CLIMATE RELATIONSHIPS WITH OCEAN AND ATMOSPHERE - THE EXAMPLE OF THE WEST AFRICAN MONSOON

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ABSTRACT

This paper presents a short review of the most recent papers dealing with the connections and interactions between the ocean and the West African monsoon. We focus first on the annual cycle of the monsoon, then on intra-seasonal variability of the African convection, and at last on the interannual to multi-decadal variability of the monsoon including the global change of climate.

Keywords: African monsoon, atmosphere, climate, ocean, precipitation

INTRODUCTION

Ocean is a fundamental part of the climate dynamics of the Earth, in particular in the Tropics. The most well-known phenomena illustrating this issue is the El Niño event in the Pacific which modifies drastically the atmospheric circulation not only in the Tropics through the coupled ocean-atmosphere ENSO (El Niño / Southern Oscillation) system, but also in mid-latitudes by perturbing atmospheric teleconnection systems like the PNA (Pacific / North America) Oscillation. To illustrate this question, the example of the West African monsoon and its links with the global climate is reviewed here taking into account the most recent results published in international literature.

THE ANNUAL CYCLE OF RAINFALL OVER WEST AFRICA

The mean seasonal cycle of rainfall over West Africa is presented on Fig. 1 through a latitude cross-section. It corresponds to a south-north-south displacement of the Inter-Tropical Convergence Zone (ITCZ), which is not a smooth one but is characterized by a succession of active phases and pauses in the convective activity. These different steps have been identified statistically by Louvet *et al.* (2003). Two of them are located at the time of the first rainy season along the Guinean Coast in April and May, the third one is what is called the “monsoon onset” at the end of June, and a weaker one occurs during the monsoon season in August. The monsoon onset is the strongest one and corresponds to a weakening of the convective activity associated with an abrupt shift to the north of the ITCZ, from 5°N to 10°N (Le Barbé *et al.*, 2002, Sultan and Janicot 2003, Gu and Adler 2004). Over the period 1968-2004, its average date is June 24th, with a standard deviation of 7 days.

The mechanism associated to this abrupt ITCZ shift is still unclear and it is one of the scientific objectives of the AMMA (African Monsoon Multidisciplinary Analysis[1]) project (2005-2007). One hypothesis highlights the role of the Saharan thermal low, which increases at the time of the onset, leading to higher moisture advection inland, and which could be due to some interactions with the North Africa orography (Drobinski *et al.*, 2005) combined with the spatial distribution of albedo and net shortwave radiative budget at the surface (Ramel 2004).

Outside of any forcing from the atmospheric circulation over the land, the coupled air-sea character of the African monsoon is well-known and could regulate the different steps of the ITCZ annual cycle. The annual cycle of the sea surface temperature (SST) in the Gulf of Guinea is asymmetrical with a rapid cooling from the highest SST in April to the lowest SST in August. The fact that SST begins to cool in April, that is at the onset of the first rainy season along the Guinean Coast, is probably not a coincidence. This evolution results from positive feedbacks between the enhancement of the monsoon winds above the Guinea Gulf associated with the convection enhancement in the ITCZ, the set-up of the equatorial upwelling, the extension of the cooling in the southern tropical Atlantic associated with the strengthening

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[1] http://amma.mediasfrance.org/

of the Santa Helena anticyclone and the enhancement of the southern Hadley circulation, and the occurrence of low-level stratus clouds over these cold waters (Okumura and Xie 2004).

This scenario has been examined recently both through new observational datasets and modelling experiments. Gu and Adler (2004) confirmed it by using recent satellite observation of the 1998-2003 high-quality Tropical Rainfall Measuring Mission (TRMM), water vapour and cloud liquid water, TMI SST, and QuikSCAT surface wind products. Okumura and Xie (2004) tested the impact of the SST in the Guinea Gulf on the West African monsoon. They compared in modelling experiments the evolution of the monsoon forced in an atmosphere model by the annual cycle of the SST with this evolution where the annual cycle of the SST is held constant in time from mid-April onward. They showed that the equatorial cooling exerts a significant influence on the African monsoon by intensifying the southerly winds in the Guinea Gulf and pushing the continental rainband inland. This evolution feedbacks positively: first, it contributes to trigger this oceanic cooling in the east; second, easterly winds accelerate in the equatorial Atlantic during northern summer, inducing local upwelling and raising the thermocline in the east, and contributes to the propagation of the cool equatorial SST westward. In a set of experiments, Biasutti *et al.* (2003, 2004, 2005) investigated the mechanisms controlling the annual cycle of the ITCZ over West Africa and the tropical Atlantic by comparing the relative importance of insolation over land and of the SST. As for Okomura and Xie (2004), they compared the evolution of the ITCZ in an atmospheric model between a realistic annual cycle and an annual cycle where SST and/or insolation is held constant in time from March onward. They concluded that West African rainfall is significantly influenced by SST through the advection of marine boundary layer temperature anomalies over Africa which causes the development of sea level pressure and surface wind convergence anomalies. They showed also that the seasonal changes in insolation control the seasonal changes in the net budget of energy input in the atmospheric column, which is balanced by horizontal energy export in the thermally direct circulation associated to convection in the ITCZ. This modulates the moisture flow advection inland and controls the rainfall production over West Africa.

Intra-seasonal variability of rainfall during the northern summer over West Africa

It is shown on Fig. 1 that the annual cycle of the ITCZ is not regular and is characterized by fluctuations at shorter time scales and especially at intra-seasonal time scales, e.g. between 10 and 90 days (Sultan *et al.*, 2003). Grodsky and Carton (2001) investigated the origin of quasi-byweekly disturbances in the surface winds observed over the tropical Atlantic with the QuikSCAT measurements. This oscillation in the wind field is due to the modulation of its zonal component and it is associated with a zonal dipole of rainfall intensity in the ITCZ between the Guinea Gulf and the western Atlantic. They suggested that this quasi-stationary oscillation is controlled by coupled land-atmosphere interactions in the West African monsoon, including a feedback cycle between the monsoon winds and clouds development in the ITCZ, soil moisture and land surface temperature, and the zonal pressure gradient between the land and the ocean. The larger scale context of this oscillation has been described by Mounier and Janicot (2004) through a Principal Component Analysis of outgoing longwave radiation (OLR) satellite measurements signing the activity of the ITCZ. They identified two independent modes of variability of the convection in the area at a time scale of about 15 days. The first one, linked to Grodsky and Carton results, is characterized by a stationary dipole of convection between West/Central Africa and the western equatorial Atlantic, modulating the low-level zonal wind component over the equatorial Atlantic. The second one depicts a meridional dipole of convection over West Africa linked to the modulation of the ITCZ latitude and associated with a westward propagative signal over the Sahel initiated over Central Africa. This second mode is similar to the signal previously identified over the Sahel by Sultan *et al.* (2003).

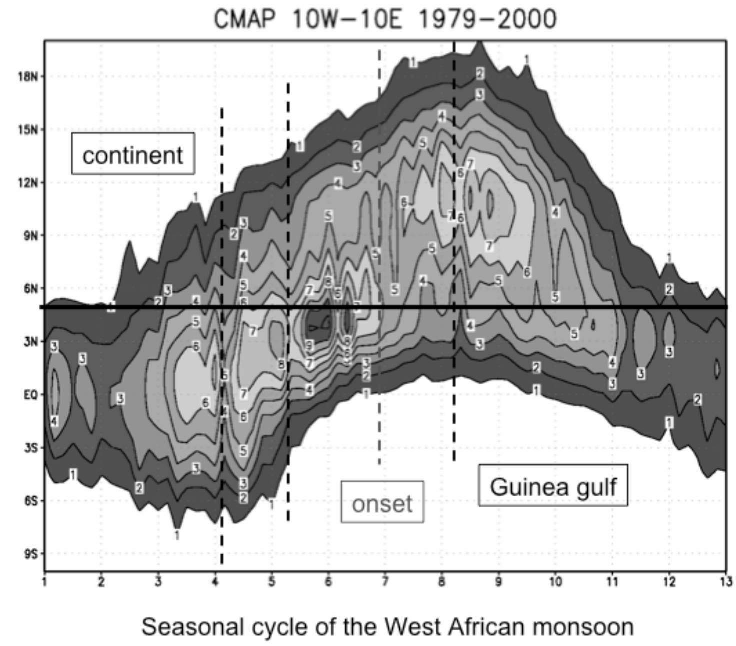

Fig. 1: The mean seasonal cycle of rainfall over West Africa through a latitude cross-section. Precipitation values (mm.day^{-1}) from CMAP dataset are averaged over 10°W-10°E and over the period 1979-2000. The black horizontal line represents the Guinean coast. Vertical lines represent the different steps of the annual cycle, detected through Varimax Principal Component Analysis (Louvet *et al.*, 2003). The red vertical line corresponds to the summer monsoon onset.

At longer time scales, Matthews (2004) highlighted the role of the Madden-Julian Oscillation (MJO) on the convective activity in the African monsoon. About twenty days prior to a maximum of convection over West Africa detected by the first main mode of convective activity at 30-70-day variability, convection is reduced over the equatorial warm pool. An equatorial Kelvin wave response to this change in warm pool convection propagates eastward and an equatorial Rossby wave response propagates westward. These two waves complete a circuit of the equator and meet up 20 days later over Africa, inducing convection enhancement through an increase of the boundary layer monsoon flow and moisture supply.

Interannual variability of rainfall during the northern summer over West Africa

While the annual cycle is the main signal of the African monsoon, interannual and decadal time scales variability of precipitation over West Africa and especially the Sahel is very high and modulates significantly the annual cycle of the monsoon. Fig. 2 shows the well-known time series of rainfall anomalies over the Sahel, updated over the period 1898-20004. While the first part of the XX$^{\text{th}}$ century has been characterized by a succession of short wet and dry periods, the second part of the century has known a very unusual evolution of rainfall with a 20-year wet period followed by another 20-year dry period. Since the 1990's, no more persistence is evident and we see an unorganized occurrence of wet and dry years. This long-term negative trend of rainfall has an amplitude that has not been observed anywhere in the world during this century (see Fig. 3).

A lot of papers have been published since the 1970's to investigate the causes of such a trend. Two main factors have been involved, the evolution of SST at the global scale and the desertification and deforestation at the regional scale of West Africa due to the anthropogenic pressure. In this paper, we describe the most recent results involving the role of the ocean only.

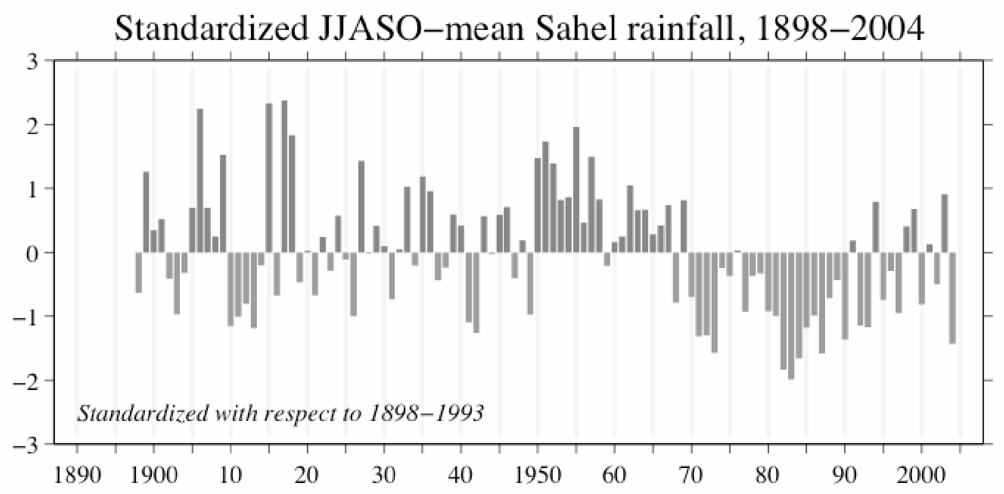

Fig. 2: Standardized mean Sahel rainfall index June-October from 1898 to 2004. From Todd Mitchell; http://tao.atmos.washington.edu/data_sets/sahel/; Joint Institute for the Study of the Atmosphere and Ocean.

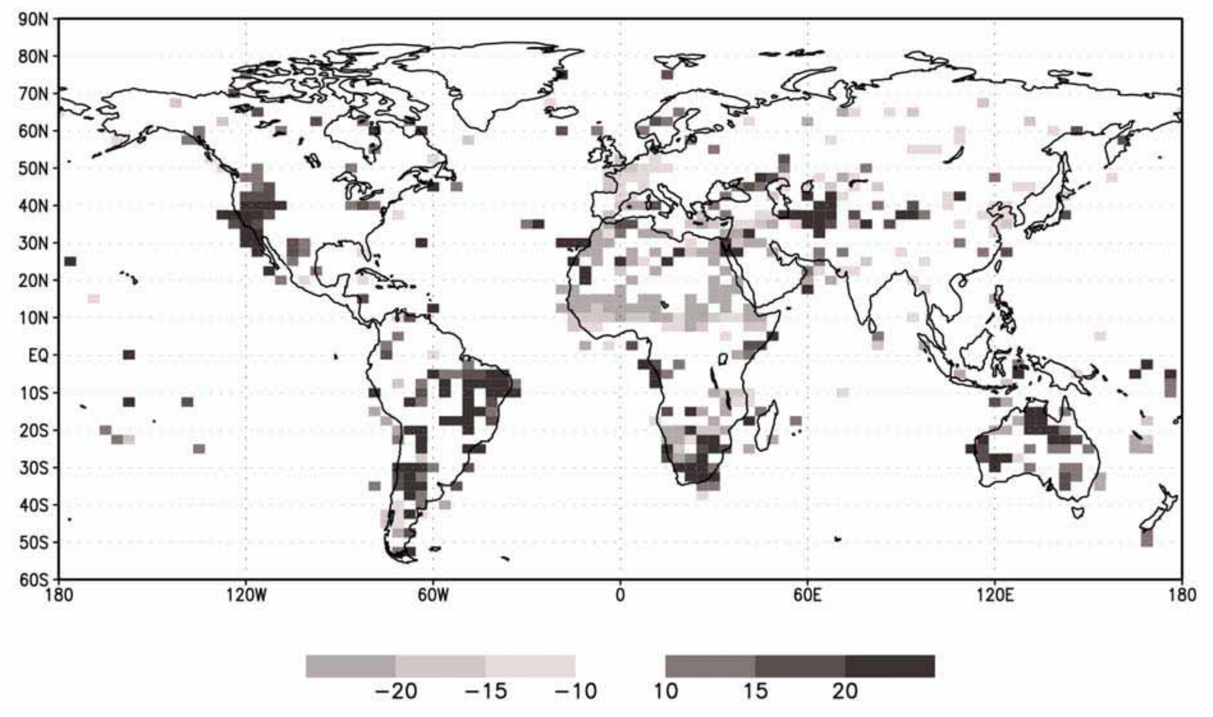

Fig. 3: Mean rainfall differences between the period 1970-1990 and the period 1950-1970 expressed in percentage of the mean over the period 1950-1990. Anomalies lower than 10% in absolute value are not represented.

Fig. 4 shows the four main modes of interannual and decadal time scales variability of SST at the global scale, computed from a Varimax Principal Component Analysis on de-seasonalised SST anomalies over the period 1945-1994. The first mode ("Global Tropical") depicts the El Niño - La Niña occurrences at interannual time scale with the highest weights located in the Pacific and the Indian oceanic basins. We see also on this pattern the effect of El Niño events in weakening the northern Atlantic trade winds and enhancing SST in the western tropical Atlantic. The second mode ("Global Extratropical") has a decadal time scale evolution with a reversal of sign between the period 1945-1973 and the period 1974-1994. The weight pattern is dominated by the Indian oceanic basin and depicts a contrast between the SST anomalies in the Southern oceans and the Northern basins. If these two first modes have a global scale extension, the third ("North Atlantic") and fourth ("South Atlantic") modes are regional ones. They cover respectively the northern and the southern parts of the Atlantic Ocean and show a quasi-decadal time scale variability.

All of these modes show more or less high connection with Sahel rainfall variability. One of the recent key published papers is the work of Giannini *et al.* (2003) examining the oceanic forcing of Sahel rainfall on interannual and interdecadal time scales. Through diagnostic analysis and an ensemble of integrations of an atmospheric model forced only by observed SST over the period 1930-2000, they show that variability of rainfall in the Sahel results from the response of the African monsoon to oceanic forcing, amplified by land-atmosphere interaction. In particular the decadal scale drying trend in the Sahel is attributed to warmer-than-average low-latitude water around Africa, and especially in the Indian oceanic basin. This impact of this global SST mode including the Indian Ocean on decadal-scale Sahelian rainfall was also found by Janicot *et al.* (2001), and Bader and Latif (2003), and Chelliah and Bell (2004) showed its impact on the global atmospheric circulation in the Tropics.

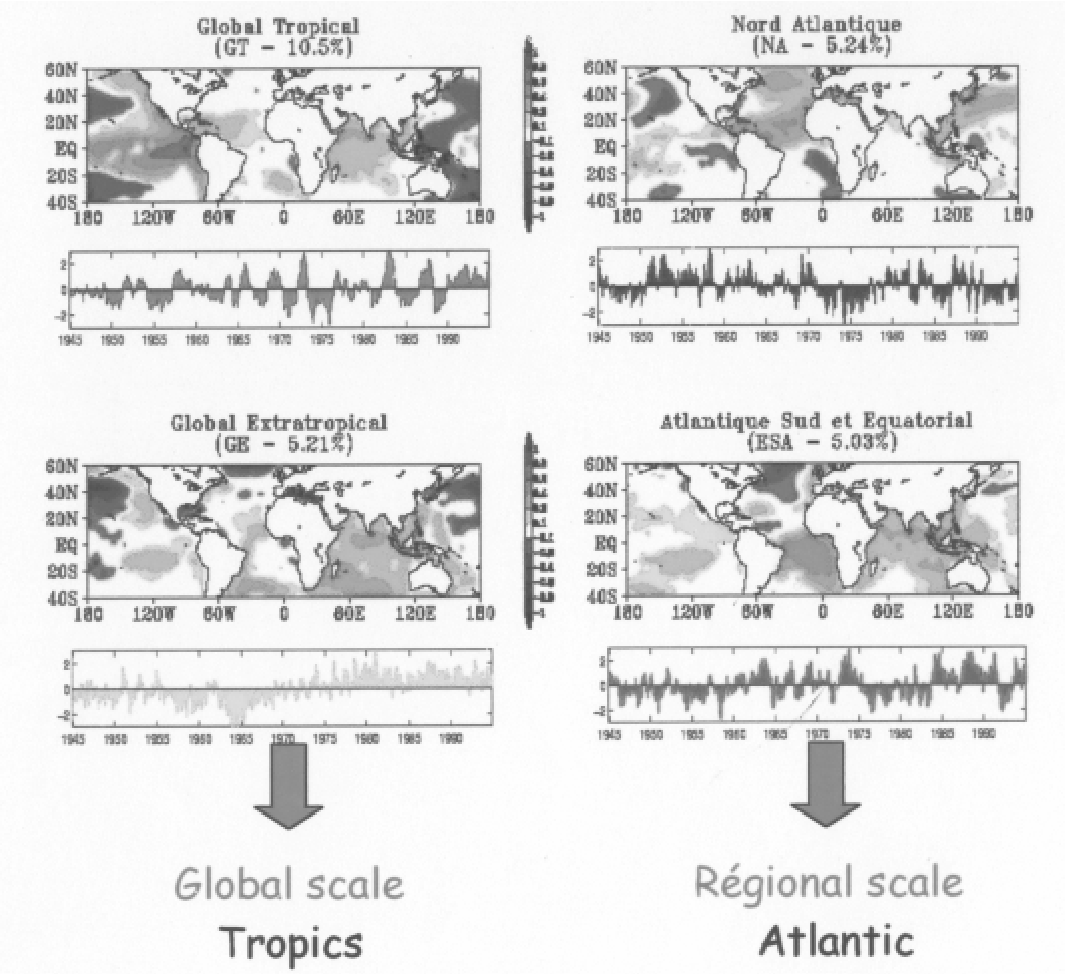

Fig. 4: Varimax Principal Component Analysis of the sea surface temperatures anomalies from 1945 to 1994 (provided by Centre de Recherches de Climatologie, Univ. Dijon). The four main modes are presented through their spatial pattern and time series. See details in the text.

At the interannual time scale, the impact of El Niño events of Sahel drought has been described in several papers including for the most recent ones Rowell (2001), Janicot *et al.* (2001), Giannini *et al.* (2003). Rowell (2001) examined in details the mechanisms of this atmospheric teleconnection between the Pacific Ocean and Africa. He demonstrated, as for the mechanism linking MJO and African convection variability (Matthews 2004), the role of the development of equatorial eastward propagating Kelvin wave from east Pacific convective heating anomalies, and westward propagating Rossby waves from the Indian Ocean in response to the anomalous west Pacific–Indian Ocean SST gradients via convective heating anomalies over the Indian Ocean. These interact over Africa to enhance large-scale subsidence over the Sahel and reduce seasonal rainfall totals. Janicot *et al.* (2001) showed that this Sahel–El Niño teleconnection has not been strong during the whole second part of the last century but has been significantly modulated by the decadal time scale SST anomaly pattern during this period. The long-term warming of the global SST mode, not only favours the long-term drying over the Sahel, but helps also to enhance the atmospheric teleconnection pattern linking El Niño events to Sahel rainfall deficits after 1980, through a fill-in of the monsoon trough and a moisture advection deficit over West Africa.

West African monsoon and ocean are also linked at the regional scale. It is well-known that warming events in the Guinea Gulf are associated with a southward location of the ITCZ and higher (lower) seasonal rainfall amounts over the Guinea Coast (Sahel) during the summer monsoon season. This is due in part to the reduced meridional gradient of temperature between the Guinea Gulf and West Africa. Vizy and Cook (2001) showed also that such an event enhances evaporation, and that the southerly flow across the Guinean Coast carries more moisture inland. This leads to increased precipitation south from the usual latitude of the ITCZ. This was confirmed by Bader and Latif (2003), among others. This scenario associates frequently a meridional anomaly of the ITCZ latitude to a rainfall dipole over West Africa between the Guinea Coast and the Sahel, and to the occurrence of what is called the “tropical Atlantic dipole” combining SST anomalies of one sign in the northern tropical Atlantic with SST anomalies of opposite sign in the equatorial and southern tropical Atlantic. It occurred very often before 1970, but after that, the rainfall dipole over West Africa has been less frequent and the Pacific-Indian ocean forcing has become more and more dominant (Janicot *et al.*, 2001).

Another ocean–African monsoon relationship at the regional scale concerns the role of the SST anomalies in the Mediterranean Sea. Rowell (2003) explored this teleconnection by forcing an atmospheric model in northern summer with idealized SST anomalies in this basin (positive (negative) anomalies up (down) to 2°C) with climatological SST elsewhere. This experiment shows that positive Mediterranean SST anomalies leads to a wetter Sahel : local evaporation enhances over this basin, increasing the moisture content in the lower troposphere; this additional moisture is advected southward across the eastern Sahara by the mean flow, leading to enhanced low-level moisture convergence over the Sahel which feeds enhanced rainfall. Then positive feedbacks between convection and the local atmospheric circulation help to extend this anomaly. Raicich *et al.* (2003) showed that Sahel rainfall is sensitive to sea level pressure anomalies over the Mediterranean Sea and especially to a zonal pressure dipole at these latitudes which is modulated in part by the activity of the Indian monsoon.

Scenarios of the climate change impact on the West African monsoon

Simulations of the climate change impact on the West African monsoon must be considered with great cautious. Such scenarios are based on integrations of ensembles of coupled ocean-atmosphere climate models combined with projections of various socio-economical developments. At the global scale, uncertainties come for an equal part from weaknesses of the models and incomplete knowledge of the future economical orientation. At the regional scale, uncertainties are larger, due in particular to the non-capability of the models to simulate accurately the small-scale processes. Another problem, specific to the simulation of the West African monsoon, is the existence of a warm bias in the SST of the eastern oceanic basins in the coupled models. This is true for the eastern part of the southern tropical and equatorial Atlantic, which induces a weaker than normal African monsoon as we have seen above. It is however possible to analyse such scenarios after having eliminated this permanent bias.

The scenarios which have been produced for the Third Report of the Intergovernmental Panel on Climate Change (IPCC) in 2001 do not provide a coherent response for West Africa and the Sahel region, even if they go in average towards a slight increase of rainfall and of the water cycle of the African monsoon. Available new simulations seem to confirm this scenario with a northward shift of the Sahara in a number of models (Liu *et al.*, 2002). For instance, Maynard *et al.* (2002) showed with a transient climate simulation of 150 years increased monsoon rainfall over West Africa at the end of the XXIst century with an enhancement of the atmospheric water cycle. The main factors explaining this evolution are the relative increase of the moisture content and atmospheric moisture transport, greater than the rainfall and evaporation relative increases, which means a weaker atmospheric water recycling. Work is presently going on towards the next publication of the fourth report of IPCC.

Conclusion

This paper has presented a short review of the most recent papers dealing with the connections and interactions between the ocean and the West African monsoon. More work is necessary to better understand the teleconnection mechanisms and the degree of coupling between the ocean and the atmosphere. Available ocean-atmosphere coupled models show significant interactions between the African monsoon system, the air-sea fluxes and the oceanic circulation (see for instance Zhao *et al.*, 2005). However these models must to be improved to eliminate their biases, particularly important in the equatorial and southern tropical Atlantic, and which limits the confidence that we can have on their results.

Ocean is not the only factor explaining the African monsoon variability from intra-seasonal to multi-decadal time scales. Another crucial factor is the interactions with the land surface processes and the role played by the soil moisture and the vegetation (see for instance Douville 2002, Philippon and Fontaine 2002). However in-situ data are very few to quantify these processes and evaluate the results produced by the climate models. This is one of the objectives of the AMMA project which is implementing in West Africa over two and three seasonal cycles a network of flux stations measuring the radiative budget at the surface, sensible and latent heat fluxes, and soil moisture profiles.

Statistical schemes of seasonal forecast of summer Sahel rainfall totals work well when they integrate both oceanic and derived land surface information (Fontaine *et al.*, 1999), as well as statistico-dynamical models predicting atmospheric indexes closely linked to the monsoon intensity rather than rainfall (Garric *et al.*, 2002). However forecasts from climate models do not work as well over West Africa, and to monitor and forecast monsoon variability in the changing climate where we live now, a high quality of these tools will be absolutely necessary.

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