Atlantic warm and cold water events and impact on African west coast precipitation

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ABSTRACT: Variability of sea surface temperatures (SSTs) in the tropical southeast Atlantic Ocean has previously been shown to significantly contribute to changes in summer rainfall along the West African as well as the Angolan coast. This study examines links between southeast Atlantic SST and African west coast precipitation variability for an extended 60-year period from 1951 to 2010. In contrast to earlier studies, our analyses cover the whole Atlantic coast from Guinea to South Africa and are not limited to specific seasons. In addition to the analyses of the total variability, pronounced anomalies in terms of warm and cold water events and their impact on African west coast precipitation are analyzed. By using for the first time a new comprehensive classification of Atlantic Niño and Niña events, consistent results are achieved for a larger region of Africa, also considering Atlantic cold water events which have rather been neglected so far.

Results show that, depending on the particular region, southeast Atlantic SSTs play an important role for coastal rainfall variability throughout the year. Furthermore, the rainfall response to Atlantic cold and warm water events appears to be asymmetric in season and magnitude. Atlantic cold events can cause a stronger decrease in rainfall along the West African and Gabon coast than the increase is in warm events. In addition, not all seasons show a significant rainfall response to both warm and cold water events.

KEY WORDS tropical Atlantic; Atlantic Niño; warm water event; African precipitation

1. Introduction

In Africa, especially in semiarid to subhumid climates, rainfall is one of the most critical factors for ecological and environmental processes. Especially, areas where agricultural production primarily depends on rainfall are extremely sensitive to changes in rainfall patterns. A decrease in rainfall or a delayed rainy season can severely affect cultivation or even cause crop failure.

One important driver of African rainfall variability are tropical southeast Atlantic sea surface temperatures (SSTs). They exhibit variability on various time scales. A detailed review on tropical Atlantic SST variability is given by Xie and Carton (2004). On the interannual scale, about every 3–5 years the southeast tropical Atlantic experiences anomalously high SSTs. Based on the Pacific term El Niño, these warm water events are termed Niño events, but in contrast to the Pacific two such phenomena have been described. One of them, the Atlantic Niño, is centred in the equatorial region as part of the Atlantic zonal mode (Philander, 1986; Zebiak, 1993). Another one close to the coast of northern Namibia and Angola is referred to as Benguela Niño (Shannon *et al.*, 1986). Additionally, Okumura and Xie (2006) specify November/December SST anomalies in the tropical Atlantic in terms of an Atlantic Niño II to distinguish it from the actual Atlantic Niño which peaks in boreal summer. Furthermore, Nnamchi *et al.* (2011) describe the Atlantic Niño as part of a South Atlantic Ocean Dipole (SAOD). Atlantic and Benguela Niños have long been analyzed in separate studies and regarded as independent events. But a few recent studies describe a strong relation between SST variability off the Angolan coast and the equatorial Atlantic (e.g. Huang *et al.*, 2004; Reason *et al.*, 2006). It is further suggested that both Niños should be perceived as one phenomenon as they are highly correlated (e.g. Lübbecke *et al.*, 2010) and warming can be observed in the whole tropical Atlantic region (Lutz *et al.*, 2013). Although warm water events in the eastern tropical Atlantic are less frequent and less intense compared to the Pacific ones, they have striking effects on regional rainfall.

A general overview of SST influence, including South Atlantic SSTs, on sub-Saharan rainfall and associated atmospheric dynamics is given by Camberlin *et al.* (2001).

Most regional studies examining SST-rainfall links focus on the northern hemisphere. Here, Kouadio (2003) show a statistical connection between tropical Atlantic SSTs and Ivory Coast rainfall during the summer monsoon season. Reason and Rouault (2006) provide evidence of a connection between SST variability in the tropical southeast Atlantic and boreal summer rainfall (JJAS) over coastal West Africa. SSTs off the coast of Angola/northern

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Namibia serve as a moisture source. Polo *et al.* (2008) use extended maximum covariance analysis to resolve time-evolving patterns of Atlantic SSTs in relation to anomalous boreal summer rainfall in West Africa. Hermes and Reason (2009) analyze the relationship between SE Atlantic winds and SSTs and coastal West African as well as Angolan/Namibian precipitation on an intra-seasonal scale. The equatorial region of the African west coast has received the least attention so far. Balas *et al.* (2007) show that, among other influences on rainfall variability in western equatorial Africa, the SST anomalies along the Benguela Coast play an important role in boreal spring (MAM).

In the southern hemispheric regions of the African west coast, Hirst and Hastenrath (1983) first found a positive correlation between southeast Atlantic SSTs and rainfall along the coast of Angola. Shannon *et al.* (1986) and Nicholson and Entekhabi (1987) show that during warm water events in the tropical southeast Atlantic abnormal high rainfall also occurs along the Namibian coast as well as further inland. Rouault *et al.* (2003) suggest that the extent inland may depend on the regional moisture convergence and atmospheric circulation anomalies. Angolan/Namibian rainfall anomalies are greatest for those events with a circulation being favourable for a strengthened westward moisture flux from the Indian Ocean and a weakened southeasterly flux away from the SE Atlantic coast. Furthermore, Muller *et al.* (2008) describe the case of an unusual wet austral summer in 2005–2006 in Namibia associated with the co-occurrence of anomalously warm southeast Atlantic SSTs and a Pacific La Niña. At the southern tip of the continent, Vigaud *et al.* (2009) connect South African precipitation anomalies to a dipole-like pattern with SST anomalies centred further south, whereas Reason and Rouault (2006) also mention a potential link between SE tropical Atlantic SSTs and southwest African rainfall.

1.1. Aims of the study

In contrast to earlier studies, which mainly focused on specific regions and selected seasons or short periods, we aim at a comprehensive study including the entire Atlantic west coast precipitation for all seasons. Furthermore, previous studies used different definitions of warm and cold events. Therefore some of the results are not comparable. Here, for the first time, one common definition of warm and cold water events is used to study the impact of anomalous SSTs on African west coast precipitation. Thus, the main objectives of this paper are:

1. To study coupled variability of tropical eastern Atlantic SSTs and precipitation of all African regions along the South Atlantic coast on the basis of different seasonal sections (1–3 months) throughout the year (Section 4.2).
2. To analyze warm and cold water events (Section 3) in the tropical southeast Atlantic Ocean and their impact on African west coast rainfall for the extended 60-year period 1951–2010 (Section 4.3).

2. Data and methods

SST data are taken from the 1° × 1° Hadley Centre Sea Ice and Sea Surface Temperature dataset version 1.1 (HadISST 1.1) which is an EOF-based reconstruction of observations (Rayner *et al.*, 2003). Data are available for the period from 1870 to the present.

Impact of SST anomalies on rainfall variability is assessed using the University of Delaware terrestrial precipitation (PRC) dataset (UDel version 3.02, Matsuura and Willmott, 2012) which is available for the period 1900–2010. The dataset is interpolated using a spherical version of the Shepard's algorithm (Willmott *et al.*, 1985) as well as climatologically aided interpolation (CAI, Willmott and Robeson, 1995; Matsuura and Willmott, 2012). In contrast to other precipitation datasets, the latter benefits from the inclusion of Nicholson's (2001) extensive African gauge data collection.

Wind stress and specific humidity data are taken from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) re-analysis (Kalnay *et al.*, 1996) which is available for the period 1948–2012. U- and V-components (horizontal velocities $\vec{v}_h = (u, v)$) of wind stress and specific humidity q are used to calculate the convergence (or negative divergence) of moisture flux $-\nabla \cdot \vec{Q}$ integrated from bottom (p_{sfc}) to the 300 hPa level (p_{top}) using the following formula (e.g. Pamén and Holopainen, 1962):

$$-\nabla \cdot \vec{Q} = -\frac{1}{g}\nabla \cdot \int_{p=p_{\text{sfc}}}^{p=p_{\text{top}}} \vec{v}_h \,\mathrm{qdp}$$

where ∇ denotes the horizontal divergence operator and g is the gravity constant.

Additionally, moisture flux convergence for six levels between 1000 and 300 hPa is computed for the detailed analysis of single levels.

To account for the fast variations of African precipitation in transitional seasons all analyses are carried out on a monthly base. Additional analyses based on 2- and 3-month means also capture seasonal signals. Thus, for all variables monthly time series as well as overlapping 2-month (e.g. JF, FM) and 3-month (e.g. JFM, FMA) seasonal means are extracted. Interannual anomalies are calculated by subtracting the mean seasonal cycle with respect to the period considered. All data are high-pass filtered using an 11-year Gaussian filter to remove trends. Furthermore, our focus lies on interannual and not on overlaying low frequency variability which is also removed by high-pass filtering.

As a first step, orthogonally (Varimax) rotated s-mode principal component analysis (PCA, e.g. Preisendorfer, 1988; von Storch and Zwiers, 1999) was applied to the standardized (all-year) precipitation anomalies in order to determine regions with similar rainfall variability. Such a 'precipitation region' is defined by all grid points having their maximum PC loading (in s-mode PCA loading patterns are spatial patterns based on weighted eigenvector components) on the same PC. Instead of using the PC scores (associated time coefficients) a weighted regional mean rainfall index is calculated from all grid boxes assigned to the same precipitation region. Each grid box is weighted by its corresponding maximum loading. s-mode PCA was also applied to all monthly and seasonal data of SST and precipitation to reduce dimensions and remove linear dependencies for subsequent analyses.

Coupled variability of tropical Atlantic SSTs and African precipitation is assessed by standard linear correlation analysis (CA) as well as canonical correlation analysis (CCA). The significance of the correlation coefficients r is estimated using the standard two-sided Student's t test. In contrast to the bivariate correlation simply linking two time series, CCA selects pairs of patterns of two space-dependent variables such as SST and precipitation whose corresponding time series are optimally correlated (for a detailed description see von Storch and Zwiers, 1999 and Wilks, 2005). It therefore provides a tool for linking large-scale atmospheric or oceanic patterns to regional precipitation patterns. Here, CCA was applied to SST- and precipitation-PCs. PCA removes the background noise in the original patterns and resolves uncorrelated PC time coefficients. Their use in CCA therefore ensures correct assessments of the canonical r. For a fully resolved CCA pattern (CCP), the canonical loadings are back-transformed using the PC loadings.

Additionally, composite analysis is used to analyze the impact of warm and cold water anomalies on African precipitation. An U-test was applied to estimate significant differences of composites. The warm or cold sample is tested against the remaining data.

The classification of warm and cold water events (Section 3) was based on the study period 1870–2011 (Lutz *et al.*, 2013). Therefore, additional information on the events is based on this long-term period. In the remaining part of this paper, for data quality reasons, the study period for our analyses is constrained to 1951–2010.

3. Classification of Atlantic Niño and Niña events

In this section, we briefly explain the procedure that was used to identify and classify warm and cold water events in the tropical eastern Atlantic. For further details refer to Lutz *et al.* (2013).

On the basis of standard deviation of SST anomalies three regions of similarly high SST variability, covering the whole cold tongue area in the tropical Atlantic, are defined: ATLN1 (17°S–7°S and 8°E–15°E) off the Angolan coast, ATLN3 (3°S–3°N and 15°W–0°W) in the equatorial Atlantic and a transitional region ATLN2 (10°S–3°S and 0°W–8°E).

For each of these regions, standardized detrended SST indices are calculated to achieve three comparable Atlantic Niño indices. As shown in Lutz *et al.* (2013), all three time series are significantly correlated (0.74–0.91, 99% level) confirming the link between Atlantic and Benguela Niños. A warm (cold) water event is then defined as a period with one of the ATLN indices exceeding one positive (negative) standard deviation for at least three consecutive months. As in most cases events are not only found in one index, but the other indices at least show anomalies of the same sign, warm and cold water events are classified into three Atlantic Niño and Niña subtypes:

- Major event: all ATLN indices exceed one positive (negative) standard deviation for at least three consecutive months (warm (cold) event criterion).
- Minor event: at least one index meets the warm (cold) event criterion; the other indices exceed an average of 0.5 std. dev., for at least one 3-month period.
- Warm (cold) episode: period consisting of multiple connected events, including at least one major event. SST anomalies between two connected events do not change the sign and the event-break does not last for more than 6 months.

This classification is based on all three index regions and does not treat them separately anymore. Thus, Atlantic and Benguela Niños, previously considered as separate phenomena, are now combined into one comprehensive Atlantic Niño with different regional characteristics. On the basis of this classification, 13 major warm events, 20 minor warm events, 6 warm episodes as well as 12 major cold events, 22 minor cold events and 2 cold episodes are found in the period 1870–2011.

Events include well-studied major warm events such as 1934, 1963 and 1984 (e.g. Shannon *et al.*, 1986; Florenchie *et al.*, 2003) which all show remarkably high peaks (Figure 1(b)). Strong cold events are found, e.g. in 1936, 1958 and 1977 (Figure 1(d)). About 50% of warm (Figure 1(a)) and cold (Figure 1(c)) water events peak in late boreal spring and early summer months (MJJ) but peaks are also found in boreal winter month December and throughout the remaining months of the year. Moreover, frequencies of months classified as Atlantic Niño and Niña months (see Table 1) are almost equally distributed across the year. Thus, all seasons are relevant for impact studies.

4. Impact of warm and cold SST anomalies on African west coast precipitation

4.1. Determination of precipitation regions

Using s-mode PCA and following the procedure described in Section 2, 39 precipitation regions are defined for Sub-Saharan Africa (20°N to the southern tip of the continent). As in this study we focus on coastal precipitation, only those regions facing the Atlantic Ocean are selected. The eight coastal African precipitation regions and their mean annual cycle are shown in Figure 2. The regions' names were chosen according to the country or region with the highest areal percentage. According to the movement of the intertropical convergence zone (ITCZ), the regional selection consists of four tropical regions (5, 6, 7, 8), one marginal tropical region (3), and two subtropical regions (1, 2). Guinea (8), W-Africa (7) and Cameroon (6) receive most of their precipitation in boreal summer caused by

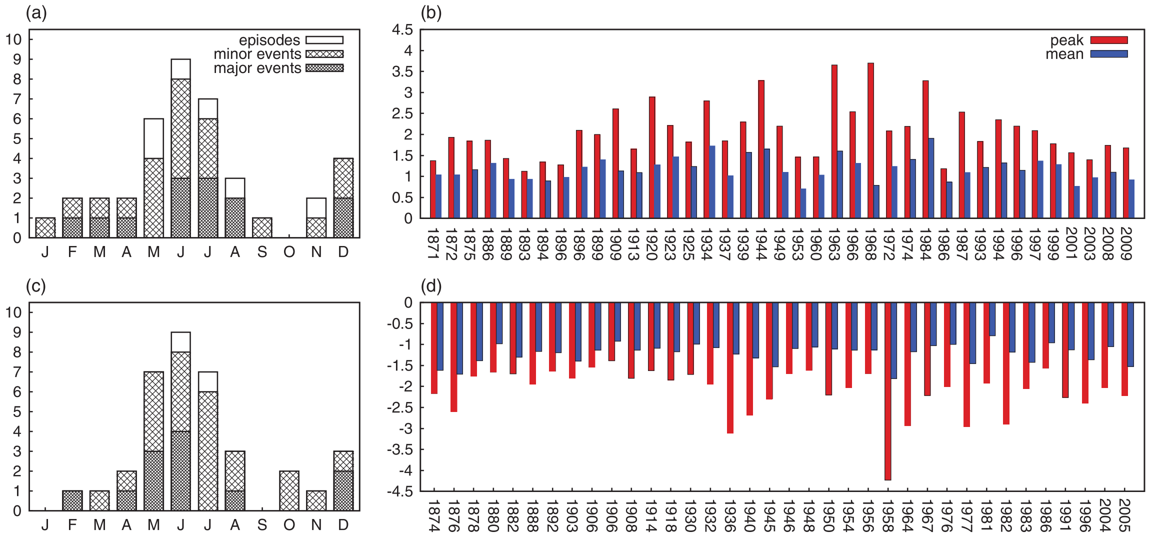

Figure 1. Left column: monthly occurrence of peaks of Atlantic Niño (a) and Niña (c) events (subtypes minor, major events and episodes) between 1870 and 2011. Right column: peak and mean values of all Niño (b) and Niña (d) events for the same time period. The *x*-axis displays the peak year of each event, not the onset year.

Table 1. Monthly frequencies of Atlantic Niño and Niña events (see classification description in Section 3) between 1951 and 2010.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Atlantic Niño	9	9	10	9	13	12	14	10	8	10	11	10
Atlantic Niña	9	10	10	12	12	11	11	10	8	7	6	7

the West African monsoon. In Gabon (5) rainfall maxima follow the equinoxes. The southwest monsoonal flow into the Angola low causes the precipitation in austral summer months over N-Angola (4). The latter receives most of the annual rainfall between November and April whereas winter months are dry. The seasonal cycle in S-Angola (3) is similar but includes a pronounced dry season between April and September. Namibia (2), mainly influenced by the subtropical highs over the Atlantic and Indian Oceans, shows a typical semiarid climate with small amounts of rainfall in austral summer and autumn. The maximum in austral winter in WS Africa (1) reflects the influence of extra-tropical cyclones within the mid-latitude westerlies. Note that hereafter the eight precipitation regions are italicized and their numbers are added in parentheses to distinguish them from the actual countries.

4.2. Links between variability of southeast Atlantic SSTs and African west coast precipitation

To assess the influence of tropical Atlantic Ocean variability on African coastal precipitation, monthly and seasonal correlation analyses are carried out for different time lags (0–4 months, precipitation lagging SST). Correlations between the three ATLN indices (see Section 3) and the eight precipitation indices (see Section 4.1) are then analyzed region by region and described below. Figure 3 shows the maximum correlation coefficients of all time lags for each SST seasonal section.

A remarkably strong link between SST and rainfall variability is evident for *W-Africa* (region 7, see Figure 2) in boreal summer months. This is consistent with previous studies (e.g. Reason and Rouault, 2006). JJA ATLN3 and the lagging JAS precipitation index are correlated at 0.76. Maximum correlations for ATLN1 and ATLN2 are found in MJJ indicating that the development of anomalies in those regions precede ATLN3 anomalies. Correlations for lag 1 and 2 are at similar magnitude and remain significant (confidence level 95%) for lags 3 and 4. As described by Reason and Rouault (2006), it takes up to 4 months to build up moisture evaporated over the tropical Atlantic off the Angolan coast that can significantly contribute to boreal summer rainfall in West Africa. In addition, our results suggest that SST influence and evaporation is not constrained to the Angolan/Namibian coastal region (ATLN1) but is also visible for ATLN2 and ATLN3 regions.

In contrast to *W-Africa (7)* clearly showing a strong SST-precipitation link of positive sign, there is only a minor or no significant connection in the boreal summer months JAS for the adjacent *Guinea (8)* region. Instead, correlation coefficients are negative ($r = -0.38$ to -0.44) for the AM and AMJ seasons. For *Cameroon (6)* a positive signal is found for MJJ ATLN1 index and JJA precipitation which is weaker for ATLN2 and 3 indicating that those two SST regions influence tropical central Africa in boreal summer to a lesser extent. For ATLN2 and ATLN3 weak negative correlations are found for boreal autumn months.

Further south, down the coast, another strong link between boreal summer SST and rainfall appears for *Gabon (5)*. ATLN1 and precipitation index are correlated at 0.76. Correlations for ATLN2 and ATLN3 are weaker

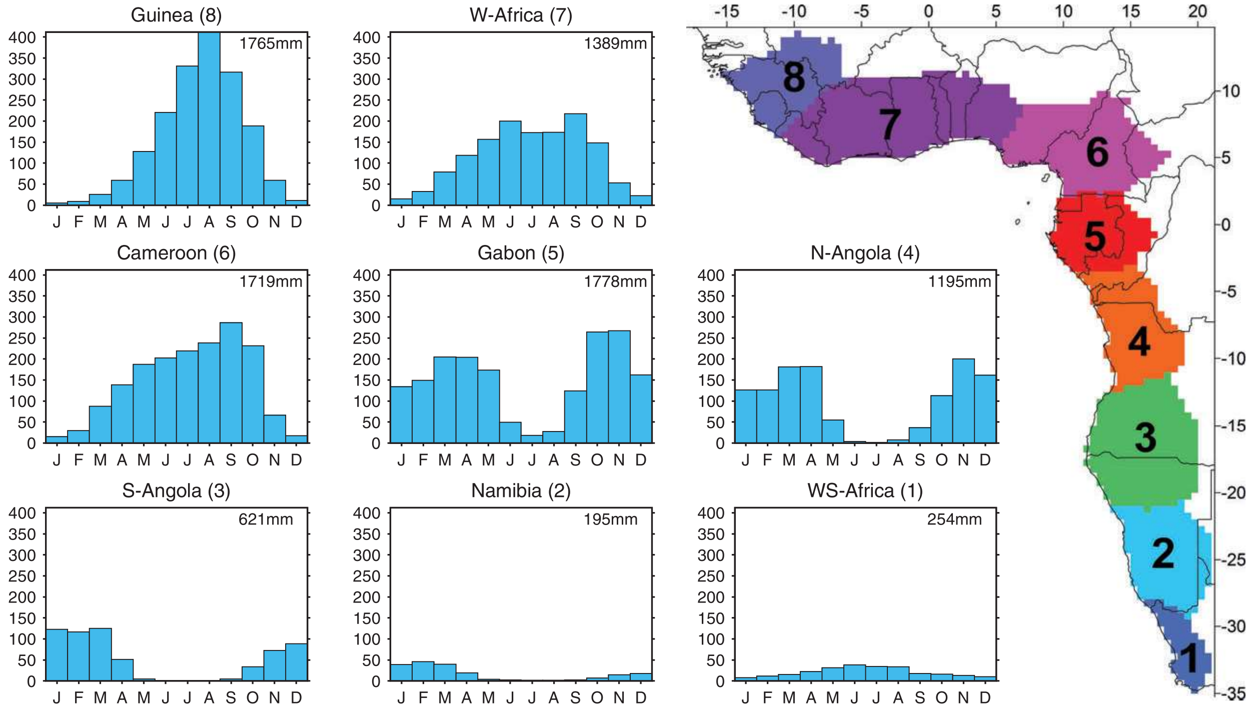

Figure 2. Precipitation regions derived from s-mode PCA (Section 2) based on standardized 1951–2010 precipitation time series. Bar charts show corresponding seasonal cycles. Only those regions facing the Atlantic coast were selected.

indicating that coastal SSTs are more important for the Gabon precipitation than equatorial ones. A second link is found in boreal winter (D/DJF).

For *N-Angola (4)* correlations reach their maximum ($r = 0.50–0.55$) in austral summer (DJ) and autumn (AM). No clear connection between SST and rainfall variability is found for *S-Angola (3)*. Results only indicate a weak signal in austral summer (J/DJ).

Analyses for *Namibia (2)* suggest a possible link between MJJ SST and SON precipitation as well as a weak influence of austral summer SST on autumn rainfall. For *WS-Africa (1)* the correlations are negative in austral spring months (O and N). Positive correlations are found for ATLN1 and ATLN2 late boreal summer (AS) SST and austral summer rainfall (DJ, 0.53/0.51) at moderate magnitudes whereas ATLN3 AMJ SST is correlated (0.52) with late winter precipitation.

To assess a potential change in the link between Atlantic SSTs and coastal rainfall before and after the so-called climate shift in the 1970s, correlation analyses are repeated for the two periods 1951–1980 and 1981–2010 and tested for significant differences (Fisher z-transformation). From our results (not shown) it can be concluded that the general pattern remains similar before and after the climate shift, e.g. there are no significant differences for the main rainy seasons in most regions. But results also point to a change in the Guinea (8) region, where negative correlations disappear in summer similar to the findings for the Sahel region (e.g. Mohino *et al.*, 2011; Rodríguez-Fonseca *et al.*, 2011). In contrast to these studies, for this region no significant changes are found for May and June. Furthermore, results point to a stronger link of Atlantic SSTs to Gabon (region 5) boreal winter rainfall and a weaker link to N-Angola (region 4) boreal spring rainfall. These findings need further investigation, but due to the abundance of results, this lies beyond the scope of this study.

Additionally, results of monthly and seasonal CCAs for time lags 0–4 months are computed and compared with the bivariate results described above. The CCPs provide a more detailed insight as they include the entire spatial resolution. Due to the abundance of patterns (for all seasons and time lags), only selected examples can be described below.

The first pair of JJA CCPs (Figure 4(a), $r = 0.83$) consists in its positive mode of a SST pattern with positive anomalies in the tropical southeast Atlantic and a corresponding precipitation pattern showing positive anomalies over Gabon, Congo and southern Cameroon as well as West Africa. The patterns clearly confirm the links described above between austral summer SSTs and precipitation in regions *Gabon (5)* and *Cameroon (6)* as well as the well-known link to *W-Africa (7)*. Furthermore it is evident that the influence of SST anomalies on boreal summer precipitation is not limited to West Africa. The whole coastal region between Liberia and Gabon is affected. When analyzing the same month for SST pattern and precipitation lags 1–2 months (JAS, ASO), a positive link to west South African precipitation appears (not shown) which also confirms the results of bivariate correlation analyzes. Note that these patterns do not show the connection to *Gabon (5)* and *Cameroon (6)*. The latter patterns therefore resemble the pattern described by Polo *et al.* (2008) who used maximum covariance analysis.

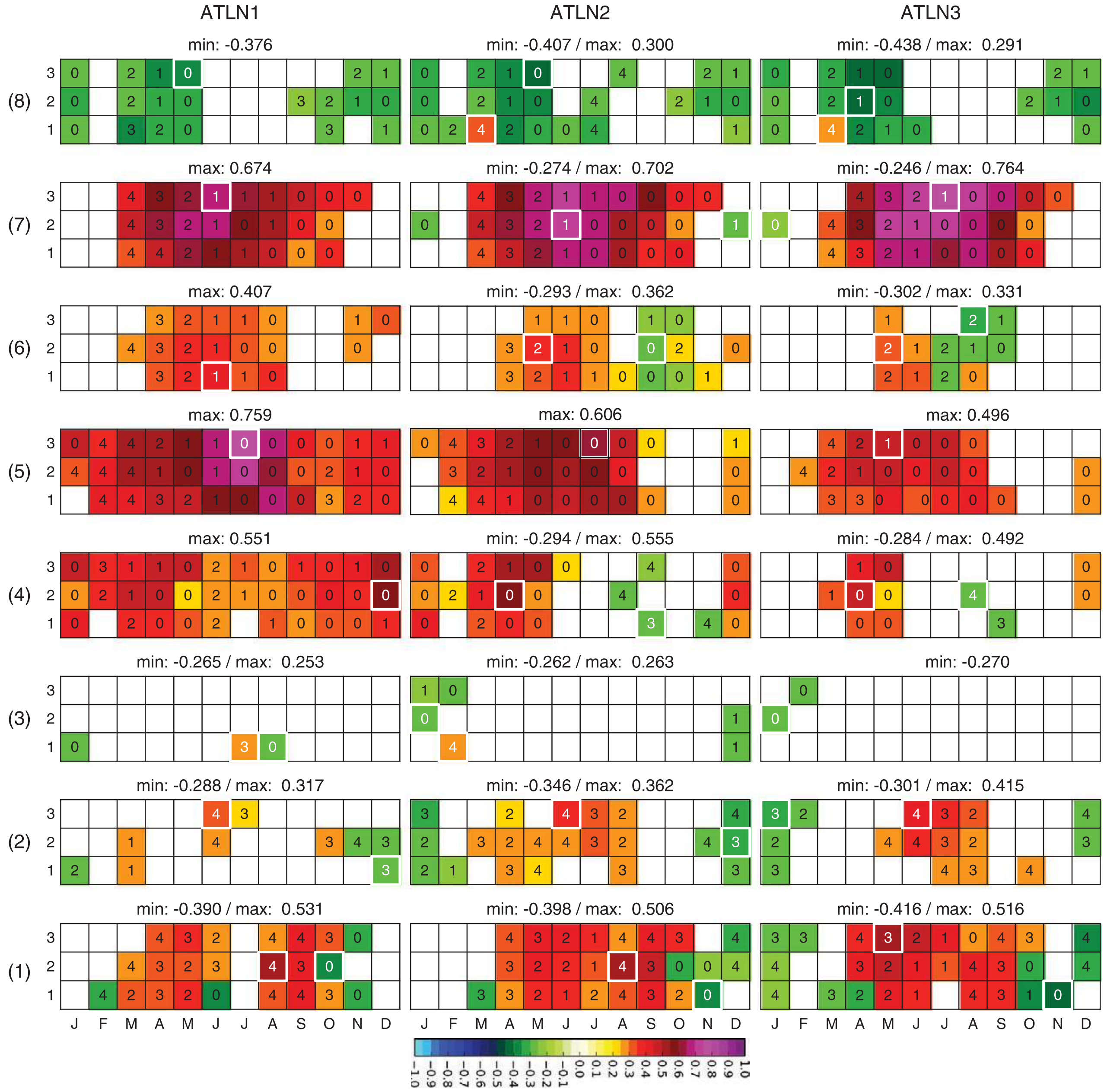

Figure 3. Monthly and seasonal correlation coefficients between ATLN1–ATLN3 indices (columns) and precipitation indices 1–8 (rows). Precipitation regions are sorted from north to south (8 to 1). For each 1- to 3-month seasonal section (y-axis) only the absolute (positive or negative) maximum for time lags 0–4 months (precipitation lagging) is shown. The label denotes the corresponding time lag of the maximum. The overall maximum is highlighted by a white frame and white label. Only significant results (95% level) are shown and displayed based on the central month (x-axis), e.g. FMA season is plotted at the position of central month M.

The second example (Figure 4(b)), the first pair of DJ patterns, represents the positive connection of tropical east Atlantic SSTs and *N-Angola (4)* precipitation. Although this study focuses on coastal precipitation, it is worth noting that the precipitation pattern also shows anomalies reaching into the African continent as far as the east coast (not shown) and confirms previous findings (e.g. Nicholson and Entekhabi, 1987). Furthermore, this pattern also indicates a link to Gabon (5) and Cameroon (6). The third example (Figure 4(c)) shows ON CCPs which capture the negative link between tropical SE Atlantic SSTs and precipitation in WS-Africa. Although no time lag was applied in this example, this pair of patterns also represents the positive link to Namibian precipitation described earlier.

The corresponding canonical scores of the three pairs of patterns (right column, solid lines) additionally include information about specific years including warm and cold water events. In Figure 4(a) for warm water events such as 1963, 1966, 1968, 1984 and 1995, anomalies are positive whereas negative values occur in cold water events, e.g. 1958, 1964, 1983 and 2005. Canonical scores of the latter two examples also include positive peaks, e.g. in 1963 and 1966, but negative anomalies are found for 1984 and

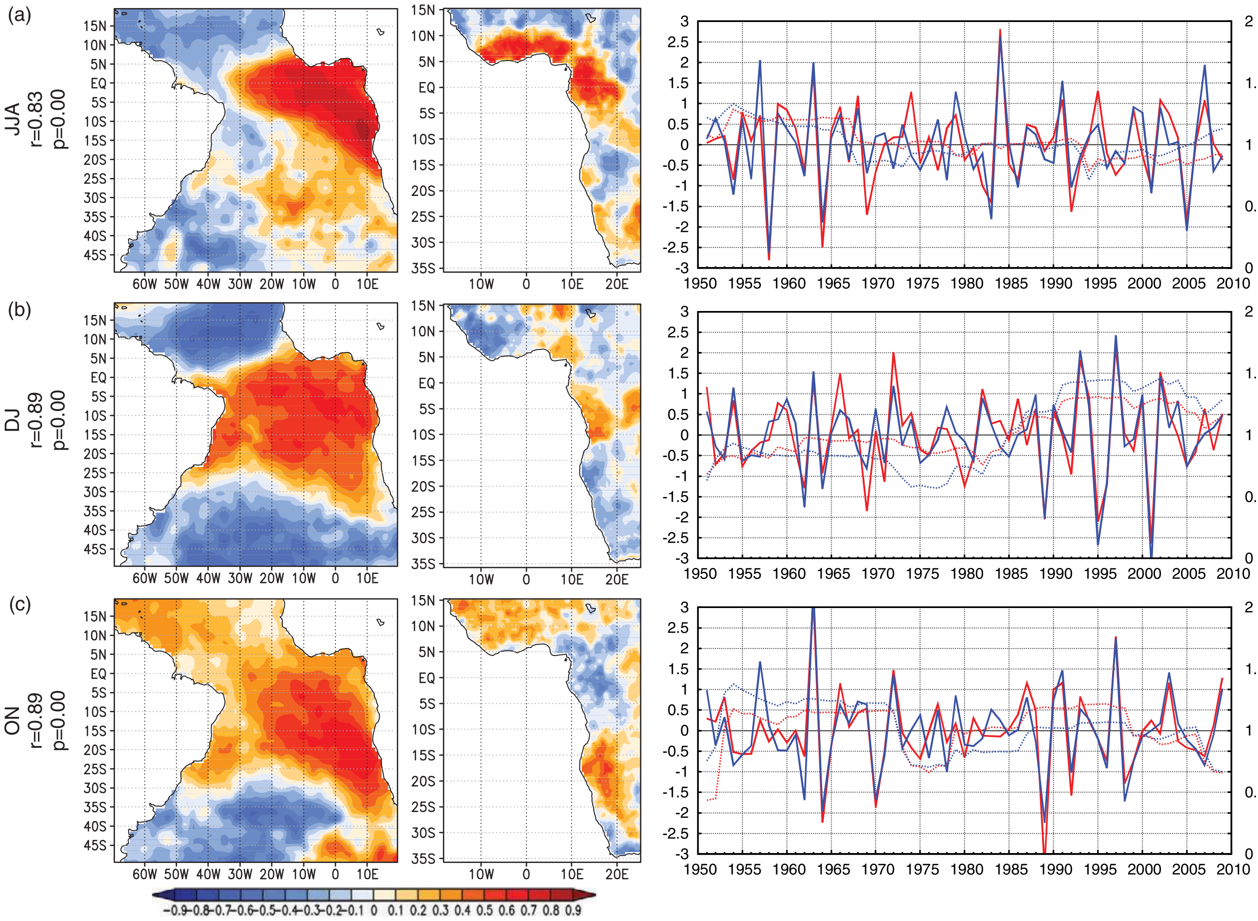

Figure 4. CCA patterns (CCPs) for SST and African west coast precipitation (1951–2010), corresponding SST (red) and precipitation (blue) canonical scores (time coefficients, solid lines, left axis), and 20-year running standard deviations (dotted lines, right axis). Examples of JJA (a), DJ (b) and ON (c) seasons are shown. For each example canonical correlation coefficients r and levels of significance p are given.

1995. This is due to the fact that some of the events are short and therefore do not last throughout all seasons. Furthermore, CCA patterns may cover areas with a different precipitation response to the same events.

Recent studies analyzing multidecadal variability show that the SST-rainfall relationship of a specific region may not be stationary over time. E.g. Losada *et al.* (2012) find that the relationship between tropical Atlantic SSTs and Sahel precipitation changes after the 1970s. As can be seen from the CCA scores and the 20-year running standard deviations (RSD) in Figure 4, pattern strength (amplitude) and also the frequency of a change in polarity vary over time. Changes are rather moderate in the first example (Figure 4(a)), but in the second example (Figure 4(b)), a higher RSD indicates a stronger amplitude after the 1980s with both strong positive and negative modes. Multidecadal changes in amplitude and frequency are also visible in the third example. A detailed analysis of these non-stationarities is beyond the scope of this paper, but should be part of a future paper.

Summarizing the findings above, it is evident that the influence of Atlantic variability is not constrained to certain months or regions (as might be thought from previous analyses). It plays an important role throughout the year, differing from region to region. Another important finding is that coupled variability is present on different time scales. Some links are only discovered on a monthly scale while other ones are stronger on the seasonal scale.

4.3. Impact of Atlantic Niño and Niña events on African west coast precipitation

As discussed in the previous section, co-variability in a certain month or season does not necessarily indicate an impact of both warm and cold water events on precipitation. Therefore, to analyze the specific impact of warm and cold water events on coastal precipitation, Atlantic Niño and Niña composites for time lags of 0–4 months are computed for the eight precipitation regions. These (and all other) composites are computed separately for each month or season and include all months classified as Atlantic Niño or Niña month (including all event classes according to Section 3). Monthly frequencies of warm and cold events (corresponding to the composite sample sizes) are given in Table 1. As most results are significant (≥95%) at lags 0 or 1 and differences between results of the latter are small, Figure 5 only summarizes results for lag 0. For the remaining lags significant results are discussed in the text.

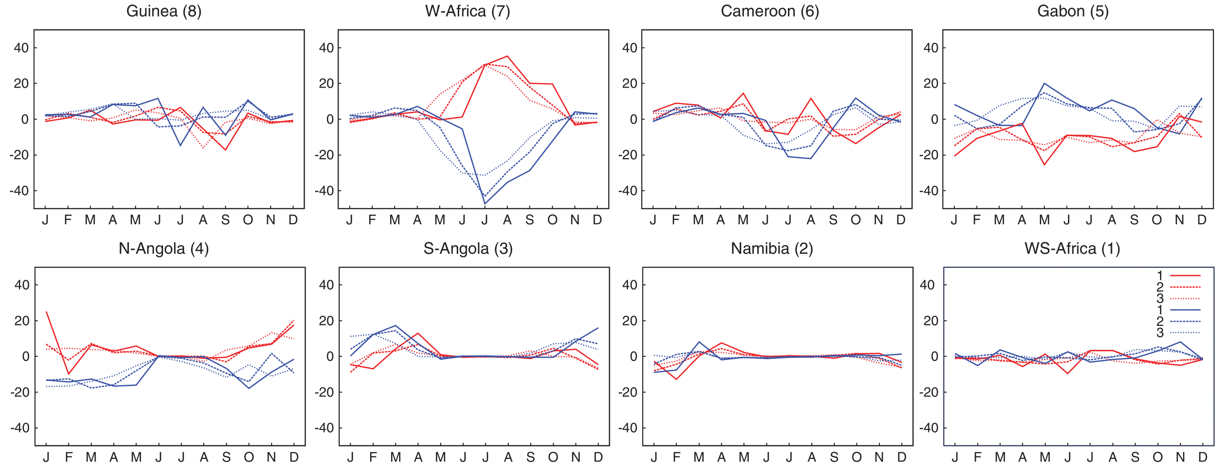

Figure 5. Atlantic Niño (red) and Niña (blue) composite mean values for all 1- to 3-month seasonal sections (line type) for the selected eight precipitation regions. The *x*-axis denotes the central month, e.g. FMA season is plotted at the position of central month M. Only lag 0 results are displayed.

For region *Guinea (8)* a significant warm water impact is only found in March (dry season) when precipitation is increased. Cold water events are associated with an increase in boreal winter and spring months except for March. The maximum increase is found in AMJ which is also the season of maximum *r* in Section 4.2.

Consistent with results of our correlation analyses and previous studies (e.g. Reason and Rouault, 2006), warm (cold) water events significantly contribute to an increased (decreased) boreal summer and early autumn precipitation (lags 0 and 1) in *W-Africa (7)*. Remarkably, in July the mean decrease (−47.3 mm) during Niña events is more pronounced than the increase (+30.4 mm) during Niño events.

In Cameroon (6) significant increase in precipitation during warm water events is observed in boreal winter months DJ. For cold water events there is a significant decrease in JJAS months.

In *Gabon (5)* significant results are found almost throughout all seasons. Warm water events contribute to a significant increase in precipitation in AMJ and early boreal summer 3-month seasons as well as August. Cold water events contribute to an even stronger decrease from May (−25.5 mm) throughout September and also in winter (JF).

For *N-Angola (4)* warm and cold water impacts not only differ in magnitude but also in season. While Niño events mainly contribute to an increase in austral summer rainfall (DJ/J), for Niña events there is a significant decrease in J/JF and also in almost all spring and autumn months with a maximum mean decrease of 17.9 mm in October.

During warm water events JJ rainfall is increased in *S-Angola (3)* and AM and AMJ rainfall in *Namibia (2)*. In both regions there is also an increase in November (lag 3–4, not shown in Figure 5). For cold water events significant increase is found for *S-Angola (3)* in March as well as a decrease in Namibia in DJ/JF (lag 2–4). In *WS-Africa (1)* warm water events are associated with an increase in August precipitation (lag 4) and a decrease in November (lag 0–3). During cold water events an increase in ON precipitation as well as a decrease in February is observed.

Figure 6 shows significance of all lag 0 composite means displayed in Figure 5 and described above. It summarizes all results being significant at 95% and 99% levels. Thus, it can be concluded that both warm and cold water events have a significant impact on African west coast rainfall throughout the year. The main influence, forming two 'clusters' in Figure 6, is concentrated on the months of May throughout November and the tropical regions Gabon (5) and W-Africa (7). But there are also significant results in the remaining seasonal sections and coastal regions. Figure 6 also reveals that cold water impacts are more extensive and affecting more seasons.

For a closer look at specific event years that are included in the composites discussed above, precipitation anomalies for all event years are plotted for all regional indices, seasons and time lags. Figure 7 displays a significant example of each region and also includes information about the event type. The selection mainly shows cold water anomalies as they have rarely been studied in literature so far. For *S-Angola (3)* and *WS-Africa (1)* Niño examples are chosen. The first example, AMJ precipitation anomalies in cold water event years, shows a clear increase in 9 out of 12 events with an average of 8.7 mm. In 3 years, 1956, 2004 and 2005, negative anomalies are found. An explanation for these exceptions can be found in the SST indices (not shown). The minor event 1956 was mainly centred on ATLN1 and ATLN2 index regions whereas values of ATLN3 index do not exceed the threshold in the months AM. A similar situation is true for minor event 2004. For major event 2005 the time lag between onset in ATLN1 and ATLN3 causes the missing precipitation response. While the events' peak is already visible in ATLN1 in MJA, it appears delayed in ATLN3 in JJA. For AM this region is even still warmer than average. This

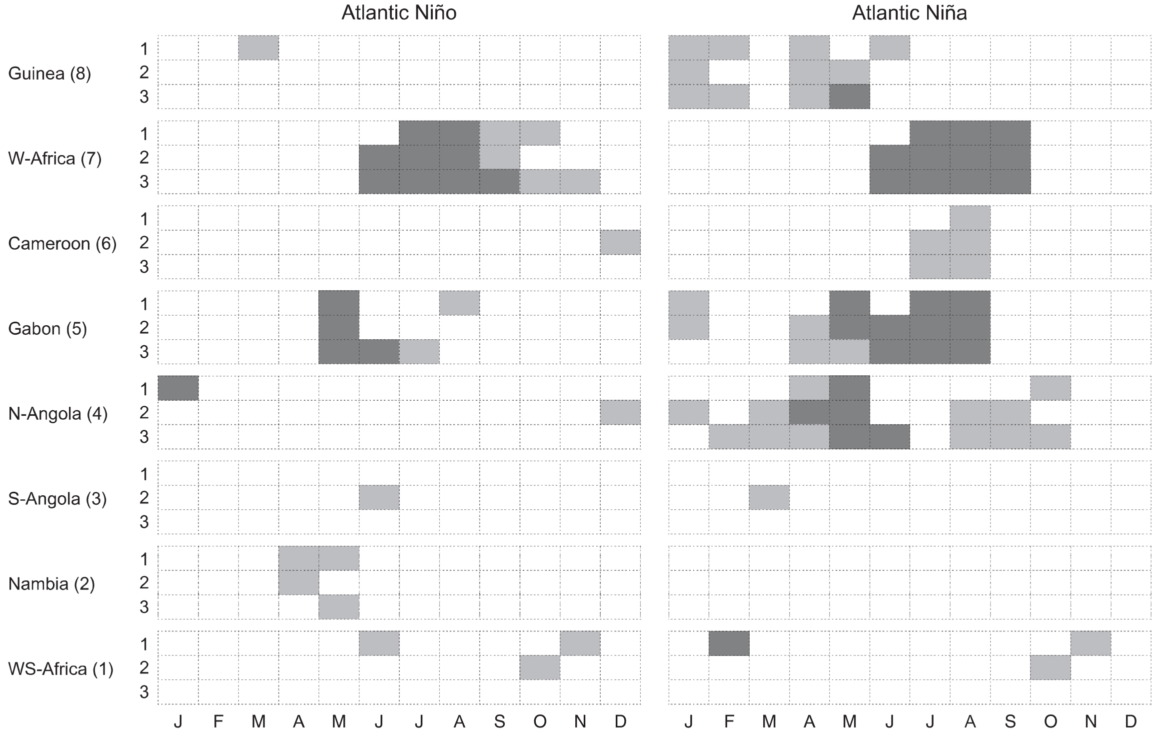

Figure 6. Significance of Atlantic Niño and Niña composite results for all precipitation regions and 1- to 3-month seasonal sections. 99% (dark grey) and 95% (light grey) levels are displayed.

shows that although the region is still clearly influenced by the tropical eastern Atlantic SSTs, the precipitation response is very sensitive to the actual temperatures. Due to the more distant location to the main warming centre it mainly depends on the influence of ATLN3 SST. In W-Africa (7) Atlantic Niña events contribute to an increase in rainfall in all events, notwithstanding the event type. Only for 1981 no response was found. In Cameroon (6), rainfall decreases in all Niña years except for 1981 and 1982. This cannot be explained by an analysis of the SSTs. Atmosphere dynamics associated with specific events may play a more important role in this case. Possible processes are further discussed in Section 6. On the other hand, minor cold events which are centred on either ATLN1 or ATLN3, both contribute to a rainfall decrease.

The remaining examples show a decrease in May in *Gabon (5)* and *N-Angola (4)* and in JF (lag 4) in *Namibia (2)* for cold water events. The two Niño examples show a significant increase in November rainfall (lag 3) in *S-Angola (3)* and a decrease in *WS-Africa (1)* in the same month (lag 1). Overall, there is no clear dependency of the magnitude of precipitation response on the Atlantic Niño type. But on the other hand, as described above, it is not important if a minor event is centred on one or the other ATLN region. This is an important finding as previous studies (e.g. Rouault *et al.*, 2003) mainly focused on events in region ABA (similar to ATLN1). Our results emphasize that Benguela and Atlantic Niños (based on ABA and ATL3 regions, the latter is similar to ATLN3) should not be considered as separate phenomena. Therefore our study is based on the analysis of one comprehensive Atlantic Niño with its subtypes which still allows for regional differences.

In summary, composite analyses of Niño and Niña events lead to two important conclusions. First, if an increase or decrease in rainfall in a specific region and season is found for warm water events, the opposite is not necessarily true for cold water events, as it is the case, e.g. for boreal summer months in *Gabon (5)*. Second, an increase (decrease) in warm (cold) events does not always occur at the same magnitude. In some cases cold water impacts are more pronounced than warm water ones, e.g. in *Gabon (5)* and *W-Africa (7)*, or vice versa. To exclude a possible shift as a consequence of high-pass filtering, results of filtered and unfiltered data were compared (not shown). Unfiltered data composites indeed confirm the two effects described above.

5. Discussion

In the previous section significant impacts of Atlantic warm and cold water events on rainfall in African west coast regions have been discussed. But which mechanisms lead to the increase or decrease in specific months or seasons? To address this question a closer look at the overlaying atmospheric dynamics is necessary.

In general, the complex climatology of Sub-Saharan Africa is mainly dominated by the position and intensity of three circulation systems, from north to south: (1) the intertropical convergence zone, (2) the southern subtropical highs (Indian and South Atlantic anticyclones) and the associated southeasterly trade winds as well as (3) the

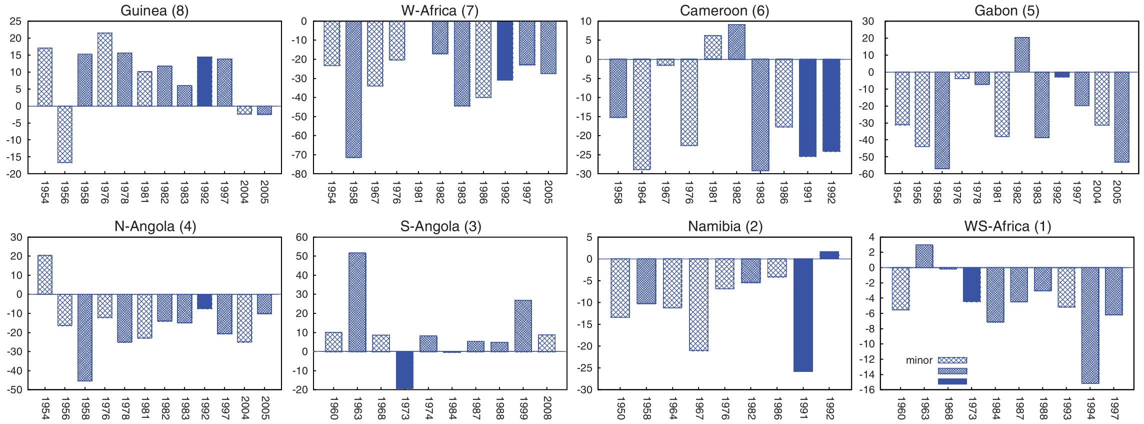

Figure 7. Precipitation anomalies in Atlantic Niño or Niña years for selected seasonal sections and time lags. Only seasonal sections that were part of an event are shown. Subtypes major events, minor events and episodes are indicated with different fill styles. Lag is 0 if not specified. The selection includes the following examples: Guinea (8) MAM Niña, W-Africa (7) JJA Niña, Cameroon (6) AS Niña, Gabon (5) May Niña, N-Angola (4) May Niña, S-Angola (3) Nov Niño lag 3 (i.e. Jul SST), Namibia (2) JF Niña lag 4 (Sep SST), WS-Africa (1) Nov Niño (Oct SST).

mid-latitude westerlies with their extra-tropical cyclones at the southern tip of the continent. Southward movement in austral summer months and northward movement in boreal summer months of these three systems cause the typical seasonal rainfall variations in different regions (for further details see Buckle, 1996; Preston-Whyte and Tyson, 1989). Rainfall variability is therefore also sensitive to any anomalous change in position or intensity of one of these systems. In addition, positive (negative) SST anomalies act to increase (decrease) atmospheric instability and therefore further contribute to anomalous rainfall (Hirst and Hastenrath, 1983).

To analyze changes during Atlantic Niño and Niña events, monthly moisture flux convergence and precipitation composites were calculated (see Figures 8 and 9). SST composites provide additional information about the monthly mean extent of warming or cooling in the southeast Atlantic. Starting at the beginning of the year, in austral summer, we now discuss mechanisms of the most remarkable changes in precipitation during Niño and Niña events.

Our results show that during Niño events in December and January moisture flux into the Angolan low is weakened whereas low latitude westward moisture flux from the Indian Ocean far into the continent is increased, causing an increase in precipitation along the Angolan coast. As suggested by Gimeno *et al.* (2010) and Gimeno *et al.* (2012), terrestrial regions such as tropical South Africa (WAF) and the Sahel region also serve as moisture sources (in addition to oceanic ones) and can therefore contribute to rainfall variations in a secondary way. Although WAF serves as a moisture source preferably in austral winter, weakened convergence and small shifts in source and sink regions may also contribute to a change in regional rainfall patterns. At the same time the low-level southwest monsoonal flow (850 hPa level, not shown) into Gabon and Cameroon is enhanced causing increased rainfall in the latter regions. During Niña events the situation is not quite inverse. There is no obvious change in the influence of the Indian Ocean, while the southwest monsoon appears to be weakened. Therefore, the southern Angolan region is not significantly affected whereas Gabon receives less rainfall.

In boreal spring months (FMA) Rouault *et al.* (2003) found that the increase in Angolan/Namibian precipitation is greatest when westward moisture flux from the Indian Ocean is strengthened and the southeasterly flux away from the southeast Atlantic coast is weakened. Local evaporation as well as enhanced atmospheric instability over the southeast Atlantic further contribute to increase precipitation, but they are not considered to provide the dominant source of moisture. In contrast, Hermes and Reason (2009) emphasize the possibly stronger influence of enhanced moisture advection from the Atlantic Ocean. Therefore the southeast Atlantic, although less dominant than the Indian Ocean, serves as an additional moisture source. Our results suggest that both processes are important but that the prevailing influence also depends on the month considered. In March the influence of the Indian Ocean is present but does not appear to be strengthened. Therefore the above-average rainfall in the northern regions may be mainly caused by a weakened southeasterly moisture flux over the coastal regions. In April enhanced southeasterly flow from the Indian Ocean into the southern part of the continent contributes to precipitation anomalies which extend further south.

In May enhanced southwesterly flow from the Atlantic into central Africa increases precipitation along the coast of Gabon and southern Cameroon in Atlantic Niño years, whereas precipitation along the West African coast is reduced. Reason and Rouault (2006) suggest that this may be due to stronger convection over Angola at the expense of the developing convection over West Africa, but they do not further discuss this feature. While we find enhanced flow into the Angolan low and reduced moisture flux towards the West African coast during Niño events, the reversed case in Niña years leads to an even more pronounced and significant decrease in precipitation (see also Figure 6). Boreal summer months already have

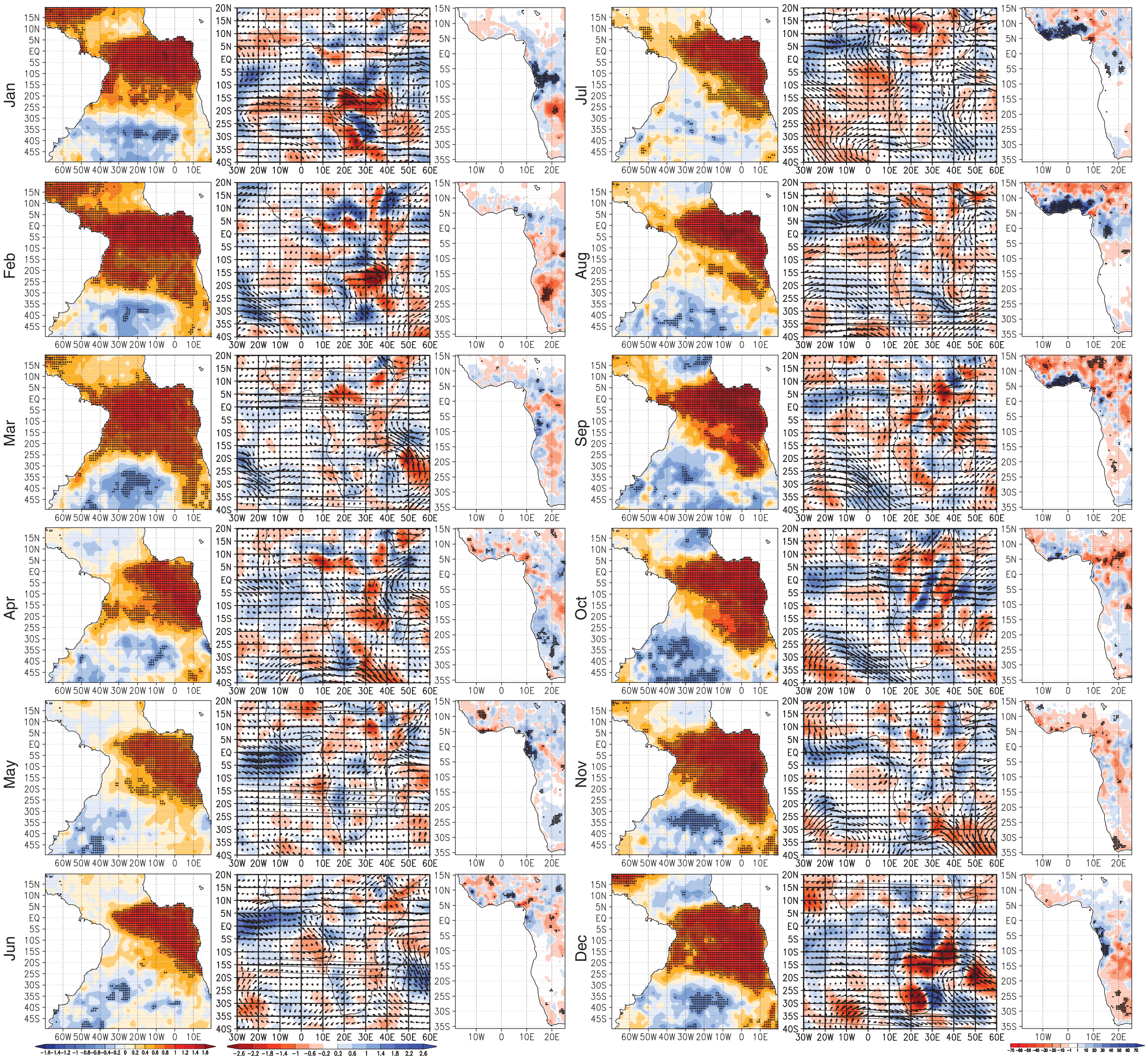

Figure 8. Monthly Atlantic Niño (all types) composites for high-pass filtered standardized SST, high-pass filtered moisture flux convergence ($g\,kg^{-1}m\,s^{-1}$) and precipitation (mm). Significant values (95% level) are highlighted with symbols (SST and precipitation) or bold arrows (moisture flux convergence).

been discussed intensively. With the northward movement of the ITCZ, enhanced (weakened) moisture flux into West Africa and stronger (weaker) convection cause increased (decreased) precipitation in years with warm (cold) SST anomalies (e.g. Reason and Rouault, 2006). Anomalies disappear with the retreat of the ITCZ. Our results confirm these previous studies. Furthermore, before and after the ITCZ and the major center of convection have reached their northernmost positions, the Guinea/Sierra Leone coast receives less (more) rainfall during Niño (Niña) years.

We move on to austral spring months focusing on South Africa. Here, in October and November in Atlantic Niño years the South Atlantic anticyclone as well as the mid-latitude westerlies appear to be displaced to the south and weakened. As a consequence South Africa receives below-average rainfall. In contrast, during November in Niña years when the anticyclone and the westerlies appear to be shifted northward, enhanced southwesterly flow towards the South African coast increases rainfall. These results agree with earlier studies which found that wet and dry austral summers over subtropical southern Africa are linked with latitudinal shifts of the mid-latitude westerlies (Vigaud *et al.*, 2009).

It can be concluded that warm and cold water events in the southeast Atlantic Ocean are accompanied by changes in the overlaying atmospheric circulation that lead to rainfall anomalies over different regions along the African Atlantic coast in different ways. In the northern regions, changes in strength of the monsoonal flow, moisture transport from the Atlantic and local convection which are dependent on the position and intensity of the ITCZ cause anomalous rainfall. In the southern part of the continent, a modification of the location and strength of the southern

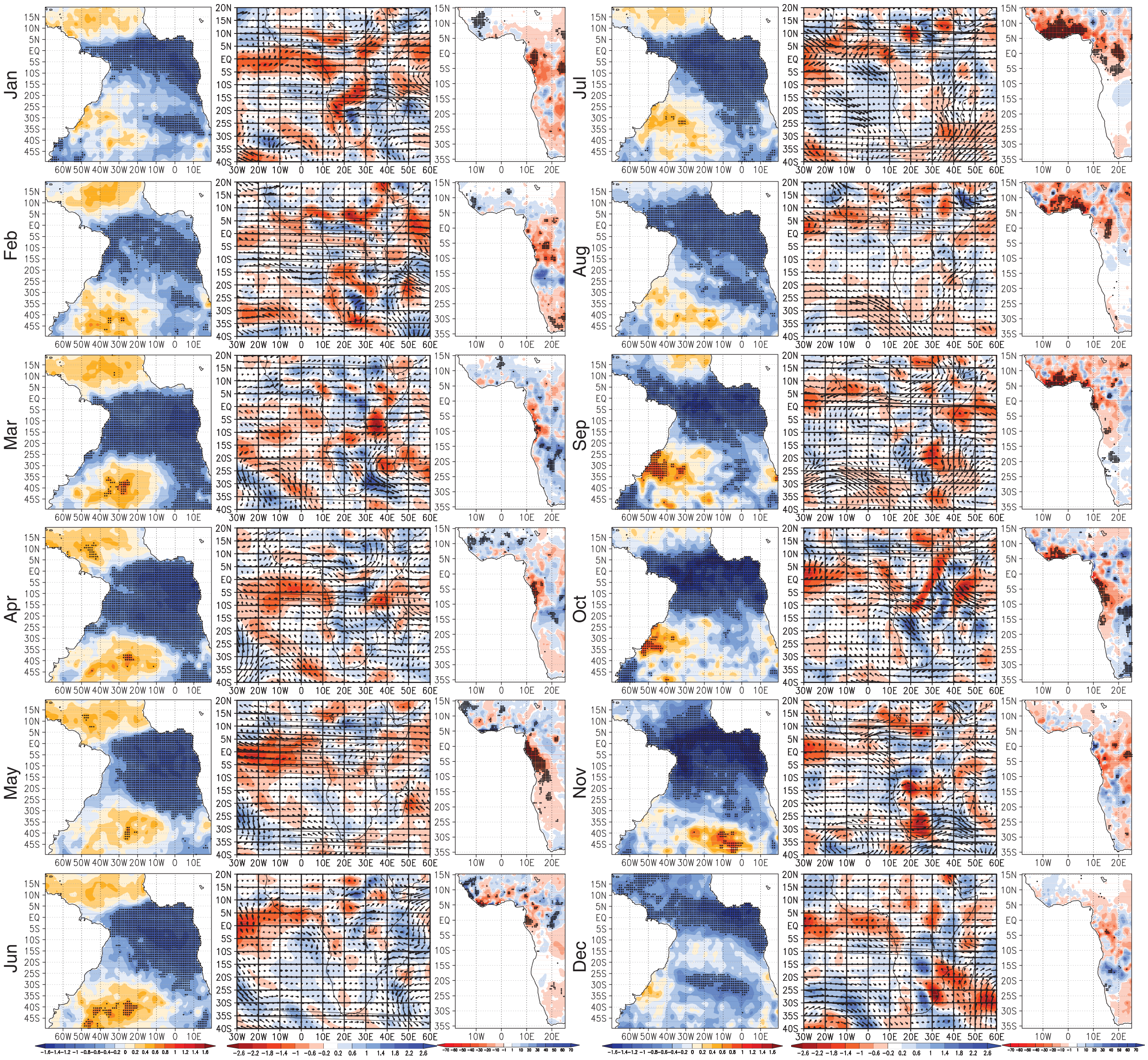

Figure 9. Monthly Atlantic Niña (all types) composites for high-pass filtered standardized SST, high-pass filtered moisture flux convergence ($g\,kg^{-1}\,m\,s^{-1}$) and precipitation (mm). Significant values (95% level) are highlighted with symbols (SST and precipitation) or bold arrows (moisture flux convergence).

hemispheric anticyclones as well as moisture transport from the Indian Ocean changes rainfall patterns. In this context, the Atlantic Ocean plays a less dominant role as moisture source. In addition, changes in local evaporation and atmospheric stability also contribute to anomalous rainfall. Therefore the northern regions are directly connected to the events via moisture transport from the Atlantic, whereas the southern regions are indirectly connected to the events through changes in the overlaying large-scale circulation.

6. Conclusions

In this study, we analyzed links between southeast Atlantic SSTs and African west coast precipitation variability as well as the impact of warm and cold water events on coastal precipitation for the period 1951–2010. In contrast to earlier studies, our analyses cover the whole Atlantic coast from South Africa to Guinea and are not limited to specific seasons. Furthermore, analyses are based on a new classification of Atlantic warm (Niño) and cold water (Niña) events. Using this classification now leads to comparable results for different rainfall regions and also accounts for less pronounced events (minor type) that, in most cases, have been neglected so far.

The main conclusions drawn from our analyses can be summarized as follows:

- Links between southeast Atlantic SSTs and precipitation are present throughout the year including different time scales (seasonal section lengths). Rainfall anomalies associated with warm and cold water events can be

observed over several regions along the South Atlantic coast of Africa, depending on the season considered.
- Significant impacts are not limited to major warm or cold water events, but are also found for minor events.
- Atlantic Niña events can cause an even stronger rainfall decrease than the increase is in Niño events. This is observed, e.g. in northern Angola and the northern hemisphere west coast.
- The rainfall response to Atlantic Niño and Niña events is seasonally asymmetric in some regions.
- Changes in the interacting atmospheric circulation during warm and cold water events lead to particular rainfall anomalies over different regions along the African Atlantic coast. The northern regions are directly connected to the events via enhanced or weakened moisture transport from the Atlantic which is dependent on the intensity of the monsoonal flow toward the continent. In contrast, the southern regions are indirectly connected to the events through changes in the location and strength of the southern hemispheric anticyclones as well as the moisture transport from the Indian Ocean.

An increase in precipitation can cause severe flooding and soil erosion, whereas a decrease severely affects water availability and therefore agricultural productivity. In West Africa, for instance, a delayed or less intense monsoon rainfall may even cause crop failure. Thus, although previous studies have mainly focused on warm events, it is equally important to study cold events which have been shown to be sometimes even more pronounced. Furthermore, our results have shown that further analyses of non-stationarities in the SST-rainfall relationship and their possible causes are needed and should be subject to a future paper.

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