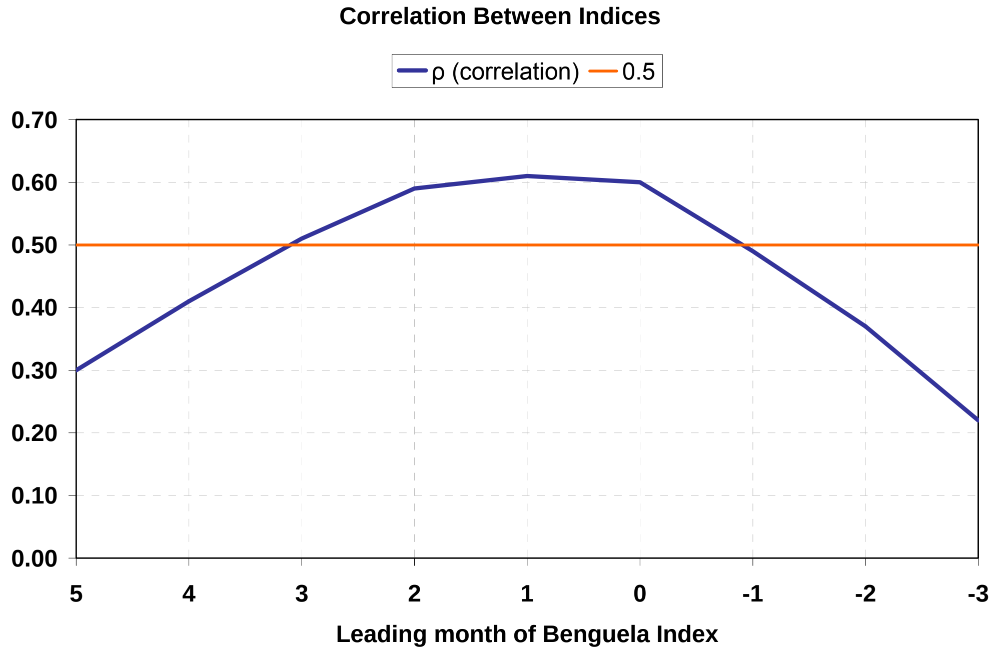

Figure 7. Correlation (blue line) between the equatorial area index and the Benguela area index with leads and lags by the Benguela index.

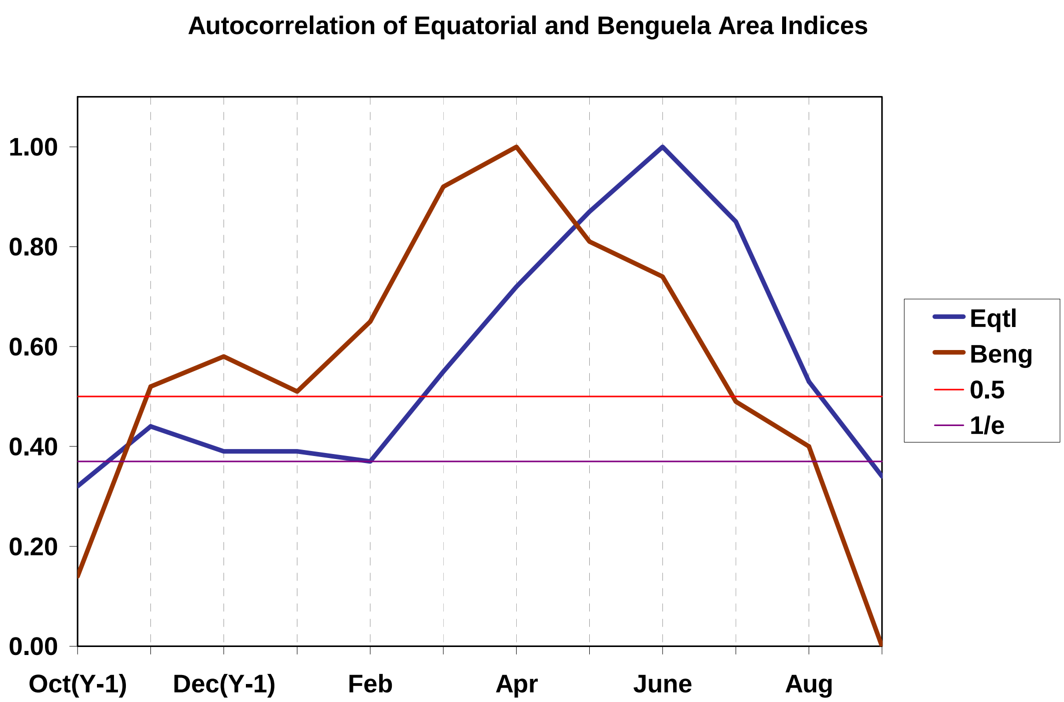

Figure 8. Autocorrelation of Benguela index (brown) and of equatorial index (blue).

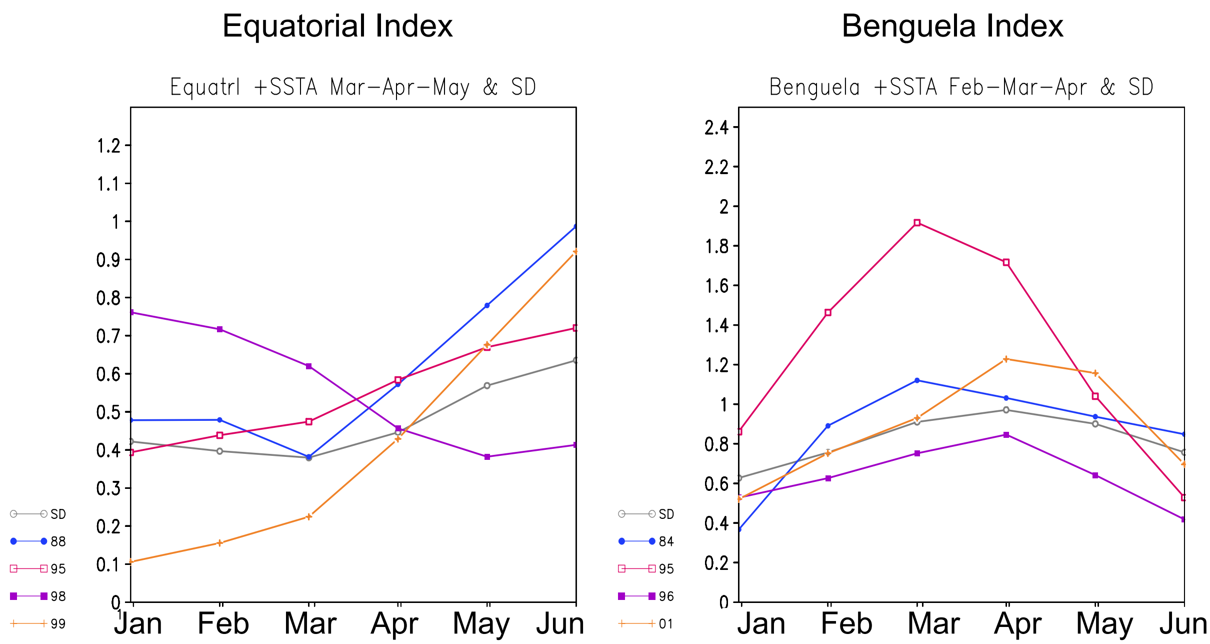

Figure 9. Sea surface temperature anomalies compared to the monthly standard deviation (gray line) for the equatorial region (left) and the Benguela region (right).

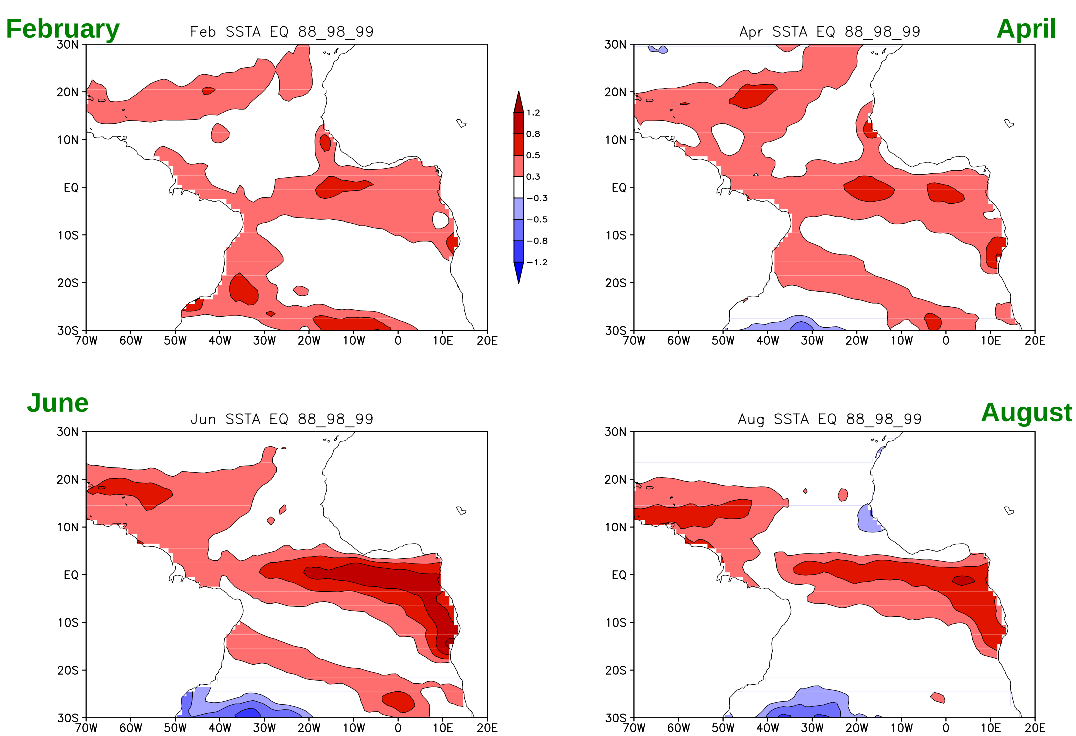

Figure 10. February, April, June and August composites of SSTA for the equatorial warm event.

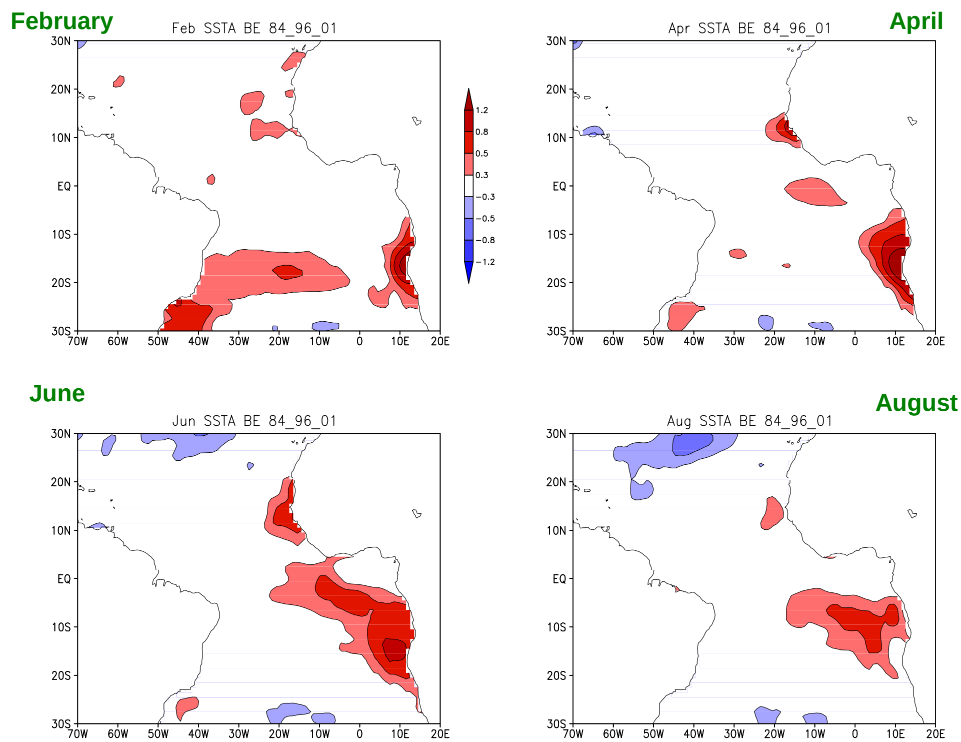

Figure 11. February, April, June and August composites of SSTA for the Benguela warm event.

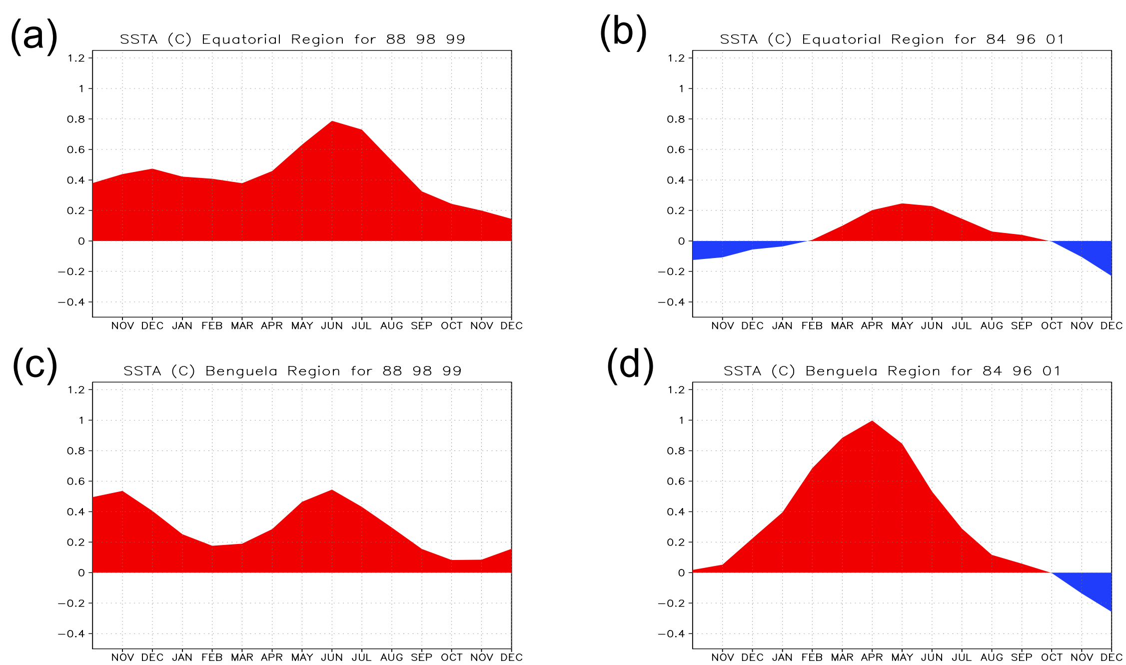

Figure 12. Time series of the composites for the equatorial area (upper half) and for the Benguela area (lower half) for the years of warming in the equatorial region (left) and in the Benguela region (right).

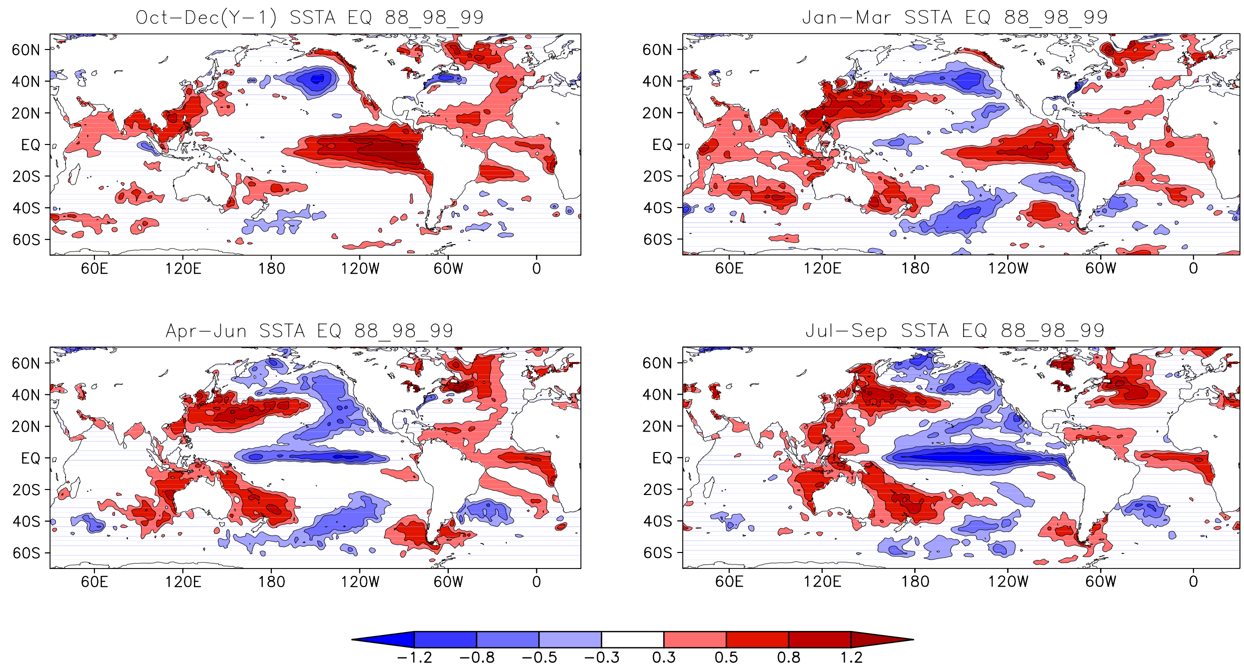

Figure 13. Global view of SSTA for the equatorial warm event.

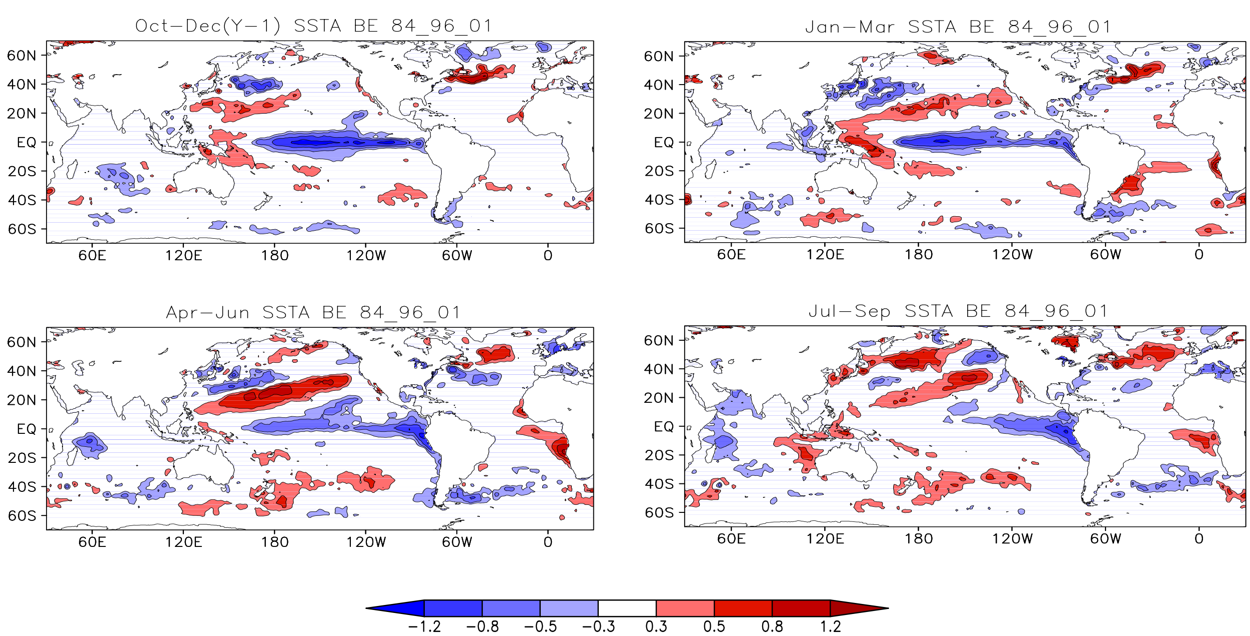

Figure 14. Global view of SSTA for the Benguela warm event.

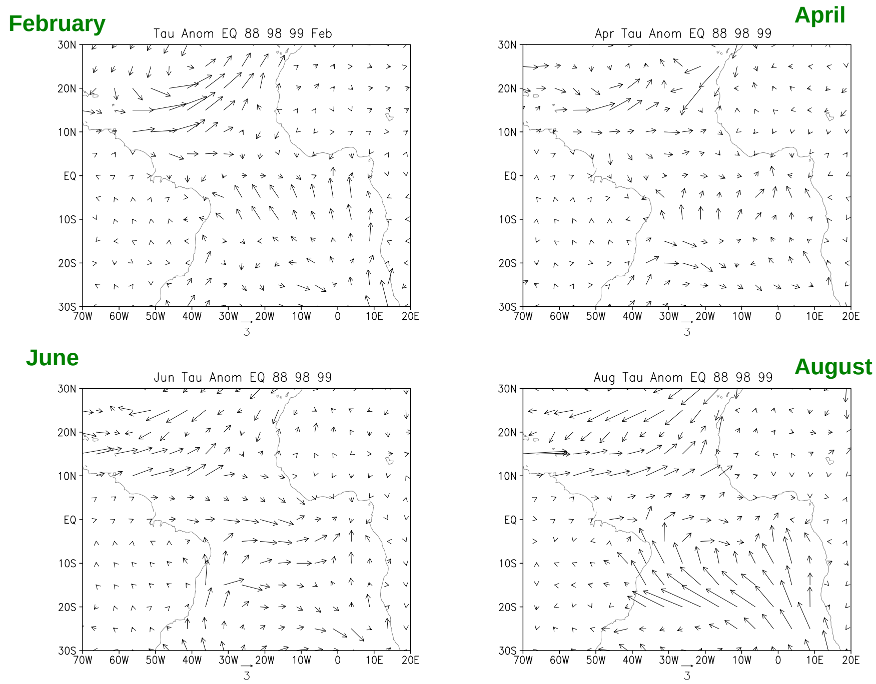

Figure 15. Pseudo wind stress composite of the equatorial warm event for February, April, June and August.

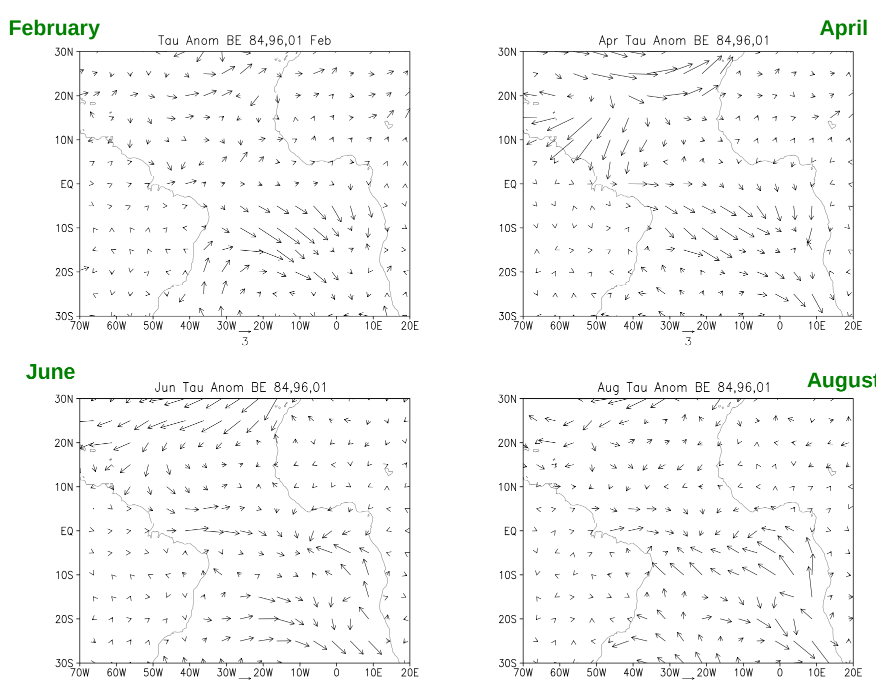

Figure 16. Pseudo wind stress composite of the Benguela warm event for February, April, June and August.

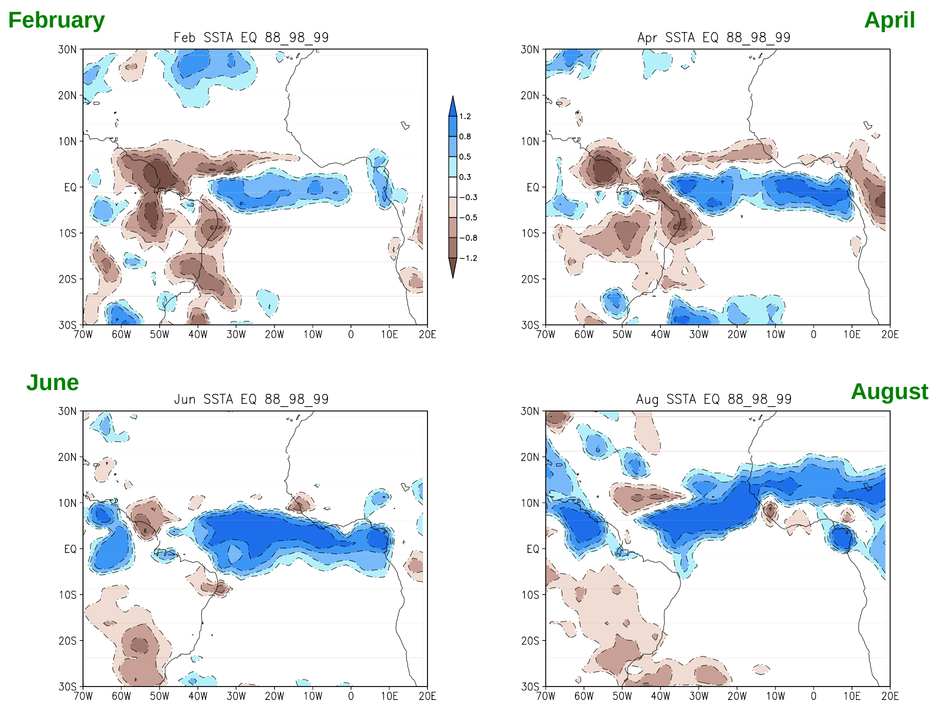

Figure 17. Precipitation rate composite of the equatorial warm event for February, April, June and August.

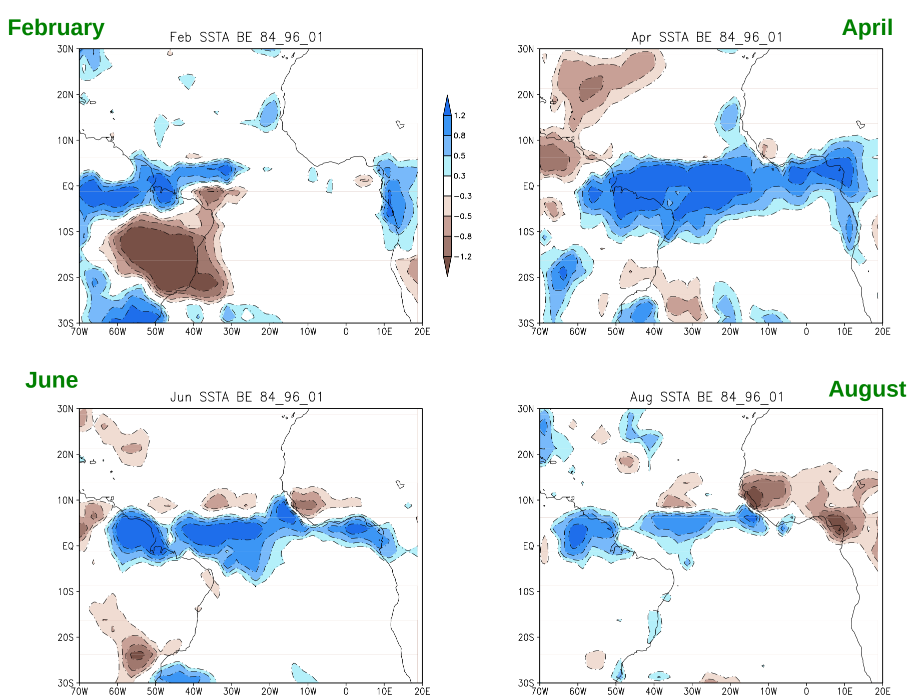

Figure 18. Precipitation rate composite of the Benguela warm event for February, April, June and August.