Role of the Gulf of Guinea in the interannual variability of the West African monsoon: what do we learn from CMIP3 coupled simulations?

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ABSTRACT

The surface ocean explains a significant part of the interannual variability of the West African monsoon (WAM). The present paper explores the role of Gulf of Guinea sea surface temperatures (SST): how is the ocean–atmosphere observed relationship reproduced by state-of-the-art coupled models?

The “Atlantic Niño” is the main mode of interannual variability in the Gulf of Guinea. SST anomalies are maximum in June–July, and are associated with a convective anomaly in the marine Intertropical Convergence Zone (ITCZ), that spreads over the Guinean coast. In most of the studied CMIP3 simulations, the interannual variability of SST is too weak in the Gulf of Guinea, especially along the Guinean Coast. As a consequence, the influence on monsoon rainfall over the African continent is hardly reproduced. Interestingly, many models exhibit a dipolar response of the marine ITCZ to the Atlantic Niño. In the observations and reanalyses, the absence of any evident shift in the position of the monsoon rainbelt is associated with a collapse of the correlations between Gulf of Guinea SST and Sahel rainfall at the end of the 20th Century. It is suggested that this may be due to the counteracting effects of the Pacific and Atlantic basins over the last decades. In CMIP3 simulations, the Atlantic Niño is often correlated with the El Niño-Southern Oscillation (ENSO). However, only one simulation catches the observed evolution of the Pacific–Atlantic relationship.

Keywords: West Africa – Monsoon – ITCZ – Sahel – Gulf of Guinea – SST – Interannual – CMIP3
1. Introduction

Sea surface temperatures (SST) in the Gulf of Guinea play an important role in the annual cycle of rainfall over West Africa (Okumura and Xie 2004). The cold tongue that develops in late spring contributes to the temperature ocean–continent gradient, which strengthens the West African Monsoon (WAM) circulation in boreal summer. The Gulf of Guinea is the main source of moisture for the WAM, and ocean–atmosphere processes are essential to understand the annual cycle of rainfall over the continent.

Because the Gulf of Guinea takes part – in a sense – to the monsoon system, SST anomalies in that basin are likely to influence rainfall amounts over West Africa. At the interannual timescale, the role of the Gulf of Guinea was discovered by Lamb (1978); but this is only since the 1990s that this issue is studied thoroughly (e.g., Lamb and Peppler 1992, Fontaine and Janicot 1996, Fontaine et al. 1998, Janicot et al. 1998, Vizy and Cook 2002).

According to the literature, the El Niño–Southern Oscillation (ENSO) in the equatorial Pacific, the Atlantic Niño in the equatorial Atlantic, and Mediterranean SST anomalies are the main oceanic sources of predictability in order to forecast rainfall seasonal amounts over West Africa (Ward 1998). It is therefore essential to better understand the coupled ocean–atmosphere processes at the origin of such interactions. It is also essential to look at those interactions in the climate models used for seasonal forecasts. Current operational systems are often based on the same coupled ocean–atmosphere models as those used for climate scenarios.

Joly and Voldoire (2009) show that the influence of ENSO on WAM rainfall simulated by CMIP3 coupled models can be quite different from the observed teleconnection. Is the interaction with the nearby Gulf of Guinea better reproduced? Joly et al. (2007) suggest that the ENSO–WAM relationship is often the only discernable statistical link in CMIP3 simulations. However, their method considers the tropical basins as a whole. A more detailed study seems therefore necessary to assess the regional influence of the Gulf of Guinea.

Even within the observed record, some issues remain unsolved. For example, some studies insist on the South–North dipolar shape of the response of WAM rainfall to Gulf
of Guinea SST anomalies (e.g., Janowiak 1988, Janicot 1992, Rowell et al. 1995, Ward 1998). This is often interpreted in terms of an anomalous displacement of the monsoon rainbelt (e.g., Vizi and Cook 2002, Nicholson and Webster 2007). However, Janicot et al. (2001) show that the dipolar variability does not hold for all of the 20th Century; and some recent studies (e.g., Giannini et al. 2005, Polo et al. 2008) challenge the idea of a modulation of the meridional position of the ITCZ. Therefore, the objectives of the present paper are twofold: (i) to compare the behaviour of state-of-the-art coupled models with the observational record; and (ii) to take advantage of the CMIP3 database to study – so far as possible – some tricky aspects of the WAM variability. After a brief description of the data and methods in section 2, the role of the Gulf of Guinea is scrutinized in section 3.

2. Data and methods

2.1 Data

2.1.1 Observed data

Three observation datasets are used in this study:

- The 1901–2002 Climate Research Unit CRU2 precipitation climatology (Mitchell and Jones 2005).
- The 1951–2000 precipitation climatology provided by the Global Precipitation Climatology Centre (GPCC, see http://gpcc.dwd.de/).
- The Hadley Centre HadISST1 SST climatology (HadC hereafter), provided for the 1870–2002 period (Rayner et al. 2003).

2.1.2 Reanalysis data

Two reanalysis products are used in the following:

- The National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) reanalysis-1, hereafter NCEP (Kalnay et al. 1996).
- The European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis, hereafter ERA40 (Uppala et al. 2005).
Both reanalyses are used in parallel all along the study to better assess the robustness of the results. The assimilation of satellite observations considerably improves the quality of reanalyses over the last three decades (Sturaro 2003), but does not guarantee their temporal homogeneity (dell’Aquila et al. 2005). Despite our prior filtering of the low-frequency in all datasets, the lack of reliability of reanalysis data before 1968 might have an impact on our results over Africa (Poccard et al. 2000).

Note that both observation and reanalysis data are interpolated onto a 128 by 64 horizontal grid (2.8° resolution).

2.1.3 CMIP3 coupled simulations

The purpose of this paper is not to study all the simulations available in the IPCC-AR4 CMIP3 database. Our set of simulations is thus neither comprehensive, nor based on any type of a priori consideration. The fifteen 20C3M (20th century) simulations presented in Table 1 include runs performed with one model at different resolutions (which might have an impact on the teleconnection), and also runs from two models from the same research group. With this selection (13 simulations from 11 research groups in 9 different countries), we expect to have a representative sample of the performance of state-of-the-art coupled models. All the information about the IPCC-AR4 can be found on the website http://www.ipcc.ch/, and the coupled models are described in Chapter 8 of the fourth Assessment Report (Randall et al. 2007). For further information, see the CMIP3 website at PCMDI: http://www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php.

2.2 Methods

2.2.1 Data filtering

In this study, the focus is on interannual variability. It is therefore necessary to filter any long-term change or interdecadal variability in both the observed and simulated time-series. The series are first detrended linearly, and then filtered using the Fast Fourier Transform (Press et al. 1992). A low-pass filter with a cut-off at 8.8 years is applied to the yearly seasonal means, while a band-pass filter is used for the monthly data to filter out both the annual cycle and the low-frequency.
2.2.2 Principal Component Analysis (PCA)

Instead of averaging SST anomalies over a fixed domain, the PCA (Hannachi et al. 2007) is employed to extract the main modes of variability of the observed and simulated fields. Each mode explains a fraction of the variance, and the associated normalized time-series (called expansion coefficients, EC) can be correlated and regressed with the grid-point anomalies of various fields.

2.2.3 Significance testing

The significance of the correlations and regressions is tested using a Monte-Carlo bootstrap technique, in order to destroy the chronological order between the two fields.

3. Role of Gulf of Guinea SST

3.1 The “Atlantic Niño” variability

3.1.1 In the observations

Fig. 1 illustrates the evolution of SST filtered anomalies in the Gulf of Guinea over the second half of the 20th Century. There is substantial interannual variability, with the strongest anomalies exceeding 0.5°C some years. The annual cycle of the standard-deviations of this SST index reveals that SST anomalies are maximum in June–July, i.e. at the beginning of the monsoon season over the African continent.

The SST index (GOGI) calculated in Fig. 1 may confound different modes of variability. Therefore, Fig. 2 displays the results of a PCA of June–July–August–September (JJAS) SST anomalies (filtered from the decadal variability and long-term trend) between 10°E–15°W and 10°S–10°N. The JJAS season has been chosen because it concentrates most of the rainfall amounts over West Africa. The first mode explains 81% of the variance with the HadC 1901–2002 data, whereas the following modes in the decomposition explain less than 6% of the variance. Because our domain is limited to the Gulf of Guinea, and because the JJAS season is considered, the PCA does not catch the so-called “meridional mode” of tropical Atlantic variability (Xie and Carton 2004).
The homogeneous map in Fig. 2 shows that the first mode corresponds to the “Atlantic Niño” (also called “zonal mode” in the literature). The orange curve (right panel) in Fig. 2 confirms that SST anomalies associated with this mode peak – on average – at the beginning of the WAM season. Fig. 2 also displays for each month of the year the correlations with ENSO SST anomalies (blue curve). It suggests that – as far as the whole 20th Century is considered – the Atlantic Niño is not correlated with ENSO, which is in agreement with Chang et al. (2006a).

3.1.2 In CMIP3 simulations

How is the Atlantic Niño variability simulated by state-of-the-art coupled models? As in Fig. 2, let us employ the PCA to extract the interannual variability of Gulf of Guinea SST in 13 of the CMIP3 20th Century simulations (20C3M) carried out for the 4th assessment Report of the IPCC. Contrary to the observed variability (§3.1.1), many models have a second mode that explains a non negligible part of the SST variance. Therefore, Table 2 indicates the variance explained by the first two modes, as well as the ratio Var2/Var1. This ratio exceeds the 40% arbitrary threshold for three simulations: CNRM, CSIRO, and MPI. For those simulations, the second mode of the PCA has thus to be taken into account. Note that it has been verified that for those simulations, the obtained second mode is robust after a VARIMAX rotation of the six main modes of the PCA.

Fig. 3 and 4 display the SST correlation/regression maps calculated from the SST EC of the first mode for all the models, as well as of the second mode for the three models CNRM, CSIRO and MPI. The same correlation/regression curves as in Fig. 2 are also shown, in order to assess the amplitude and the life-cycle of SST anomalies in the Gulf of Guinea, and the possible correlations with ENSO events.

The three simulations (CNRM, CSIRO, and MPI) that have two important modes of SST variability in the Gulf of Guinea exhibit a similar large-scale mode of SST variability, that affects all the Tropics. In the CNRM and MPI simulations, this tropical mode is even the main mode of SST variability in the Gulf of Guinea, and explains about half of the SST variance. Interestingly, the SST patterns for the three simulations closely resemble those obtained in Joly and Voldoire (2009) for the ENSO teleconnection. Such a strong response of Gulf of Guinea SST to ENSO in JJAS is not
detected in the observations (§ 3.1.1) and has to be distinguished from the intrinsic variability of the Gulf of Guinea. Joly and Voldoire (2009) show that in those simulations – because of the delay in the atmospheric response to ENSO, and because of the lingering of SST anomalies in the tropical basins – JJAS SST anomalies in the Gulf of Guinea are part of the ENSO teleconnection with the WAM.

Regarding the other modes detected by the PCA in Fig. 3 and 4, the variability simulated in the Gulf of Guinea can be rather different from the observed one:

- Five of the modes (CNRM-2, CSIRO-1, HADCM3, INGV, NCAR) are confined along the coasts of Angola and Namibia, south of the equator. The SST anomalies for those modes are maximum in September–October (November–December for the CNRM simulation), i.e. later than in the observations (June–July, cf. Fig. 2).
- In most simulations, the SST pattern does not reach the Guinean coast (e.g., HADGEM1, IPSL, MIROCmed, MPI-2).
- In five simulations (CCCMAt63, INM, IPSL, MIROChi, MIROCmed, MPI, MRI), SST anomalies are weaker than those observed. On the contrary, in GFDL and HADGEM1, the modes are much stronger.
- In some simulations (e.g., GFDL and MRI), SST anomalies peak at the end of the monsoon season, a few months after the observations (cf. Fig. 2).

From the CMIP2 to the CMIP3 models, a lot of work has been done to improve the ENSO, with some success (AchutaRao and Sperber 2006). The above results suggest that concerning the Atlantic Niño variability there is also some room for improvement.

3.1.3 Possible interactions between the Atlantic Niño and ENSO

In some simulations, the loadings in the equatorial Pacific in Fig. 3 and 4 suggest that the Atlantic Niño can be significantly correlated with SST anomalies in the equatorial Pacific, that are either of the same sign (e.g., MRI), or of the opposite sign (e.g., INGV). This is not the case in the observations (Fig. 2). Because of the essential role of ENSO for the interannual variability of the WAM in the observations, but also in the simulations (Joly and Voldoire 2009), it seems interesting to determine if the Atlantic Niño variability simulated in state-of-the-art coupled simulations is independent of ENSO.
The homogeneous maps display the grid-point synchronous correlations with JJAS SST. However, ENSO has no special reason to peak in JJAS. On the contrary, ENSO SST anomalies are usually maximum in winter in the observations, so the potential inter-basin co-variability might not be synchronous. As in Fig. 2, the blue curve in the right panel of Fig. 3 and 4 therefore tries to detect the possible lagged correlations between ENSO and the JJAS variability of SST in the Gulf of Guinea. Eight simulations (CCCMAt63, HADCM3, HADGEM1, IPSL, MIROChi, MIROCmed, MPI, and NCAR) have a mode that is independent from ENSO. In the five other simulations, the mode detected in the Gulf of Guinea is significantly linked to the end of ENSO events of the opposite sign (CNRM-2, CSIRO-1, GFDL, INGV), of the same sign (INM), or to the beginning of same sign ENSO events (MRI).

At this stage, the statistical links have been assessed for the whole 20th Century. The stationarity of the ENSO–Atlantic Niño relationships is assessed in the § 3.3.

### 3.2 Response of the ITCZ

#### 3.2.1 In the observations and reanalyses

In the following, the first normalized EC of the PCA is used as a time-series representative of Atlantic Niño SST anomalies in the Gulf of Guinea. Fig. 5 shows the correlation and regression values with several datasets, in order to depict the associated convective anomalies.

- With the interpolated rainfall data derived from in situ measurements (CRU and GPCC), the Atlantic Niño is correlated with WAM rainfall amounts over the Guinean coast (correlations exceed 0.6). With the CRU data, some weak negative correlations are also significant over the Sahel.

- The reanalyses allow to study the response of the marine ITCZ, and cover a longer period than satellite-derived rainfall estimates. In ERA40 and NCEP, rainfall anomalies associated with the Atlantic Niño appear maximum over the ocean. This pattern is fully consistent with other studies (e.g., Ruiz-Barradas et al. 2000): the Atlantic Niño has a strong convective signature in the ITCZ. The signal is however two times stronger in ERA40 than in NCEP. Note that the Guinean coast lies at the margin of the anomalies.
To go further in the comparison of the two reanalyses, Fig. 5 also displays the Outgoing Long-wave Radiation (OLR), that is commonly used as a proxy for the tropical convection. Note that the OLR is taken positive for an upward flux. The positive anomaly over the Gulf of Guinea therefore corresponds to an increased convection. Contrary to the precipitation field, OLR regression values are of the same order in ERA40 and NCEP, perhaps thanks to the assimilation of satellite data for the last decades of the 20th Century. However, the patterns are slightly different. Interestingly, there is a dipolar counterpart over the central Sahel in ERA40.

### 3.2.2 In CMIP3 simulations

The response of the ITCZ to SST anomalies in the Gulf of Guinea is important for seasonal forecasting over West Africa. However, the variety in the simulated SST variability (§ 3.1.2) leads inevitably to a large variety of rainfall responses in state-of-the-art coupled models. This is illustrated by the correlation/regression maps of Fig. 3 and 4. In most of the simulations, correlations are weak, which means that the simulated SST mode is not necessarily associated with a clear rainfall response. In only seven simulations (CSIRO-1, GFDL, HADCM3, HADGEM1, INGV, MPI-1, MRI), correlations outreach the arbitrary 0.7 threshold, at least for some grid-points. The rainfall patterns are hardly comparable to the observed ones (Fig. 5). Over the Guinean coast, only the GFDL simulation has a response of the WAM that is comparable to the observed one. Actually, in most simulations the rainfall pattern does not affect the African continent. It seems often related to the SST pattern, especially when it does not reach the coast.

Some interesting remarks can be further inferred. The higher resolution in MIROChi and NCAR does not yield a more realistic variability in the Gulf of Guinea. Surprisingly, the low resolution MIROCmed simulation performs better (on this specific issue). Besides, some models have the same model components. For example, INGV and MPI use respectively the ECHAM4.6 and ECHAM5 atmosphere models; and INGV, CNRM and IPSL use the OPA8 ocean model. There is however no evident resemblance between the variability simulated in those simulations. Obviously, the biases cannot be attributed to a single component, which confirms that the Atlantic Niño is a coupled phenomenon, with both the ocean and the atmosphere involved.
It seems necessary to study the processes at the origin of the biases in each model. Improving the mean state and the variability of the Gulf of Guinea in coupled models should improve the response of monsoon over the continent. This is however a huge work, that cannot be undertaken in the framework of this intercomparison paper. Some studies have already shown that the mean state and the variability of the tropical Atlantic are poorly reproduced in state-of-the-art coupled models. Breugem et al. (2006) show that the temperature in the north tropical Atlantic is 1°C to 3°C too cold in CMIP3 models. The position of the ITCZ is most of the time shifted to the south, which is also the case in SST-forced simulations (Biasutti et al. 2006). Near the equator, SST in summer is too warm in the east, and too cold in the west of the basin, which leads to a west–east zonal gradient instead of east–west as in the observations. Note that Davey et al. (2001) found the same conclusion for the CMIP2 models. More recently, Richter and Xie (2008) show that the biases of the wind at the surface equatorial Atlantic lead to a shoaling of the thermocline in the east of the basin, which prevents the cold tongue from developing in summer. According to them, the biases in the tropical Atlantic mainly originate from the atmospheric model, and are amplified by the coupling.

3.3 Stationarity of the relationships

3.3.1 In the observations

Some studies insist on the dipolar structure of the WAM rainfall response to SST anomalies in the Gulf of Guinea (Janowiak 1988, Janicot 1992, Rowell et al. 1995, Ward 1998, Nicholson and Grist 2001, Nicholson and Webster 2007). Giannini et al. (2005) state that this dipolar structure might be artificial. From their observed and simulated data, they extract a Guinean and a Sahelian pattern that represent two different mechanisms of rainfall variability. Interestingly, Janicot et al. (2001), Rowell (2001), and Polo et al. (2008) suggest that the dipolar response may depend on the period considered. With the 1901–2002 CRU climatology, we find indeed a weak negative response over the Sahel (Fig. 5), which disappears when the second half of the 20th Century is considered (GPCC, ERA40, and NCEP). Resolving this issue could be worthwhile for seasonal forecasting. The Sahel is indeed characterized by low rainfall
seasonal amounts, and a high interannual variability. Assessing the potential role of the Gulf of Guinea for Sahelian rainfall seems therefore a challenging, but important task. The JJAS Gulf of Guinea SST index, derived from the PCA in Fig. 2, gives us the opportunity to assess the stationarity of the SST–rainfall relationships in the observed record. Fig. 6a shows that with Guinean Coast (GC) precipitation the running correlations are quite stable all along the 20th Century, with a slight increase from 0.5 to 0.65, which may not be significant given the weaker confidence in the data registered during the first half of the Century. On the contrary, the correlations with Sahelian rainfall are much less robust (Fig. 6c), which is consistent with Janicot et al. (2001) and Rowell (2001). Correlations are significant from the 1920s to the 1960s, but drop rapidly, and are no longer significant during the last three decades of the 20th Century. This explains the absence of any robust dipole with the recent data (Fig. 2), and is consistent with Polo et al. (2008). Why such a strong evolution in the Gulf of Guinea SST–Sahel rainfall relationship since the 1960s? The observed record is probably too short to firmly answer this question.

Rowell (2001) puts forward that the non-stationarity of the Sahel–Gulf of Guinea relationship cannot be attributed to the modulation of the SST variance, or to possible errors in the rainfall or SST data. He suggests that it might be the multi-decadal fluctuations in the underlying atmospheric state that may have affected the mechanisms linking the Atlantic to the Sahel. In the following, we present an interesting feature of the SST–rainfall relationships, that tends to confirm this hypothesis.

At the interannual timescale, Sahelian rainfall are mainly influenced by SST anomalies in the equatorial Pacific (Janicot et al. 2001, Rowell 2001). Joly and Voldoire (2009) show that this influence generally takes place during the developing phase of ENSO events. According to Fig. 2, the equatorial Atlantic and Pacific seem to vary independently, as far as the whole 20th Century is considered. Fig. 6c shows that this does not hold for some specific periods. Atlantic–Pacific correlations are indeed significant over the last decades (about minus 0.5), which corresponds to Atlantic Niño events in boreal summer (JJAS) that precede late-fall ENSO peaks (OND, for October–November–December). The physical processes of such interactions between the Pacific and Atlantic tropical basins are currently under research (Rodrìguez-Fonseca et al. 2009, Wang et al. 2009). In our case, opposite SST anomalies in the equatorial Atlantic
and Pacific are likely to have counteracting effects over the Sahel, which might explain the collapse in the Gulf of Guinea–Sahel relationship for that period. Our hypothesis is that a warm anomaly in the Gulf of Guinea results in a decrease of rainfall over Sahel in the absence of ENSO event (the rainfall dipole revealing a meridional shift of the ITCZ). When this warm anomaly in the Gulf of Guinea coexists with a developing La Niña – as was statistically the case at the end of the 20th Century (Fig. 6c) – the cold anomaly in the equatorial Pacific favors a wet anomaly over the Sahel (Rowell et al. 1992, Janicot et al. 1996, Rowell 2001, Janicot et al. 2001), that counteracts the direct effect of the Gulf of Guinea SST anomaly. Thus, the joint effect of opposite SST anomalies in the equatorial Pacific and Atlantic could be the absence of significant anomalies over the Sahel, at least at the scale of the rainfall seasonal amounts.

Fig. 6c makes eager to study separately the beginning, the middle, and the end of the 20th Century. Fig. 7a therefore repeats the same correlations/regressions as in Fig. 2 for those three periods. Note that the first period is the worst in terms of data quality, so the first diagram is just a rough estimate. Interestingly, the first and the last period exhibit a similar behaviour, with SST anomalies maximum in June in the Gulf of Guinea (orange curve), and correlations with ENSO significant in late autumn (blue curve). For both periods, SST anomalies in the Gulf of Guinea are statistically linked with onsetting ENSO events of the opposite sign. Surprisingly, over the second period, i.e. the middle of the 20th Century, the Atlantic Niño variability is delayed by about 2-3 months, at the end of the monsoon season, and is not significantly correlated with ENSO, as expected.

Fig. 7b illustrates the rainfall response for each of the three periods. It complements Fig. 5, and confirms that the dipolar response of Sahelian rainfall depends on the considered period, rather than on the chosen rainfall dataset.

The opposite fluctuations of the correlations in Fig. 6b and 6c are really intriguing, and might be one clue to understand the response of Sahelian rainfall. However, this hypothesis requires further investigation, along with some physical piece of evidence. This lies beyond the scope of the present study, but is obviously an interesting starting point for further research.
3.3.2 In CMIP3 simulations

Given the lack of realism of the simulated response over West Africa (§ 3.2.2), the issue of the dipolar response of WAM rainfall cannot be addressed directly in CMIP3 simulations. Note however, that in Fig 3 and 4 many models clearly exhibit a dipolar response of the ITCZ, at least over the ocean. This gives credit to the hypothesis of a displacement of the rainbelt during Atlantic Niño events. Unfortunately, such a response of the marine ITCZ cannot be confronted to reanalysis or satellite-derived data, that cover a shorter period, characterized by the co-variability with ENSO diagnosed in Fig. 6c.

Using the CMIP3 database, the length of the simulations and the multimodel approach give us the opportunity to further explore the issue of non-stationarity tackled above. However, since the simulated response of WAM rainfall is hardly comparable to the observed one (§ 3.2.2), only the inter-basin SST co-variability is considered in the following. It has been shown in § 3.1.3 that in five simulations (CNRM-2, CSIRO-1, GFDL, INGV, INM), the Atlantic Niño variability is significantly correlated with decaying ENSO events in the equatorial Pacific (blue curves in Fig. 3 and 4). Those relationships are not comparable to the relationship observed at the end of the 20th Century, between Atlantic Niño events and developing ENSO events of the opposite sign (§3.1.4). In the other simulations, the correlations with ENSO might be significant for some specific periods, as in the observations. Therefore, Fig. 8 displays – for the simulations – the same 31-year running correlations as in Fig. 6c. In order to compare to the observations, the simulations in which the Atlantic Niño is significantly linked to decaying ENSO events are discarded from the analysis. Fig. 8 reveals that negative correlations – as observed at the end of the 20th Century – are present in only two simulations: CCCMAT63 and MIROCmed. Besides, the timing is comparable to the observed one in the sole MIROCmed simulation. This shows that the observed Pacific–Atlantic relationship is hardly reproduced by state-of-the-art coupled models. It may be a special feature of the observational record, perhaps due to natural variability.

3.4 Associated atmospheric anomalies

Given the deficiencies underlined in CMIP3 simulations (§ 3.1.2 and 3.2.2), only reanalysis data is used in this paragraph, to give a brief description of the atmospheric
anomalies associated with the Atlantic Niño. Compared to the numerous studies that focus on some specific years or periods, often using composites, the main interest of this short paragraph is to consider a longer period (at least 44 years), with prior filtering of the low-frequency (§ 2.2.1), and using a linear analysis.

As clearly shown in Fig. 6b, the period covered by current atmospheric reanalyses is characterized by a rapid vanishing of the Gulf of Guinea–Sahel relationship. Therefore, the atmospheric response highlighted with our analysis is only representative of the response of WAM rainfall over the Guinean coast (cf. Fig. 6a).

The Atlantic Niño is a coupled ocean–atmosphere phenomenon (Ruiz-Barradas et al. 2003, Frankignoul and Kestenare 2005, Chang et al. 2006b). In this paragraph, the purpose is to explore the interactions with the WAM system. Therefore, only atmospheric fields are considered. Fig. 9 is based on the same kind of correlation/regression maps as in Fig. 5. *During a warm event*, the atmospheric circulation is strongly modified near the surface. The velocity potential (KHI1000) in Fig. 9a reveals a stronger convergence of the wind in the ITCZ, and the stream-function in Fig. 9b indicates a weakening of trade winds (cyclonic/anticyclonic anomaly in the northern/southern hemisphere).

Over the SST anomaly, the surface air masses are moister (not shown). This enhanced moisture feeds the convection in the ITCZ, and is also advected by the mean flow. Fig. 9c shows that the vertically integrated moisture advection calculated by ERA40 exhibits a westward anomaly that reaches the Guinean Coast. This anomaly is consistent with a weakening of the trade winds, and might explain in part the observed rainfall anomaly in Fig. 5.

Fig. 9 also illustrates the response of the large-scale circulation in the higher levels of the troposphere. There are significant discrepancies between ERA40 and NCEP reanalyses, especially at 600hPa. However, more interesting is the fact that in both reanalyses there is no anomaly of the African Easterly Jet (AEJ) or of the Tropical Easterly Jet (TEJ), over the African continent. This is consistent with the absence of rainfall dipole or ITCZ shift in our analysis. In the reanalyses, and for the considered period, the Atlantic Niño is associated with strong atmospheric anomalies in the low troposphere. The convection over the Guinean coast is at the margin of those anomalies, that are stronger over the ocean. To the first order, the interannual variability of SST in
the Gulf of Guinea seems therefore to act mainly as a “forcing” for the rainfall seasonal amounts over the Guinean Coast. As explained in § 3.3.1, if reanalysis data was available, considering the period 1937–1969 alone would enable a robust study of the processes involved in dipolar response of the WAM over the Sahel.

4. Conclusion

The oceans play a key role in the variability of the tropical climate. The present paper explores the role of the Gulf of Guinea in the interannual variability of the WAM. Our purpose is to take advantage of the CMIP3 database to try to contribute to the understanding of SST–WAM interactions. Besides, it seems important – especially for seasonal forecasting applications – to assess precisely the capability of state-of-the-art coupled models to reproduce such phenomena. Concerning the WAM, most papers focus on the decadal and long-term evolution of Sahelian rainfall (Lau et al. 2006, Biasutti and Giannini 2006, Hoerling et al. 2006, Cook and Vizy 2006). There are fewer studies tackling the issue of the interannual variability of the WAM. In a companion paper, Joly and Voldoire (2009) focus on the remote influence of ENSO. The present paper addresses the regional interaction with the Gulf of Guinea in a set of CMIP3 simulations.

The interannual variability in the Gulf of Guinea is maximum in June–July, because of the Atlantic Niño (also called “zonal mode”). In the atmospheric reanalyses, a warm SST anomaly is associated with a warmer and moister air near the surface, and a strong modification of the large-scale circulation in the low troposphere (Fig. 9), that lead to a strong enhancement of the convection in the ITCZ (Fig. 5). Rainfall seasonal amounts are also affected over the continent, along the Guinean coast, at the margin of the low-layer anomalies.

In most CMIP3 simulations, the interannual variability of SST appears to be too weak in the Gulf of Guinea, especially along the Guinean coast. Besides, the detected modes do not necessarily peak in summer as in the observations. Such a variety in the simulated SST variability leads inevitably to a large variety of rainfall responses. The observed influence on monsoon rainfall over the Guinean coast is hardly reproduced in CMIP3 models. Interestingly, many models exhibit however a dipolar response of the marine ITCZ to the Atlantic Niño. In the observations and reanalyses, this dipolar response of
WAM rainfall is statistically not significant, as far as the *second half of the 20th Century* is considered. For shorter periods, or for some specific years, many authors have found a dipolar response over West Africa, with warm SST anomalies leading to less monsoon rainfall over the Sahel. Fig. 6b shows that this relationship is in fact not stationary over the 20th Century, and disappeared during the last decades. We suggest that this may be due to the counteracting effects of the Pacific and Atlantic basins. At the end of the 20th Century, the Atlantic Niño is indeed correlated with developing ENSO events of the opposite sign (Fig. 6c), that have opposite effects on Sahelian rainfall. Considering the CMIP3 database, in three simulations ENSO has a strong and spurious influence on the variability of the Gulf of Guinea, and in five simulations the simulated Atlantic Niño is correlated to decaying ENSO events. Only one simulation catches the observed evolution of the Pacific–Atlantic relationship, which may thus be due to natural variability (Fig. 8). This discussion on the stationarity of the obtained statistical links confirms the relevance of an analysis at the scale of the whole Century, before studying the stationarity of the detected phenomena, and then studying some shorter periods or specific years. Moreover, our results help to reconcile previous works based on different periods.

Several interesting aspects are not studied in the present paper. To progress in the comprehension of the WAM relationships with the Gulf of Guinea, it would be much interesting to take into account the possible interactions with the intraseasonal timescales. Forthcoming studies should also have a look at the possible non-linearity of those interactions, by studying separately the role of the warm *versus* the cold SST anomalies.

Cook and Vizy (2006) argue that it is necessary to improve the mean state of the simulated WAM in climate models. However, we believe that to improve the interannual variability of the WAM in climate models, more effort has also to be dedicated to the simulation of ENSO and Atlantic Niño variability. Many institutions now use coupled simulations for seasonal forecasting. The faults of the simulated SST–WAM interactions diagnosed in Joly and V oldoire (2009) and in the present paper are therefore to be taken into account, in order to enhance the forecasting skills over West Africa.
For demographic, socio-economic, and climatic reasons, West Africa is probably one of the most vulnerable regions in the world. This has been the case for centuries. However, the climate change and the demographic explosion are likely to endanger the current fragile equilibrium. Any progress in the understanding and forecasting of the African climate is therefore of great importance.

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References


Table captions

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Tables

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