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The West African dipole in rainfall and its forcing mechanisms in global and regional climate models

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सार – पश्चिमी अफ्रीका में 20वीं शताब्दी के वर्षा परिर्वतन की वढ़ती हुई अवस्था साहेल और गाइना तटीय क्षेत्र में 1960 के दशक में और उससे आगे के वर्षों में सूखे की प्रवृति को सुयोजित रूप से प्रस्तुत करती है । 1970 और 1998 के बीच एस. एच. जेड. से और अधिक भीषण सूखे की स्थितियों के साथ संबद्ध होते हुए जी. सी. आर. में सकारात्मक वर्षा की असमानताओं के साथ आगे बताई गई तीनों प्रणालियों साहेल क्षेत्र (एस. एच. जेड.) और दक्षिण की ओर गाइना तटीय क्षेत्र (जी. सी. आर.) के बीच आउट ऑफ फेज संबंध को बताती है । पश्चिमी अफ्रीका का यह वर्षण का द्विध्रुव हाल ही के दशकों में समूचे उपसहारा क्षेत्र में अभिगमन की प्रक्रियाओं से सुसंबद्ध है ।

दीर्घ अवधि प्रेक्षणात्मक आंकड़ा और भूमंडलीय जलवायु निदर्श आउट पुट में डब्ल्यू. डी. आर. समान रूप से पाए गए हैं । इसमें प्रति सहसंबद्धता की स्पष्ट माप निर्भरता देखी गई है । निम्न आवृति परिसर में जी. सी. आर. से एस.एच.जेड. वर्षा के परिवर्तन वियुग्मित किए जा रहे हैं । यह पाया गया है कि अन्तः वार्षिक डब्ल्यू. डी. आर. के उतार चढ़ाव अटलांटिक महासागर और विशेष रूप से गाइना की खाड़ी में समुद्र सतह तापमपन (एस. एस. टी.) से काफी जुड़े हुए हैं । मृदा नमी का द्विध्रुव असमानताओं के प्रणोदन में महत्वपूर्ण योगदान नहीं है ।

क्षेत्रीय जलवायु निदर्श के साथ सुग्रह्य अध्ययन उष्णकटिबंधीय अटलांटिक एस. एस. टी. और डब्ल्यू. डी. आर. के बीच भौतिक सम्पर्क को प्रभावित करता है । एस. एस. टी. को बदलने वाली वर्षा की अनुकरित प्रतिक्रिया अरैखिक है और दीर्घ अवधि प्रेक्षण की तरह ही समान श्रेणी में है एस. एस. टी. का प्रभाव कुल वर्षा की विभिन्नता का 40 प्रतिशत तक रहता है, विशेष रूप से पश्चिमी अफ्रीका के सुदूर दक्षिणी भागों, और यह दिन प्रति दिन की विभिन्नताओं के संबंध में 1 प्रतिशत के स्तर पर सांख्यिकीय रूप से महत्वपूर्ण है। ग्रीन हाउस गैसों (जी. एच. जी.) के संकेतों के तहत भूमंडलीय जलवायु निदर्श प्रयोगों से लिए गए 21वीं शताब्दी के उत्त्रार्ध में निर्धारित उष्म उष्णकटिबंधीय अटलांटिक एस. एस. टी. से जी. सी. आर. (लगभग +300 मि.मी. के आसपास) में वर्षा की मात्रा में वृद्धि और जुलाई–अगस्त की वर्षा की ऋतु के दौरान एस. एच. जेड. (लगभग –150 मि.मी.) में ताजे जल की आपूर्ति में कमी हुई है । इस प्रकार वर्षा की मात्रा में एस. एच. जेड. – जी. सी. आर. की विषमता में भविष्य में वृद्धि हो सकती है जो पश्चिम अफ्रीका के सम्पूर्ण उप सहारा क्षेत्र में पहले से चल रहे उत्तर से दक्षिण की ओर स्थानांतरण को प्रभावित कर सकती हैं ।

ABSTRACT. The leading mode of 20th century West African rainfall variability represents a well-documented drought tendency in the Sahel and the Guinea Coast region from the 1960s onward. The following three modes describe an out-of-phase relationship between the Sahel Zone (SHZ) and the Guinea Coast region (GCR) to the south, with positive rainfall anomalies in GCR being associated with even more severe drought conditions in SHZ between 1970 and 1998. This West African dipole in rainfall (WDR) has been of high relevance to migration processes in recent decades over the entire subsaharan region.

WDR is equally revealed in long-term observational data and global climate model output. There is a clear scale-dependence of the anticorrelation, SHZ rainfall changes being decoupled from GCR ones in the low-frequency range. It is found that the high pass filtered interannual WDR fluctuations are closely tied to Atlantic sea surface temperatures (SSTs), particularly in the Gulf of Guinea. Soil moisture is not a dominant player in forcing the dipole anomalies.

Sensitivity studies with a regional climate model support the physical link between tropical Atlantic SST and WDR. The simulated rainfall response to changing SST is non-linear and in the same order of magnitude as in the long-term observations. The SST impact accounts for up to 40% of total rainfall variability, particularly over the southernmost part of West Africa, and is statistically significant at the 1% level even with respect to the remarkable day-to-day variations. Prescribing late 21st century warmer tropical Atlantic SST as derived from global climate model experiments under increasing greenhouse gas (GHG) concentrations, leads to increasing rainfall amount in GCR (around+300mm) and a reduction in freshwater supply in SHZ (around -150mm) during the July-August main rainy season. Thus, the SHZ-GCR contrast in rainfall amount may rise in the future, inducing ongoing north-to-south migrations in whole subsaharan West Africa.

Key words – West African rainfall, Sahel zone, Guinea coast region, West African dipole.

1. Introduction

One of the most prominent long-term features in 20th century climate probably is the multi-decadal drought period in the subsaharan part of West Africa (Nicholson *et al.* 2000). Particularly, the SHZ has experienced a substantial drying tendency since 1960 with the 1980s being the dryest years of the entire century (Nicholson 1993). This large-scale climate anomaly extended far south to the Gulf of Guinea, albeit of less amplitude (Le Barbe *et al.* 2002; Paeth and Hense 2003a), and caused severe socio-economic implications in West African countries (Benson and Clay 1998).

Less attention has been paid to the regional heterogeneity of rainfall patterns in this highly sensitive region. Nicholson and Palao (1993) have defined the basic pattern of sub-Saharan rainfall variability and pointed to an out-of-phase relationship between the SHZ, covering the 12° N to 22° N sector, and the GCR to the south. This dipole behaviour of West African rainfall has also been reported in relation to El Niño-Southern Oscillation (Saravanan and Chang 2000; Camberlin *et al.*, 2001; Janicot *et al.*, 2001; Paeth and Hense 2003b). The regional dipole in rainfall anomalies represents much more than a climatological characteristic since it is assumed to be responsible for large-scale migration processes in West Africa, when persisting over several years or even decades. Demographic studies have shown that most West African countries observe a general migration tendency from the northern SHZ to the coastal area (Findley 1994). It is hypothesized that mechanisms, forcing the SHZ-GCR contrast in rainfall amount, are partly counteracting the processes, responsible for the general drought tendency in subsaharan West Africa (Mo *et al.*, 2001), hence, mitigating the negative precipitation trend in GCR but amplifying it in SHZ.

Understanding the driving mechanisms and future trend of WDR is of crucial importance to political measurements and plannings. Many studies have revealed that subsaharan rainfall is largely affected by SST, partly in the tropical Pacific basin (Camberlin *et al.*, 2001; Janicot *et al.*, 2001) and mainly in the tropical Atlantic (Chang *et al.*, 2000; Ruiz-Barradas *et al.*, 2000; Nicholson 2001; Paeth and Hense 2003a,b). Vizy and Cook (2001) have suggested a physical mechanism how a tropical Atlantic heat source may affect West African rainfall amount and strengthen the regional contrast between SHZ and GCR. The link is based on a linear atmospheric Kelvin and Rossby wave response to tropical oceanic heating, according to the Gill model (Bretherton and Sobel, 2003). Whereas GCR is much more tied to SST, the SHZ has been shown to be very sensitive to changes in land surface properties in terms of vegetation cover, albedo and soil moisture (Clark *et al.*, 2001; Douville *et al.*, 2001; Semazzi and Song, 2001). Several studies agree in considering SST as a primary source of sub-Saharan rainfall variations which are amplified and temporally extended by interaction with the land surface, predominantly vegetation cover (Zeng *et al.*, 1999; Long *et al.*, 2000; Wang and Eltahir, 2000; Nicholson, 2001). This particularly holds for SHZ, where slow vegetation changes, either in response to atmospheric forcing or anthropogenic activity, imply the largest persistence of climate anomalies on the whole continent (Long *et al.*, 2000). Soil moisture is also supposed to play a major role in determining the amount and distribution of West African precipitation by enhancing the thermal gradient as a crucial factor in the monsoon system (Cook 1999; Saha and Saha 2001; Fontaine *et al.*, 2002). Extratropical climate is of minor relevance to rainfall variability in tropical West Africa (Paeth and Hense 2003b). However, North Atlantic and Mediterranean SSTs seem to contribute to the low-frequency variations of Sahelian precipitation (Los *et al.*, 2001; Rowell 2003).

Given this prior knowledge of WDR, the present study is dedicated to access the importance of WDR in the context of West African rainfall variability and to cast some light on its forcing factors. The space-time characteristics of WDR are derived from the Climatic Research Unit (CRU) observational data set (New *et al.*, 2000). Furthermore, it is examined whether global and regional climate models are able to simulate the anticorrelation between SHZ and GCR rainfall in response to these forcing factors. This is a fundamental issue as climate models hold the prospect of prescribing scenarios of climate change in order to evaluate the sensitivity of WDR, as a crucial trigger of future migration processes, to global warming. Global climate models make us believe that West African rainfall may increase under enhanced greenhouse conditions (Houghton *et al.*, 2001; Hulme *et al.*, 2001; Paeth and Hense 2003a) but little is known of the regional aspect of this signal. Therefore, the global climate model ECHAM4 (Roeckner *et al.*, 1996) and regional climate model REMO (Jacob 2001; Jacob *et al.*, 2001) are used to address these aspects at different time and spatial scales. Particularly, the dynamical downscaling approach with REMO represents an extension of an earlier work by Vizy and Cook (2002), incorporating more case and sensitivity experiments and providing more insight into the nature of the WDR response at the regional scale. Thus, the present study is consistent with the scientific demand for more intense global and regional modeling attempts in the context of climate change over Africa as pointed out by Desanker and Justice (2001) and Jenkins *et al.*, (2002).

The following section gives a short description of the considered observational and model data sets. Section 3 presents the results with respect to various data sets and in section 4, the main conclusions from this analysis are drawn.

2. Data sets

As reanalysis products have been shown to have major deficiencies in the tropics with respect to temperature (Trenberth *et al.*, 2001) and rainfall (Lim and Ho 2000), real-climate precipitation variability over West Africa is derived from the CRU data set (New *et al.*, 2000). This data set is based on a statistical interpolation approach, incorporating all available observational data. It is covering the land surfaces except Antarctica with a regular 0.5° grid. We use monthly-mean data over the period 1901 to 1998, averaged to seasonal means over June to September as these months account for about 70% of total annual rainfall amount in subsaharan West Africa (Paeth and Hense 2003b). Poccard *et al.*, (2000) have compared NCEP reanalyses with the CRU data and concluded that the latter provides a more realistic description of rainfall patterns in West Africa.

Global climate model simulations are derived from the ECHAM4 - T42 atmospheric general circulation model (GCM) (Roeckner *et al.*, 1996). An ensemble of 6 experiments over the period 1903 to 1994 is considered, starting from different atmospheric initial conditions. The lower boundary conditions are prescribed by, observed SST and sea ice extent (GISST 2.2, Parker and Jackson 1995). In addition, increasing GHG concentrations are prescribed as observed during the 20^{th} century. The spectral T42 resolution roughly corresponds to a 2.8125° Gaussian grid. This model is found to reproduce West African rainfall patterns and variability in a reasonable way (Paeth and Hense 2003a). However, the intertropical convergence zone (ITCZ) migrates too far north and produces too much rain in SHZ, which is likely due to the missing feedback with vegetation cover and surface albedo (Zeng and Neelin 2000; Schnitzler *et al.*, 2001). Assuming that the West African monsoon system is largely affected by SST and the ECHAM4 model is reliable, this SST-forced ensemble is supposed to capture the WDR-SST relationship and to simulate WDR dynamics partly in-phase with the observations.

The dynamical downscaling is managed with the hydrostatic regional model REMO (Jacob 2001; Jacob *et al.*, 2001; Paeth *et al.*, 2003). It has been developed at the Max Planck Institute for Meteorology on the basis of the former operational weather forecast model Europa-Modell of the German Weather Service (Majewski, 1991). The dynamics is based on primitive equations with temperature, circulation, surface pressure, water vapour and cloud water content as prognostic variables. Moist convection is parameterized by the Tiedtke mass flux scheme (Tiedtke 1989). In order to account for the specific stability conditions in the West African monsoon circulation, the original Tiedtke convection scheme has been slightly modified. The lower threshold of cloud thickness, which allows the generation of rainfall, has been set to 1500 m instead of 3000 m. Soil processes are simulated by a 5-layer soil model down to 10 m depth. In the present study, REMO is run with 20 hybrid vertical levels in a horizontal 0.5° resolution, covering the northern and central part of Africa, the Mediterranean, the southern part of Europe and the Arabic Peninsula within the sector 30° W to 60° E and 15° S to 45° N. SST and lateral boundary conditions are prescribed by the global ECMWF reanalyses (ERA15, Gibson *et al.*, 1997), forcing the model every 6 hours. Note that the model is not nudged within the model terrain. Land surface characteristics like orography, vegetation, albedo and soil properties are taken from GTOPO30 and NOAA satellite data. Vegetation cover and albedo are linearily interpolated from monthly means to daily values. This idealized annual cycle is the same in every simulation year. Thus, interannual land cover changes are not taken into account.

In a former study, REMO has been validated with respect to various observational data sets (Paeth *et al.*, 2003). It turned out, that the model has remarkable skill in reproducing the complex dynamics of the West African monsoon and the tropospheric jet streams. Rainfall patterns also appeared to be realistic. The basic model deficiency consists of an under estimation of sub-sahelian rainfall amount. Instead, precipitation off the coasts of tropical Africa clearly exceeds the observed magnitude. Both features are likely due to the grid box presentation of orography and the missing feedback with land cover (Schnitzler *et al.*, 2001). Anyhow, this misjudgement is systematic and rainfall distribution as well as interannual

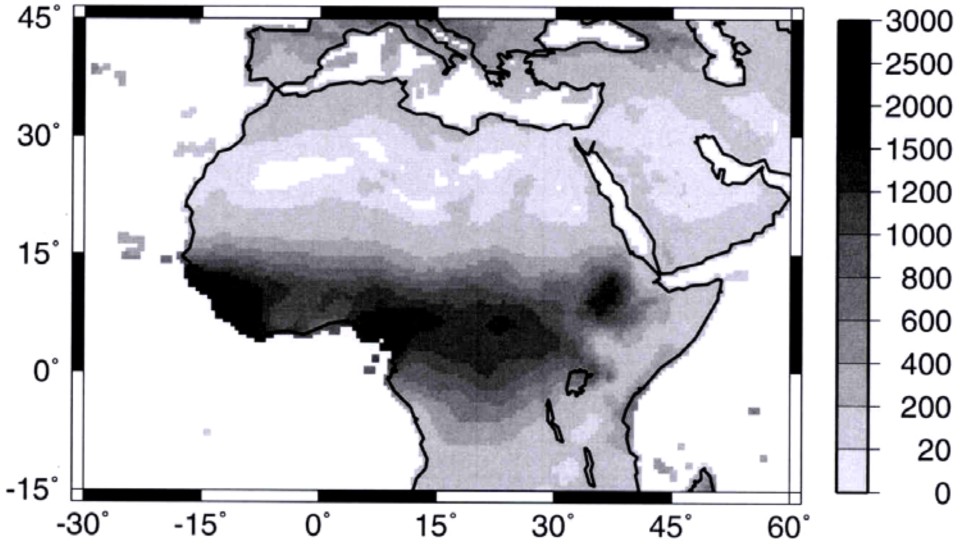


Fig. 1. Long-term mean pattern of observed annual rainfall in the African sector in mm, CRU data set 1901-98

variability are close to real climate. Thus, sensitivity studies with REMO are assumed to provide reliable insight into the relative WDR changes with respect to a specific forcing.

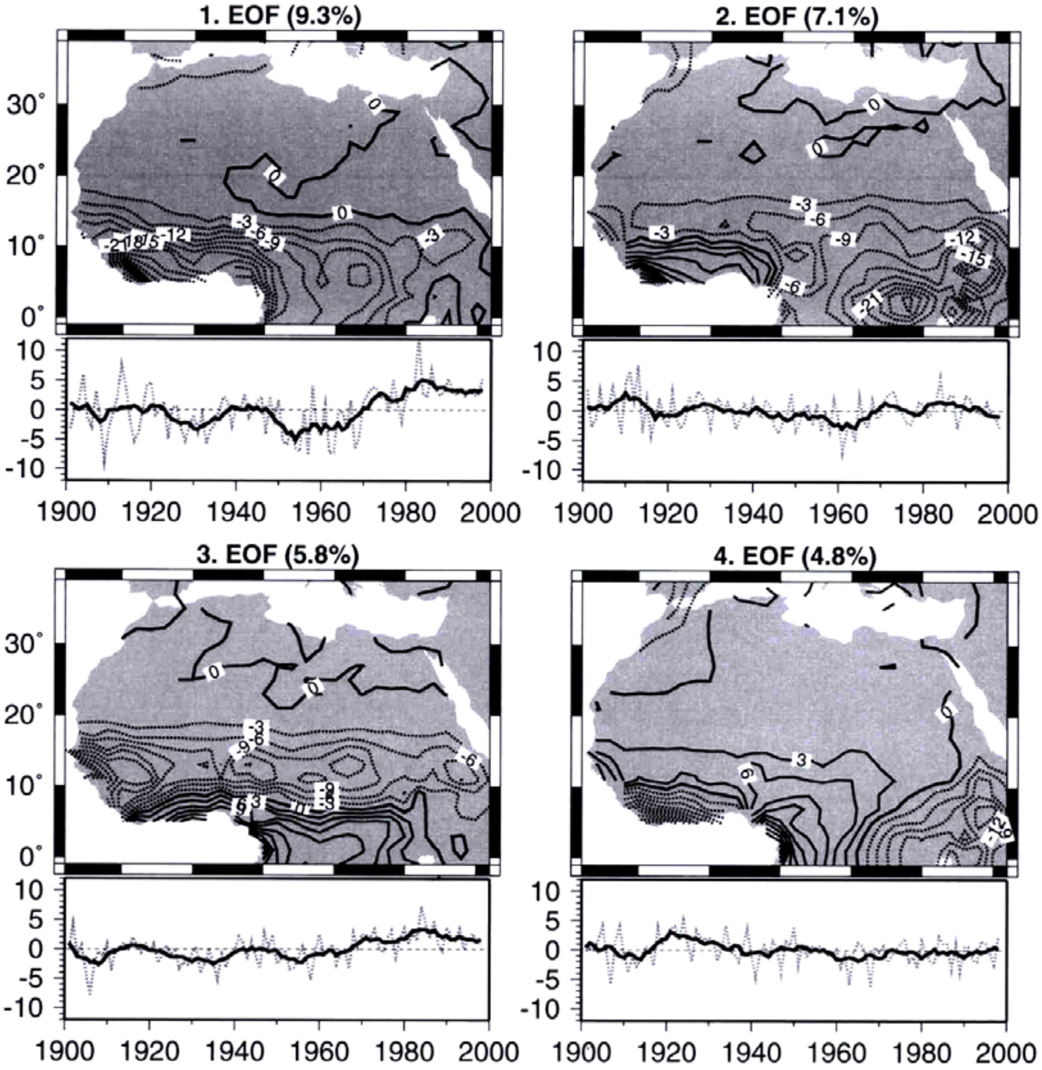
Two kinds of REMO experiments are realized: (*i*) An idealized SST forcing is imposed as lower oceanic boundary condition, systemically changing the SST by a constant factor over a predefined oceanic region. (*ii*) REMO is forced with realistic SST changes as expected from global climate model predictions into the 21st century. For this purpose, a coupled version of the ECHAM4 is taken into account, involving the OPYC ocean model. An empirical orthogonal function (EOF) analysis is applied to extract the basic patterns of the SST response to increasing GHG concentrations. The difference pattern between late 21st century and mean 20th century SST is superimposed on the present-day SST pattern. The resulting SST field is finally used to force the REMO atmosphere in order to detect the changes in rainfall induced by GHG-induced SST. As it will be shown that the WDR-SST relationship is already prevailing at quite short time scales, the REMO experiments only cover July and August, representing the main period during the subsaharan rainy season (Paeth and Hense 2003b). The simulations with realistic SST forcing are applied to July and August in 1987, 1988 and 1990. While 1988 was characterized by abundant rainfall in southern West Africa and 1987 was rather consistent with the long-term mean, 1990 was abnormally dry (Paeth *et al*., 2003). This multi-year approach holds the prospect of evaluating whether substantial changes in the lateral boundary conditions may secondarily affect the WDR-SST relationship.

3. Results

3.1. *Observations and global climate model data*

The observed rainfall climatology over Africa reveals a prominent gradient in precipitation amount from the tropics to the subtropical latitudes with almost 3000 mm/year in Guinea and in the vicinity of the Cameroons Mountain and less than 400 mm/year in the central SHZ (Fig. 1). North of the Sahara rainfall rises from south to north, reaching up to 800 mm over southern Europe. This pattern derived from the CRU data set is in excellent agreement with Saha and Saha (2001). It basically reflects the remarkable climatological gradients in freshwater availability between GCR and SHZ.

The leading patterns of West African rainfall variability are inferred from EOF analysis based on observed monthly values of total precipitation during the 20th century (Fig. 2). The long-term mean seasonal cycle has been removed. The first EOF accounts for no more than 9.3% of total variance (top left panel). The pattern describes more or less homogenous anomalies over entire West Africa with the amplitude decreasing from GCR to SHZ. This gradient reflects the higher amplitude of the


1. EOF (9.3%)

2. EOF (7.1%)

3. EOF (5.8%)

4. EOF (4.8%)

Fig. 2. Leading 4 EOF patterns and principal components of monthly-mean rainfall over West Africa, the mean annual cycle being removed, CRU observational data 1901-98. The numbers in brackets denote the explained variance by the respective EOF. The contour interval is 3 hPa

year-to-year fluctuations of GCR rainfall compared with SHZ. However, the variational coefficient, which is the ratio between standard deviation and mean, has been found to be higher in SHZ (Paeth and Hense 2003a), implying that a smaller rainfall change over SHZ might be more severe than a larger one over GCR. The corresponding principal component (PC) time series reveals a negative rainfall trend from the 1960s onward. Thus, the first EOF is representative of the famous drought tendency over the entire sub-saharan part of West Africa (Nicholson *et al*., 2000). EOFs 2-4 describe more heterogeneous rainfall anomalies with an anticorrelation between GCR and SHZ precipitation. Although the EOFs are orthogonal in terms of the entire region, this dipole is a common feature to EOFs 2-4, together accounting for almost 18% of total variance. The PC 2 and 3 time series indicate mainly positive anomalies of the north-south gradient since the late 1960s, partly compensating the long-term decreasing trend over GCR from EOF 1. On the other hand, EOFs 1-3 altogether contribute to a substantial reduction in rainfall amount over SHZ, especially in the 1980s which were found to be the dryest decade during the instrumental period (Nicholson and Palao 1993). In terms of the amplitude the strongest 20th century rainfall anomaly is related to EOF 1, representing a spatially homogenous drying tendency over subsaharan West

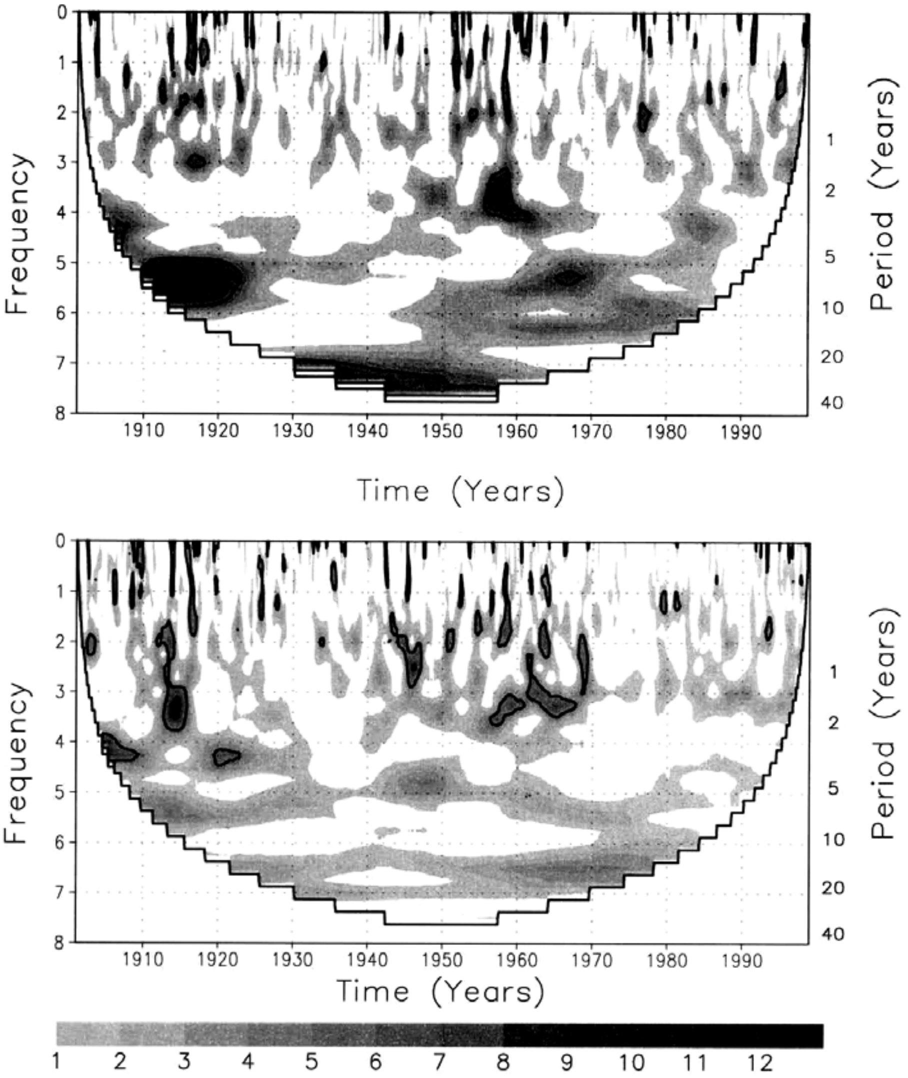


Fig. 3. Morlet wavelet power spectrum of PC 1 (top) and PC 2 (bottom) as displayed in Fig. 1, CRU monthly means 1901-98. Values of covariance < 1 are masked out, values significant at the 5% level are marked in bold outline

Africa. In addition, there must be a mechanism which induces a contrary behaviour of GCR and SHZ rainfall fluctuations. During the second half of the 20th century this mechanism has been responsible for a further deterioration of life conditions in SHZ while the coastal region could partly profit by its compensating effect. Assuming that such regional discrepancies in low-frequency rainfall changes are associated with migration processes (Findley 1994), the dipole structure is of large socio-economic relevance.

Fig. 3 indicates that the wavelet spectrum of the PC 1 time series (top panel) reveals some low-frequency components even at the interdecadal time scale whereas PC 2 is subject to fluctuations in the interannual and shorter-scale range. The long-term component in EOF l is associated with the multi-decadal drought tendency over entire West Africa. The wavelet spectrum of EOF 2, which, among others, is representative of the WDR pattern, implies that the contrary behaviour of GCR and SHZ rainfall arises from a mechanism which is active at quite short time scales from intraseasonal to interannual.

A more direct way to display the WDR behaviour is a point-wise correlation with respect to a data grid point in

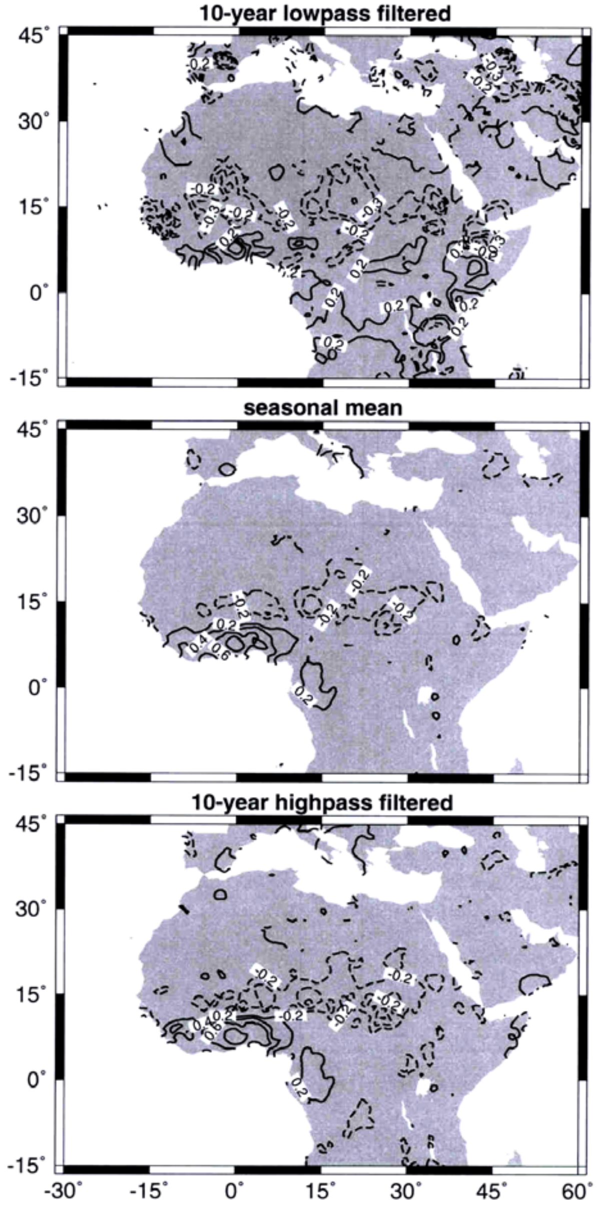


Fig. 4. Correlation patterns of central Ghana rainfall with all remaining grid boxes, based on different time scales, CRU observational data 1901-98. Plotted are only correlation coefficients |> 0.2| which are statistically significant at the 5% level with respect to the seasonal-mean values. The contour interval is 0.2 (0.1) for positive (negative) coefficients

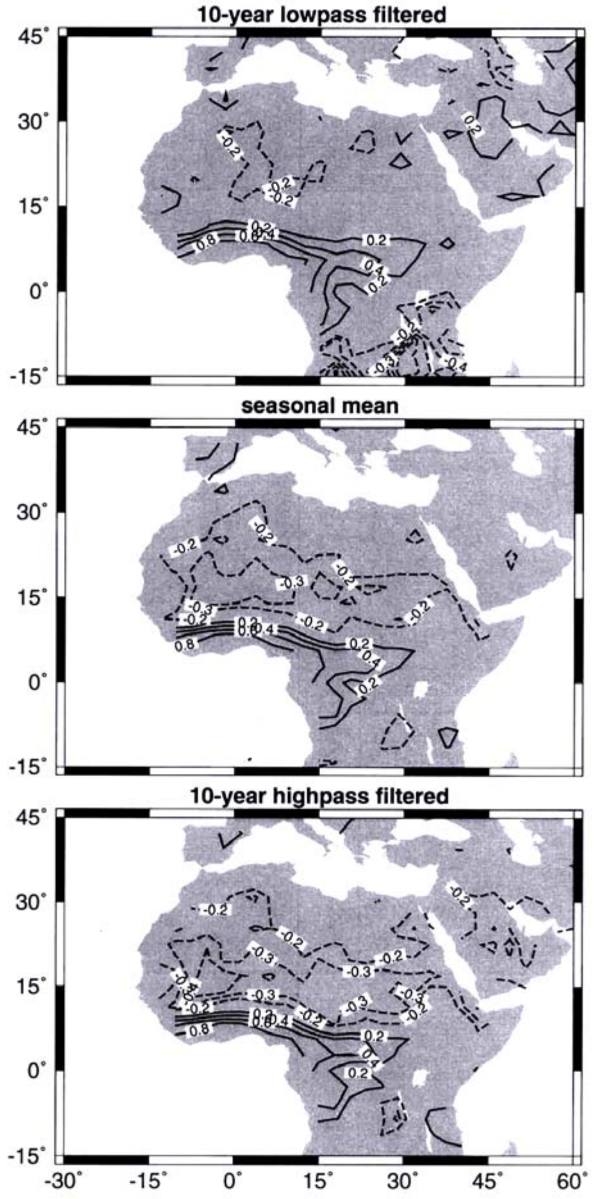


Fig. 5. Same as Fig. 3 but for the ECHAM4 6-member ensemble mean 1903-94

central Ghana (1° W, 8° N). Fig. 4 shows the correlation patterns as derived from the CRU observational data set. In order to gain insight into the time-scale dependence of the GCR-SHZ relationship, the June-to-September seasonal-mean time series (middle panel) are once running-mean lowpass filtered, removing all time scales upto 10 years (top panel), and once highpass filtered, eliminating the low-frequency variations longer than 10 years (bottom panel). At first glance, negative correlations between a southern region from the Guinea Coast to 12° N and the Sahel up to 20° N is prevailing at all time scales. In detail however, WDR is less striking after lowpass filtering. In the lower two cases, only values statistically significant at the 5% level are drawn. In terms of the lowpass filtered time series, there is no significant anticorrelation between GCR and SHZ precipitation given the substantial reduction in the degrees of freedom. There

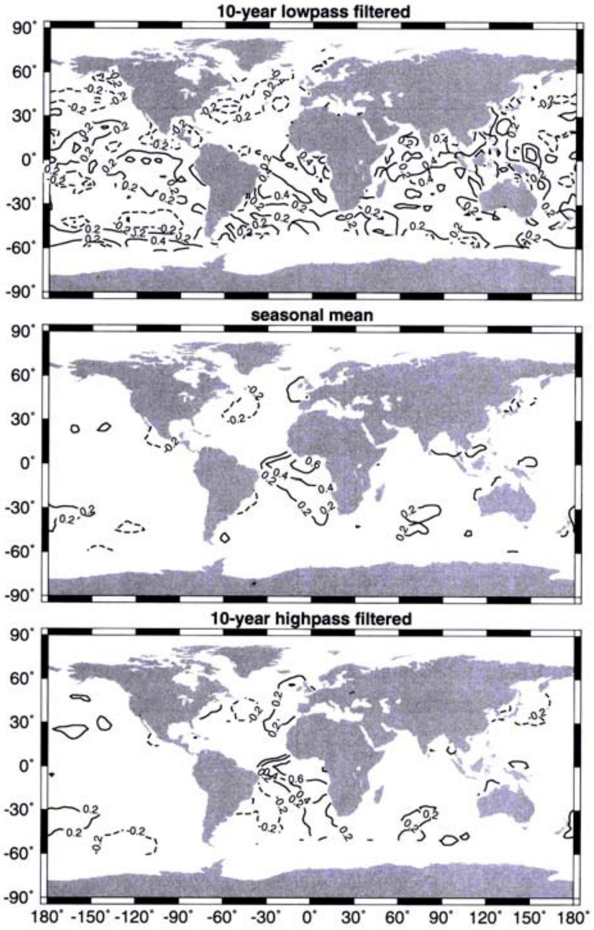


Fig. 6. Correlation patterns between the rainfall dipole and global SST, based on different time scales, CRU and GISST observational data 1903-94. Plotted are only correlation coefficients |> 0.2| which are statistically significant at the 5% level with respect to the seasonal-mean values. The contour interval is 0.2

are mainly two physical explanations why the dipole regions largely decouple from each other at longer time scales: (*i*) Several studies have pointed to the crucial role of local feedbacks with the land surface characteristics in strengthening the low-frequency variability of SHZ rainfall (Zeng *et al*., 1999; Long *et al*., 2000; Nicholson 2001). Thus, it is conceivable that the contrary rainfall response in GCR and SHZ comes along with the same mechanism, whereas SHZ precipitation is more strongly affected by vegetation, albedo and soil moisture feedbacks, extending the anomaly over several years and decoupling it from GCR rainfall, which itself is more directly linked to the initial forcing mechanism. (*ii*) One of the dipole regions, in contrast to the other one, is closely tied to a specific low-frequency feature in the climate system, more or less independent of the initial forcing mechanism.

More inference about this question can be made from Fig. 5, showing the same approach but based on the ECHAM4 6-member ensemble mean. The simulated patterns are basically in agreement with the observations, albeit smoother due to the coarser resolution. In general, the amplitude of the anticorrelation is slightly higher which is probably related to the averaging over 6 ensemble members. Given that all 6 realizations are forced with the same lower boundary SST data, this finding may be interpreted as a first indication of the SST field playing a role in the WDR dynamics rather than internal atmospheric variability. The model confirms that WDR is most clearly prevailing, if the decadal component is removed from the time series. As the considered ECHAM 4 version does not incorporate any dynamical feedbacks with the land cover, explanation 1, as mentioned above, is unlikely to account for the dipole anticorrelation deteriorating in the red part of the spectrum of West African rainfall variability. The basic question now addresses the processes which affect the WDR fluctuations at various time scales. For the following steps, a standardized index time series, indicative of the WDR temporal variability, is constructed by averaging over the GCR and SHZ regions, respectively, according to Figs. 3 and 4, building the difference GCR minus SHZ, subtracting the long-term mean, and normalizing with respect to the standard deviation.

3.2. *Driving factors*

It is a well-known fact that West African monsoon variations are closely tied to SST changes, particularly in the tropical oceans (Chang *et al*., 2000; Ruiz-Barradas 2000; Saravanan and Chang 2000; Paeth and Hefise 2003a, b) .Therefore, it is hypothesized that SST is also a dominant player in the WDR fluctuations. Fig. 6 depicts the correlation patterns between the observed global SST and WDR index time series with respect to the same time scales as in Figs. 3 and 4. The contour lines are again restricted to values significant at the 5% level referring to non-filtered seasonal means. The year-to-year changes of WDR during the rainy season come along with a warmer eastern tropical Atlantic, particularly in the Gulf of Guinea region (middle panel). The teleconnection to the eastern tropical Pacific as suggested by Saravanan and Chang (2000) as well as Janicot *et al*., (2001) is not emerging over this centennial time window. The weak and sporadic correlations with the Southern Ocean are not interpretable and may be explained by minor data reliability in this part of the world. In terms of the 10-year lowpass filtered time series, the relationship with the tropical Atlantic is much less pronounced (top). Instead a connection to the

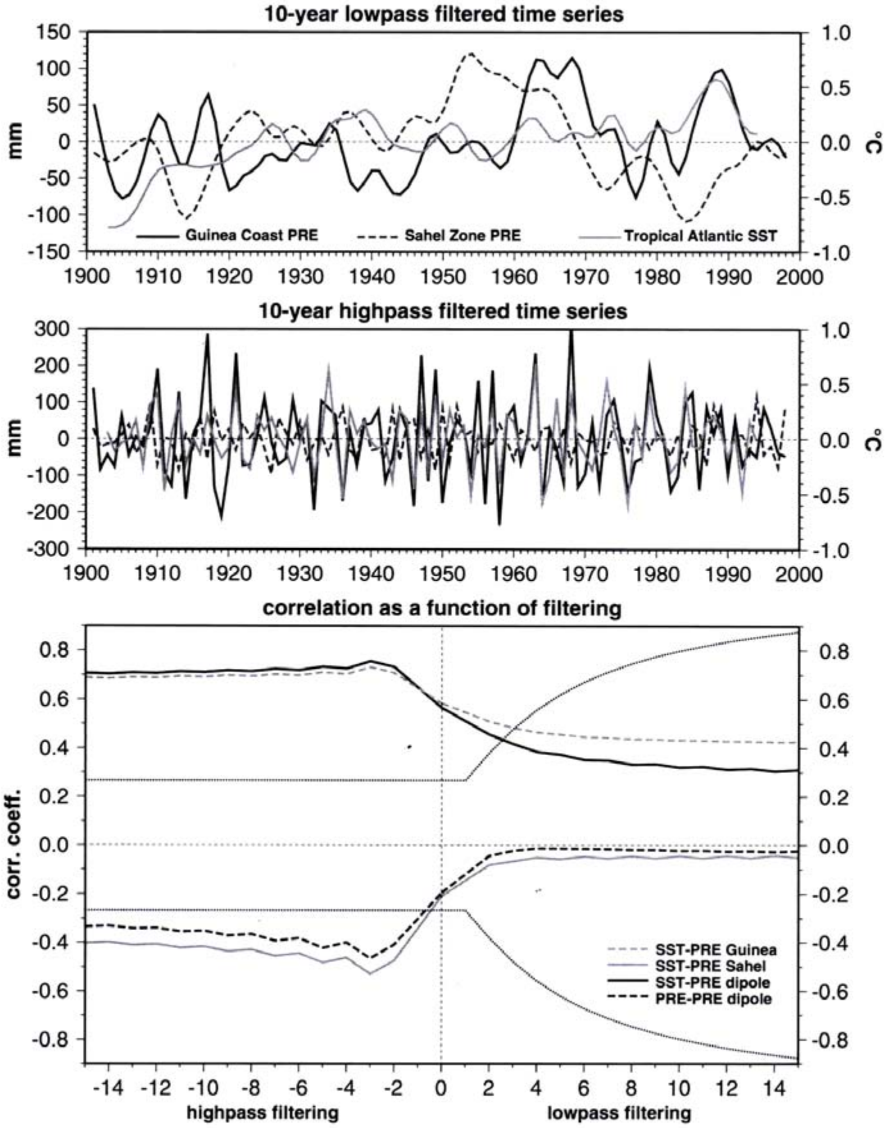


Fig. 7. 10-year lowpass (top) and highpass (middle) filtered time series of Guinean Coast and Sahel rainfall as well as tropical Atlantic SST, (bottom) correlation coefficients between these time series as a function of filtering, the abscissa denoting the years of lowpass and highpass filtering. Zero marks the unfiltered seasonal means. The dotted lines represent the 1% significance level

extratropical North Atlantic occurs. It is found that this extratropical influence mainly concerns the decadal variations of SHZ rather than GCR rainfall (not shown). This has also been reported by Los *et al*., (2001). On the other hand, the peak monsoon climate over the southernmost part of West Africa is directly affected by the eastern tropical Atlantic, especially at the interannual time scale. Thus, given the intense low-frequency component of North Atlantic SST variability, it is not surprising that long-term SHZ rainfall fluctuations are independent of the GCR anomalies in the south, which themselves are linked to the typically interannual time scale of tropical SST variations. As a consequence, the WDR-SST relationship is most striking, if the decadal and longer-scale components are removed from the time series (bottom panel). The WDR index is even closer correlated with the tropical Atlantic than the GCR rainfall time series alone (not shown), ensuring that the northern center of the dipole actually provides additional information on the rainfall SST link over West Africa at interannual time scales. The ECHAM4 ensemble-mean WDR index largely reproduces this picture (not shown).

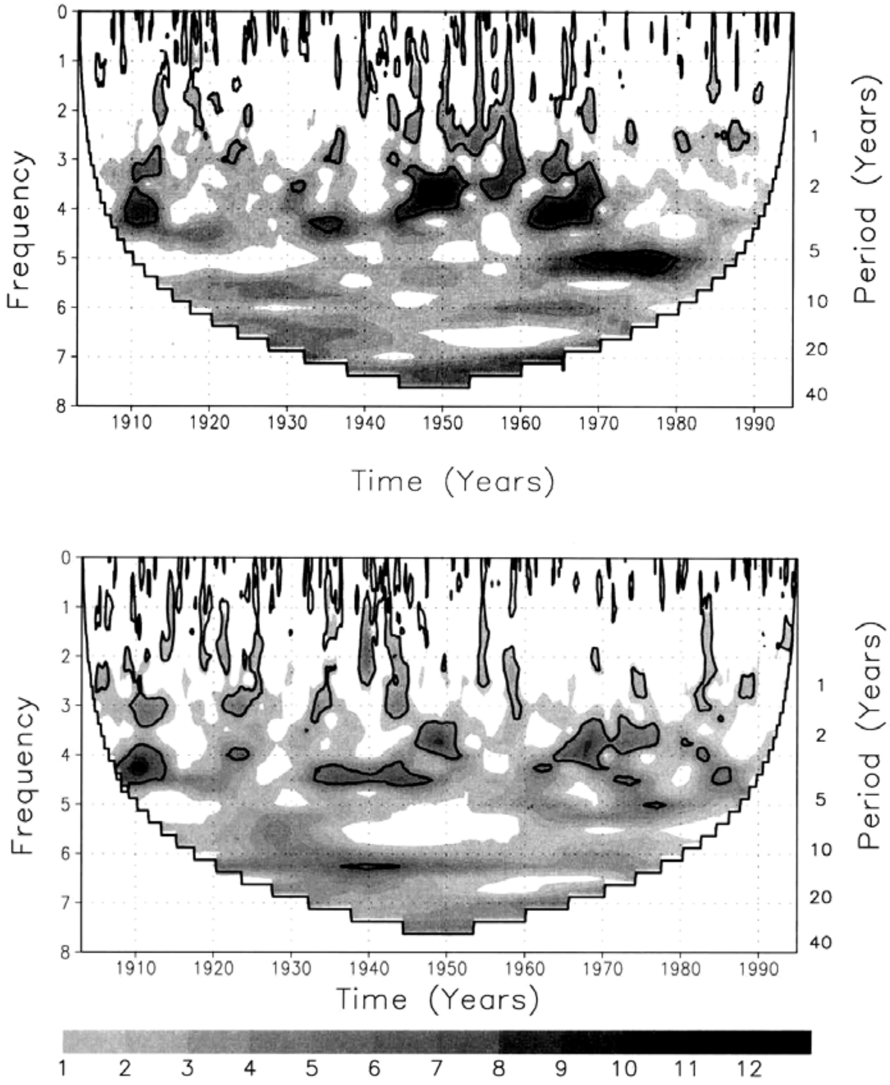


Fig. 8. Morlet wavelet cross amplitude spectrum between the West African rainfall dipole and tropical Atlantic SST, CRU data (top) and ECHAM4 ensemble mean (bottom) with GISST data, monthly means 1903-94. Values of covariance < 1 are masked out, values significant at the 5% level are marked in bold outline

In order to gain more insight into the coherence between tropical Atlantic SST and GCR, SHZ as well as WDR rainfall changes, appropriate standardized regional-mean time series are constructed, representing the centers of the dipole, the dipole itself and the Gulf of Guinea SST. The top panel of Fig. 7 shows the respective 10-year lowpass filtered seasonal mean time series. The SHZ precipitation is subject to a stronger decadal component than in GCR, probably due to the land surface interactions and the teleconnection to extratropical SST dynamics. The most striking long-term feature consists of the multi-decadal drought tendency since the late 1950s. At first sight, the decadal GCR and SHZ variations look barely coherent with each other. The same is true for SHZ rainfall and tropical Atlantic SST. However, the Gulf of Guinea SST is increasingly linked to low-frequency variability over GCR, particularly during the second half of the 20th century when data quality was improved. With respect to the highpass filtered seasonal-mean time series (middle panel), the anticorrelation between GCR and SHZ as well as the coherence between GCR and SST is prevailing. Obviously, the year-to-year changes of WDR are largely in-phase with low-latitude Atlantic SST. The amplitude of the interannual rainfall fluctuations is much higher over GCR than over SHZ, although the decadal means are varying in the same order of magnitude. The bottom panel depicts the correlation coefficients between all rainfall indices and Gulf of Guinea SST, depending on the years of lowpass and high pass filtering. Zero refers to the original unfiltered time series. The strongest coherence occurs between the highpass filtered WDR and Gulf of Guinea SST time series, amounting to r = +0.7. It is slightly stronger than the GCR-SST relationship, because some information is contributed by the SHZ dynamics which itself is negatively correlated with tropical Atlantic heating (r = –0.4). All considered time series, including the WDR anticorrelation, are significantly coherent with each other, if the low-frequency variations are removed. At longer time scales, the positive correlation between Atlantic SST and GCR rainfall, and hence WDR, is still persisting (r = +0.3), however, it is not statistically significant due to the substantial reduction in the degrees of freedom. Decadal changes in SHZ precipitation are independent of the SST in the Gulf of Guinea region. Thus, it can be concluded that the eastern tropical Atlantic plays an important role in the interannual variability of WDR, with warmer SST enhancing the north-south gradient in freshwater availability, while it is not responsible for the long-term behaviour of SHZ rainfall.

The basic challenge now is to understand the physical processes on the ground. At first glance, it may be surprising that a warmer tropical Atlantic induces a dipole response in West African rainfall, although at the seasonal scale, the whole region is characterized by a southwesterly monsoonal flow, which extends far north into the ITCZ (Saha and Saha 2001). A simple mechanism may incorporate the following causal relationship: A warmer ocean surface comes along with more latent heat fluxes into the atmosphere (Paeth *et al*., 2003). The summer monsoon, enriched on this moisture, overflows the West African sub-continent and favors the generation of deep convection. Thus, rainfall amount should be homogenously increasing over the whole region, instead of causing less precipitation over the Sahel. Obviously, this view is too simple. In fact, Vizy and Cook (2001) have suggested a more complex mechanism: According to the shallow water equations, a tropical Atlantic heat source is associated with a linear Kelvin and Rossby wave response in the atmosphere, incorporating the Walker circulation and the West African monsoon system. Due to a general subsidence over the Gulf of Guinea, deep convection of moist air is not occurring locally over the warmer ocean surface but shifted northward to the southernmost part of West Africa. The enhanced upward motion over GCR is accompanied by stronger near-surface inflow. This lower-tropospheric convergence also implies a stronger northeasterly Harmattan wind, which in turn reduces the rainfall amount over SHZ. At the same time, the advection of humid monsoonal air masses from the south is maintaining the deep convection over GCR. A more detailed study on these processes, involving regional dynamical downscaling, is currently in preparation.

Wavelet analysis is also an appropriate tool to determine the spectral relationship between two time series. Fig. 8 displays the cross spectral power between the monthly WDR and Gulf of Guinea time series using Morlet wavelets (Torrence and Compo 1998). The values are scaled in covariance units. The black lines indicate that cross spectral power exceeds the 5% significance level. The patterns are largely resembling the bottom spectrum in Fig. 3, representing the EOF of the WDR pattern. In terms of the observational data (top panel), the oceanic impact on WDR is mainly prevailing at relatively short time scales from intra to interseasonal. In addition, there are some peaks in the interannual range but not persisting during the whole century. Especially, in the 1950s to 1970s a stronger low-frequency component occurs. At decadal to multidecadal time scales, the WDR fluctuations are not related to Gulf of Guinea SST, likely due to the mechanisms described above. The simulated ensemble-mean time series largely reproduces the observed wavelet spectrum when linked to the same SST observational data (bottom panel). Even the shift to longer periods during the second half of the 20th century is in good agreement. However, the model reveals a weak decadal signal in the middle of the 20th century which does not show up in the observations. Given that the ECHAM4 ensemble mean basically reflects the SST-driven part of variability, the in-phase relationship between simulated and observed WDR time series is indicative of the crucial role of tropical Atlantic SST in forcing the WDR variations. Another important inference is that the WDR response to SST changes can already be evaluated from relatively short model integration periods an essential aspect in costly regional model studies.

Apart from SST, other studies have pointed to the possible role of soil moisture in governing the thermal gradients, and hence rainfall distribution, over West Africa with a time lag of several months (Cook 1999; Fontaine *et al*., 2002). In Fig. 9 the highpass filtered seasonal mean time series (June-September) of ensemble-mean WDR is cross correlated with the corresponding simulated monthly-mean fields of soil moisture in West and central Africa. Appropriate observational data of soil moisture have not been found for comparison. It is obvious that the monthly-mean soil moisture during January to May is not leading the WDR dynamics during June to September, at least in the ECHAM4 climate model. On the other hand, soil moisture anomalies come along with simultaneous WDR fluctuations during the rainy season (June-September). Trivially, soil moisture is

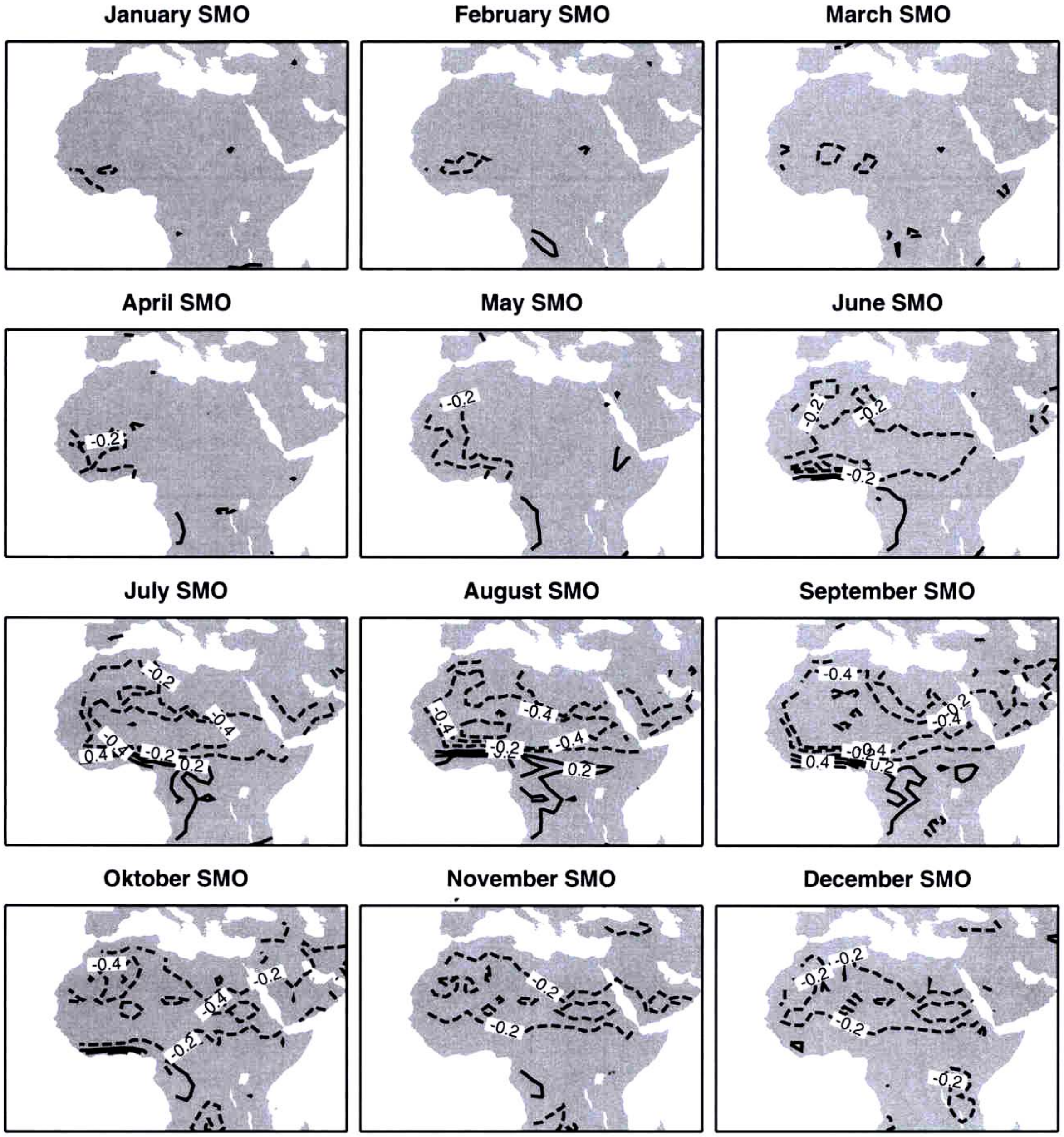


Fig. 9. Cross correlation patterns between monthly-mean soil moisture (SMO) and the seasonal-mean rainfall dipole (Jun.-Sep) over West Africa, the long-term trend being removed, ECHAM4 6-member ensemble mean 1903-94. Plotted are only correlation coefficients |> 0.2| which are statistically significant at the 5% level. The contour interval is 0.2

locally increasing with rainfall amount. Furthermore, soil moisture during October to December is still reminiscent of the WDR anomaly during the previous rainy season, particularly in SHZ. Thus, West African rainfall variability is leading soil moisture rather than the latter is a predictor of rainfall changes in summer. Of course, this analysis is not sufficiently in-depth to account for all the conceivable impacts of soil moisture on precipitation, for instance at other time and spatial scales. This aspect will be subject to further investigations. Anyhow, the main conclusion of this study is that WDR is closely related to SST changes in the tropical Atlantic. Therefore, regional dynamical downscaling is used to gain more insight into the spatial nature of the WDR response to SST.

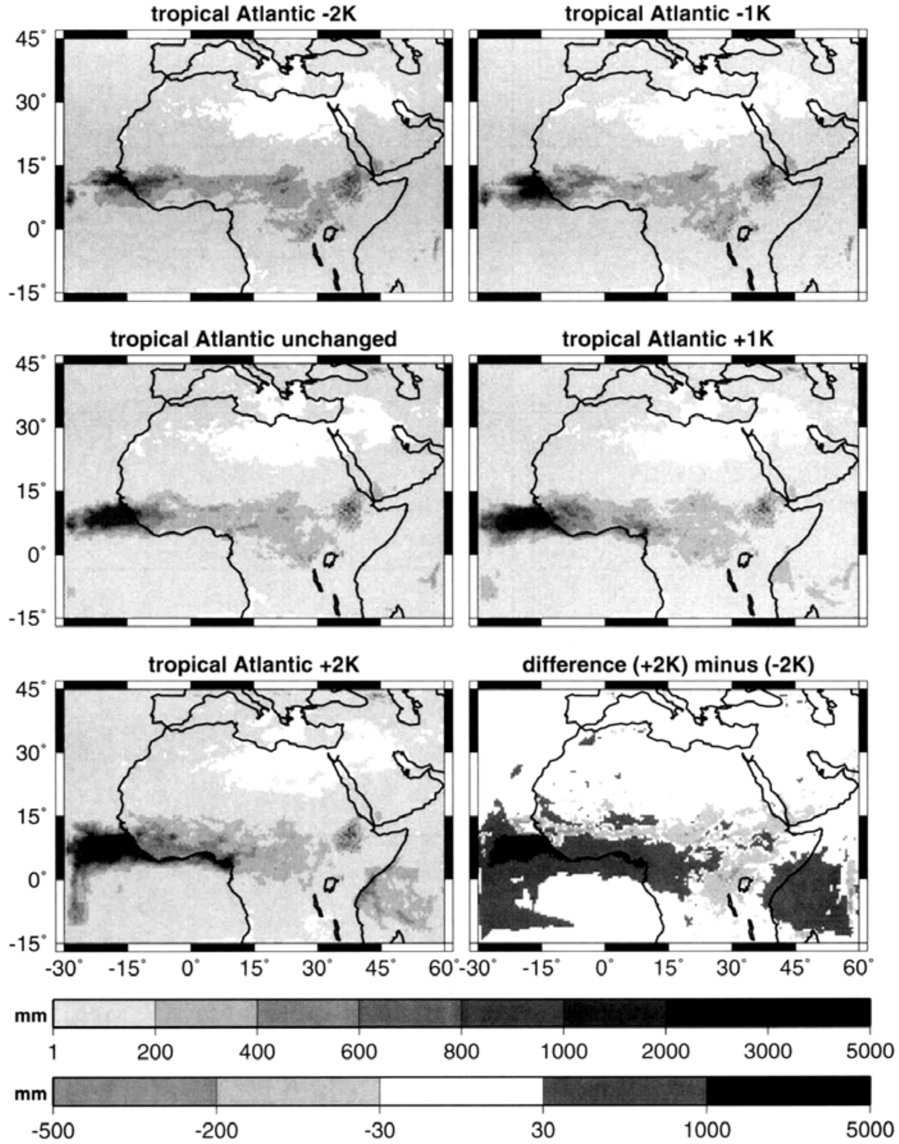


Fig. 10. Total rainfall amount during July-August 1988 as derived from REMO sensitivity studies with idealized tropical Atlantic SST forcing (15° S-10° N) (panels 1-5) and difference pattern warmest minus coldest tropical Atlantic (bottom right)

3.3. *Regional climate model experiments*

The hydrostatic regional climate model REMO (Jacob 2001, Jacob *et al.*, 2001) is run over the entire West and central Africa in a 0.5° horizontal resolution. It is nested in the ERA15 global data set as lateral and lower boundary conditions. In a first attempt, the oceanic surface has been changed in an idealized way: SST is warmed up homogenously over the tropical Atlantic (15° S - 10° N) and the subtropical North Atlantic (10° N - 45° N), respectively, in order to distinguish between the tropical and extratropical Atlantic impact. The small region of Indian Ocean and Mediterranean SST is changed accordingly. Four scenario runs, increasing and decreasing the SST by 1K and 2K, respectively, and one present-day experiment have been integrated under lateral and boundary conditions in July and August 1988. With respect to Fig. 8, this two-month main rainy-season period is assumed to be sufficient to describe the basic SST impact on WDR. Fig. 10 depicts the simulated July-August total rainfall amount of the 5 experiments under low-latitude SST forcing as well as the difference pattern

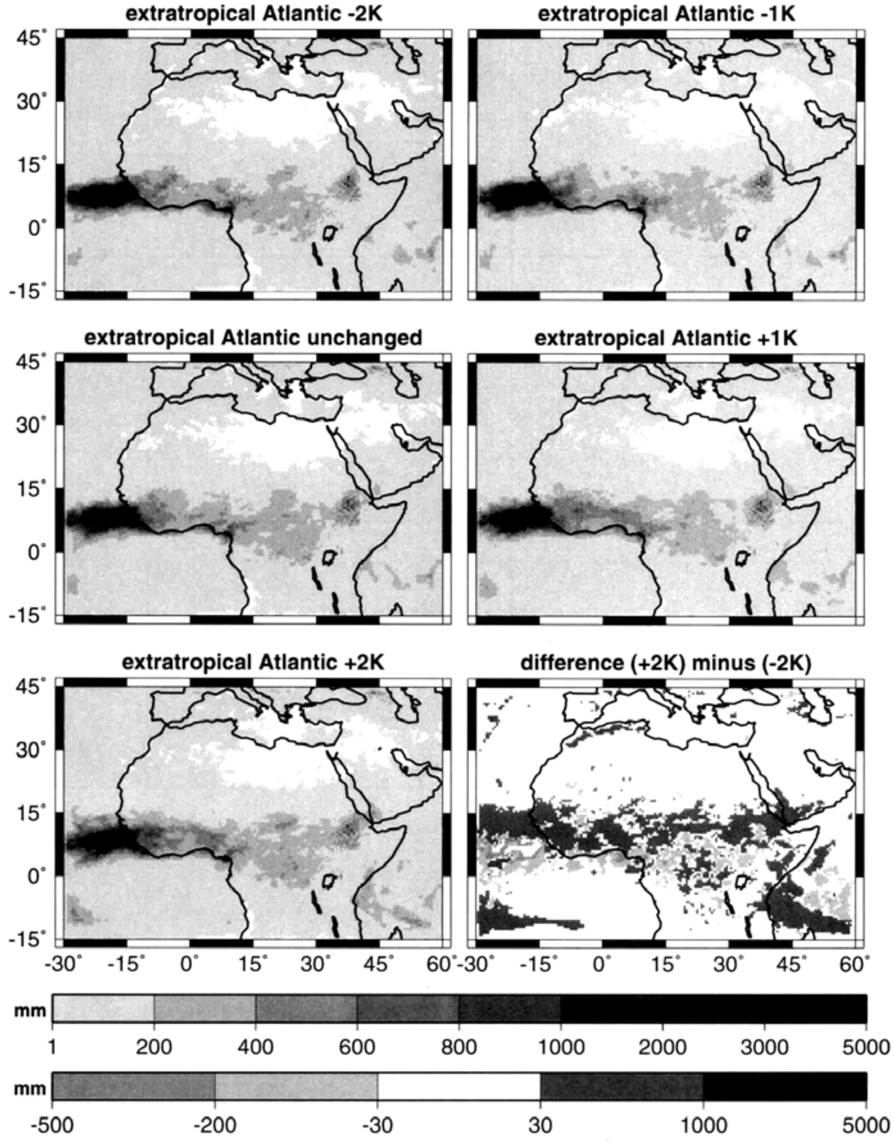


Fig. 11. Same as Fig. 8 but for idealized extratropical SST forcing (10° N - 45° N)

between the two extreme forcing cases ±2K (bottom right panel). It is found that a prescribed warmer tropical Atlantic induces rising rainfall amount over GCR, central tropical Africa, eastern tropical Africa and, particularly, off the Guinea Coast. At the same time, rainfall over most part of SHZ tends to decrease, albeit of lower amplitude, which however, appears to be considerable (up to 200 mm per 2 months) given the lower mean amount of SHZ precipitation. It has to be noted that total rainfall west of tropical West Africa, amounting to almost 5000 mm, is likely to be overestimated by REMO, although validation data over this part of the Earth is still uncertain. Moreover, the delimitation between GCR and SHZ is 5° shifted to the south, compared with Figs. 3 and 4. So far, it can not be concluded whether this a peculiarity of REMO or a realistic feature given the forcing data and the higher horizontal resolution.

Fig. 11 refers to the same experimental design but now only the extratropical ocean surfaces are changed and prescribed. The difference pattern looks largely opposite to the WDR response pattern in terms of tropical SST forcing, North Atlantic heating being associated with wetter conditions over the Sahel. The southernmost part of West Africa is barely affected by changes in the subtropical oceans, so far as included in the REMO

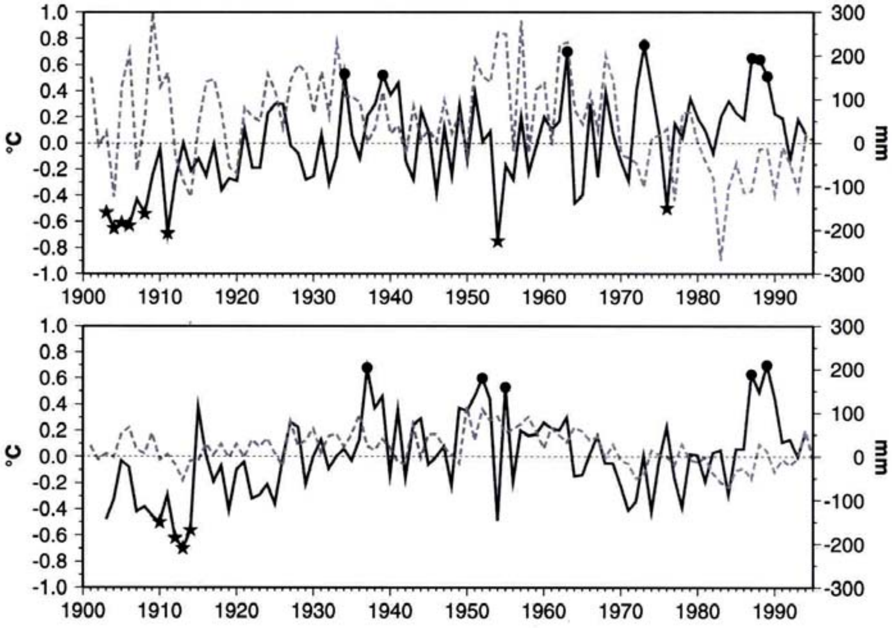


Fig. 12. Observed 20th century SST anomalies as departures from the 1903-94 long-term mean, derived from the GISST observational data set: tropical (top) and extratropical (bottom) Atlantic in the REMO sector. The dark circles indicate the warm composite years, the stars the cold ones. The dashed lines denote the time series of 20th century observed rainfall anomalies in GCR (top) and SHZ (bottom)

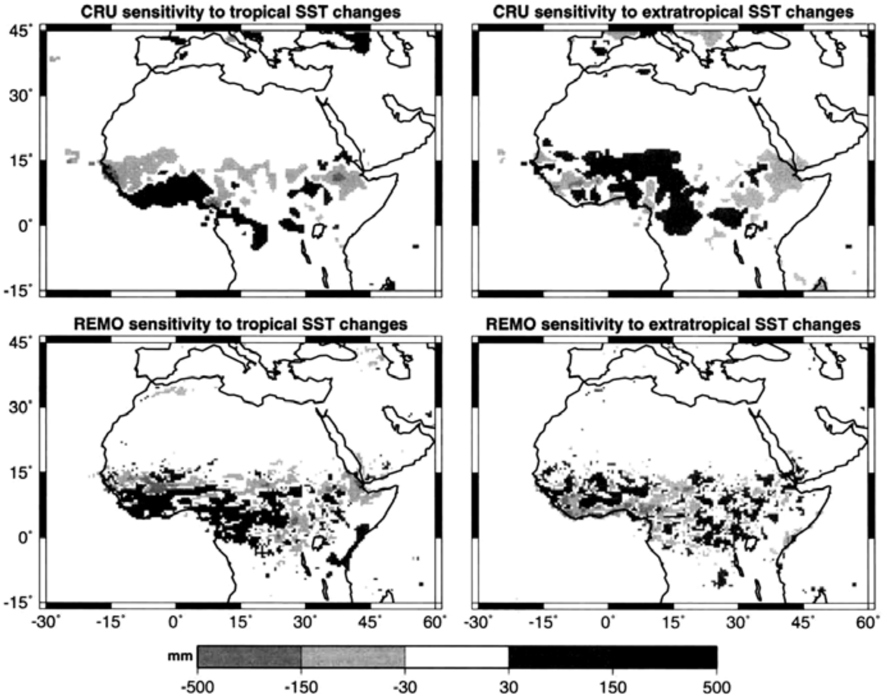


Fig. 13. Comparison of rainfall sensitivity to tropical (left panels) and extratropical (right panels) Atlantic SST forcing in REMO, the SST being reduced by 1K with respect to July-August 1988, and the CRU observational data composites according to Fig. 10

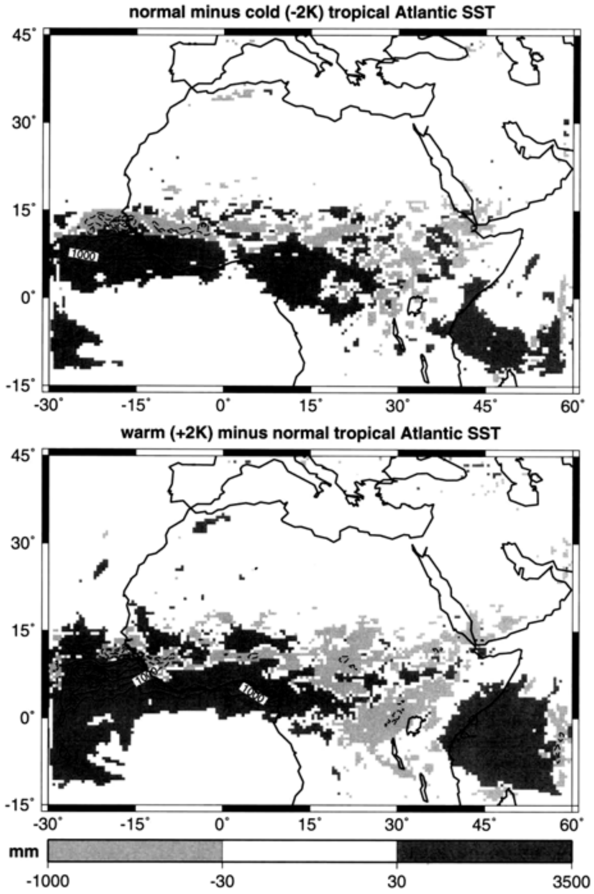


Fig. 14. Non-linearity of the REMO response to tropical Atlantic SST changes: July-August rainfall response 1988 minus colder SST (top) and warmer minus 1988 SST (bottom). The contour interval for increasing (decreasing) rainfall is 500 (200) mm

domain. In addition, the response amplitude is much smaller. Thus, the impact of extratropical SST is minor at this intraseasonal time scale as also inferred from high pass filtered observations and global climate model data (Fig. 6).

In general, the rainfall response pattern to SST variations as simulated by REMO looks realistic, but what about the amplitude? In order to address this question, composite patterns of the observed SST related rainfall anomalies are constructed. Fig. 12 displays the observed non-standardized SST time series as July-August means during the 20th century, averaged over the respective tropical (top panel) and extratropical (bottom panel) ocean surfaces within the REMO domain. For reasons of comparison, the observed time series of 20th century rainfall anomalies in GCR and SHZ are also drawn. The reference year 1988 shows up with one of the warmest Atlantic Ocean surfaces during the observational period. At the beginning of the century, an overall warming trend is suggested by the GISST data set. It is fairly unknown to which extent this trend is realistic or spurious due to bad data reliability. There is a clear in-phase relationship between the GCR rainfall and tropical Atlantic SST variations as mentioned before. The subtropical North Atlantic time series is partly reminiscent of the low-frequency component of 20th century SHZ rainfall with positive anomalies in the 1940s to 1960s and a long-term negative trend afterwards. The maximum amplitude of SST fluctuations in both regions is less than 1.5K. Thus, the maximum SST forcing in REMO (±2K) can not be validated by the observational data. However, the 1988 minus 1K scenario is comparable with the CRU rainfall composites derived from Fig. 12, the thick dots (stars) indicating the years with warm (cold) SST anomalies in summer. The mean difference between the composites is about 1K. Fig. 13 shows the warm minus cold difference patterns of the CRU 20th century composites (top panels) and the REMO present-day (1988) minus 1K colder SST (bottom panels) for tropical (left-hand side) and extratropical (right-hand side) oceanic surfaces. The basic structure of the REMO response and the observed long-term composite difference is similar for the tropical SST forcing. There is also some kind of agreement with respect to the extratropical forcing but, in general, the response is quite weak. Note that too much conformity in detail is not to be expected, since a single summer response is compared with a centennial-mean response and West African summer rainfall is not exclusively governed by SST. The observed pattern is spatially much more homogenous. This is partly due to composite averaging. In addition, it is pointing to some synoptic-scale processes which are resolved in REMO and not in the CRU data set, being based on a statistical interpolation of sparse station data. These processes may render the rainfall response in REMO much more heterogeneous in space. The amplitude of SST-related rainfall anomalies is in excellent agreement between REMO and the long-term observations. Thus, it is concluded that REMO provides a reliable estimate of the WDR sensitivity to SST forcing. Therefore, REMO will be used in a second attempt to access the West African rainfall response to realistic SST scenarios, for instance under future climate change conditions (subsection 3.4).

Another interesting aspect of the WDR-SST relationship concerns the non-linearity of the rainfall response. The top (bottom) panel in Fig. 14 refers to a cold (warm) tropical Atlantic SST anomaly of 2K relative to 1988. It can be seen that the typical GCR-SHZ dipole pattern emerges for anomalies of opposite sign. However, warming the Gulf of Guinea with respect to the anyhow

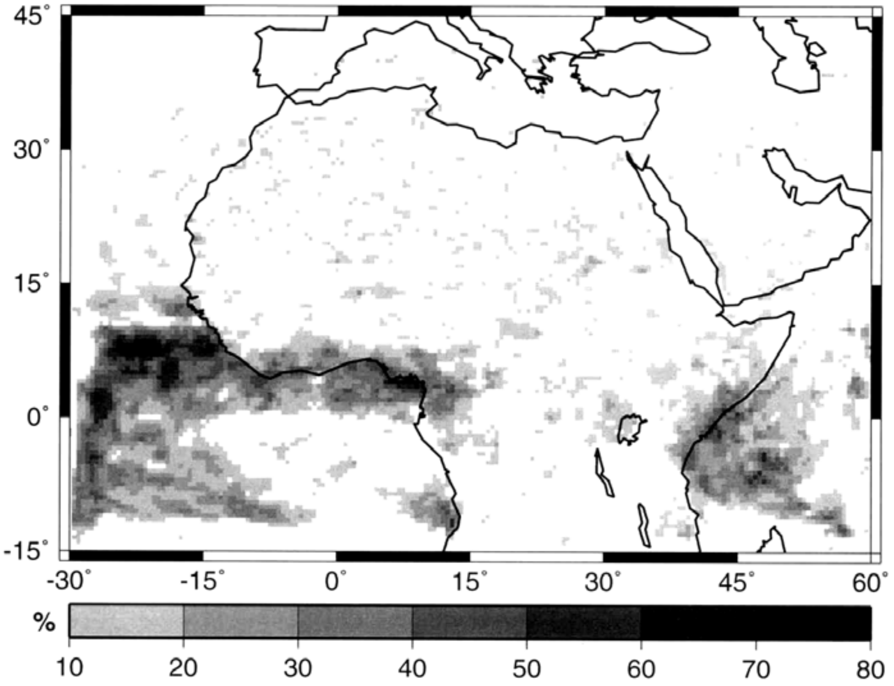


Fig. 15. Impact of changing tropical Atlantic SST on total day-to-day rainfall variability during July-August 1988, explained variance in %. Values larger than 10% are statically significant at the 1% level

warm 1988 anomaly (cf. Fig. 12) leads to a much stronger increase in rainfall over tropical West Africa and off the western Guinea Coast than cooling causes a reduction. The same holds for eastern tropical Africa, albeit of lower amplitude. Thus, nonlinear processes must be at work, intensifying the rainfall response with increasing temperature or from a certain threshold of oceanic heating onward. This knowledge is essential when evaluating the risks of global warming in West Africa. Furthermore, excessive tropical SST warming (+2K relative to 1988 is much more than ever observed during the 20th century), may even induce more rainfall amount over some parts of the southern SHZ, counteracting the basic mechanism suggested in subsection 3.2. On the other hand, this strong oceanic forcing does obviously not exceed the threshold value proposed by Vizy and Cook (2001), from which onward the land-sea temperature gradient is so much reduced that the entire monsoon circulation collapses, resulting in a substantial decrease in rainfall amount over whole subsaharan West Africa.

It may be asked whether the SST-induced systematic changes in rainfall are statistically significant with respect to the remarkable internal variability. In the case of the two-month REMO experiments, this mainly addresses the intense day-to-day variability of convective rainfall in the low latitudes. The relative contribution of large-scale SST changes to total West African rainfall variability can be inferred from analysis of variance (ANOVA). As the method requires data which fit a normal distribution (von Storch and Zwiers 1999), running pentade-means of daily precipitation are considered instead of the daily values themselves. Given ensemble data of the form X_{ij}, referring to time i and SST experiment j, the statistical model $X_{ij} = \mu + a_j + E_{ij}$ is set up with the overall mean μ the so-called treatment effect a_j, describing the impact of the SST forcing, and internal variability E_{ij} (von Storch and Zwiers 1999). The relative contribution of systematically changing SST to total pentadal rainfall variability in the ensemble can be calculated by square sum decomposition. The explained variance of the statistical model at each grid point is illustrated in Fig. 15, based on the tropical ocean forcing. Only values significant at the 1% level are displayed. Over large parts of the Guinea Coast and eastern tropical Africa, SST variations account for a considerable part (up to 50%) of total rainfall variability, even with respect to the intense day-to-day fluctuations. Off the western Guinea Coast, in the Bay of Biafra and off the Somali Coast, SST contributes almost 80% even at this intraseasonal time scale. On the other hand, the daily variations in SHZ rainfall seem to be less affected by the systematic SST forcing. On the one hand, this is due to the

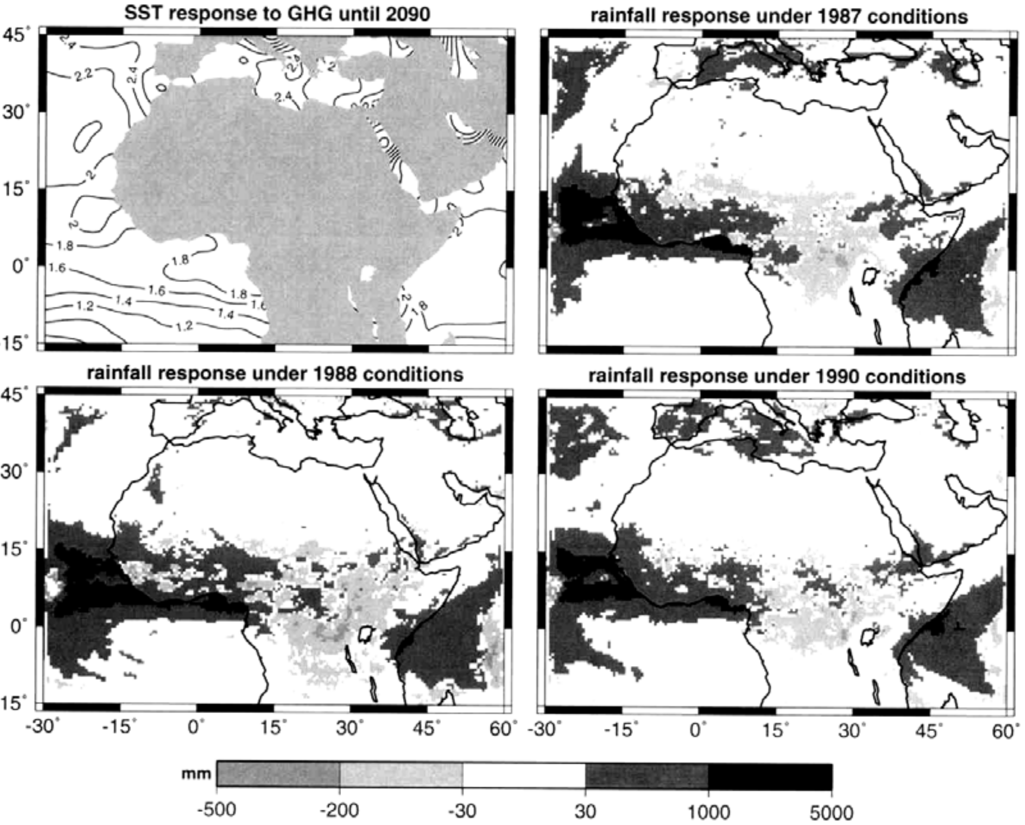


Fig. 16. Atlantic SST response pattern (°C) to increasing. GHG concentrations in the year 2090 with respect to the 20th century long-term mean (top left), the contour being 0.2° C, and July-August rainfall response patterns (mm) to such an GHG-induced warmer Atlantic Ocean in three years with different lateral boundary forcing (panels 2-4)

larger distance to the Gulf of Guinea (cf. Paeth and Hense 2003a, their Figs. 3(a+b). On the other hand, it does not imply that the SST-induced rainfall response is negligible over the Sahel (cf. Fig. 10), but the SST signal is largely blurred out by the strong daily variations. In general, the typical time scale of SHZ rainfall events is shorter, involving more meso-scale systems, than over GCR which is more influenced by the larger-scale monsoon circulation (Kamara 1986).

3.4. *Climate change implications*

The previous results are very promising and enhance our believe in the regional climate model. Therefore, REMO is also used to evaluate the impact of global warming on the dipole behaviour of West African rainfall as a key factor in future migration processes. The following sensitivity study is of preliminary nature and needs to be further improved. Here, the global warming scenario indirectly enters the REMO experiments via the SST forcing, whereas the radiation budget of the REMO atmosphere is not modified, for example with regard to higher GHG concentrations. Moreover, the lateral boundary forcing is still derived from the ERA15 data, which are not necessarily aware of any global warming signal. The simple issue of this approach is to detect the isolated effect of GHG-induced warmer SST in the REMO domain on West African rainfall. The SST forcing pattern is provided by a coupled climate change experiment until the end of the 21st century. In this ECHAM4/OPYC simulation GHG concentrations are prescribed according to the IS92A scenario, which amounts to somewhat less than 1% rise per year (Houghton *et al*., 2001). In order to extract the SST reponse to radiative heating, an EOF analysis of monthly-mean SST is carried out. The leading EOF reveals a considerable warming trend throughout the whole 21st century with highest amplitude over the tropical and, especially, subtropical oceans. Multiplying the 2085-2095 decadal-mean PC anomaly with the corresponding EOF pattern leads to the top left map in Fig. 16. With respect to late 20th century climate, SST is rising by 1K in the vicinity of the Benguela current, by up to 3K in the Mediterranean and even by 4K in the Red Sea and the

Persian Gulf. This anomaly pattern is assumed to represent a reliable SST forcing for late 21st century climate, although it is derived from a single scenario run instead of Monte Carlo experiments, since it has been shown that near-surface temperature signals in the low latitudes are largely independent of varied initial conditions (Paeth and Hense 2002).

In the REMO experiments, the present-day SST fields are warmed up by these GHG related SST anomalies and used as lower boundary condition for REMO. Three July-August periods are integrated: 1988 as a wet year in GCR, 1990 as a dry year and 1987 as an intermediate year (Paeth *et al.*, 2003). These cases have been selected in order to account for the interaction between SST forcing and different lateral boundary conditions. Such sensitivity studies are much more realistic than the idealized experiments in the previous subsection for two reasons: (*i*) The amplitude of the SST heating is derived from coupled climate modelling instead of prescribing an arbitrary and constant warming rate. (*ii*) The pattern of SST changes is consistent with the major ocean dynamics and does not reveal any exaggerated gradients like at the borders of the idealized SST forcing patterns, to which the tropical atmosphere is highly sensitive. On the other hand, the "realistic" SST forcing pattern is still inconsistent with the ERA15 lateral boundary forcing and radiation processes in REMO, as both systems are not operating under late 21st century conditions. Furthermore, land cover changes may also be a crucial factor in future rainfall changes over West Africa (Douville *et al.*, 2000). Incorporating these forcings' in REMO is a basic challenge for future investigations.

The remaining panels in Fig. 16 describe the rainfall response to late 21st century oceanic heating as simulated by REMO under 1987, 1988 and 1990 lateral boundary conditions. The patterns largely correspond to the bottom right panel in Fig. 10, which was related to the idealized SST forcing. The same is true for the amplitude of the precipitation changes. In general, warmer ocean surfaces around the West African subcontinent induce more abundant rainfall over the southernmost part of West Africa and less freshwater input in SHZ. Different lateral boundary conditions only have a minor impact on this basic feature, for instance in 1988 the dipole response appears somewhat less clear than in the other years. Assuming that the coupled climate model provides a reliable estimate of future SST and REMO reasonably simulates the rainfall sensitivity to SST changes, these results suggest that global warming may strengthen the north-south gradient of freshwater availability over subsaharan West Africa, possibly accompanied by ongoing north-south migration, increasing population density in GCR and accelerated land degradation.

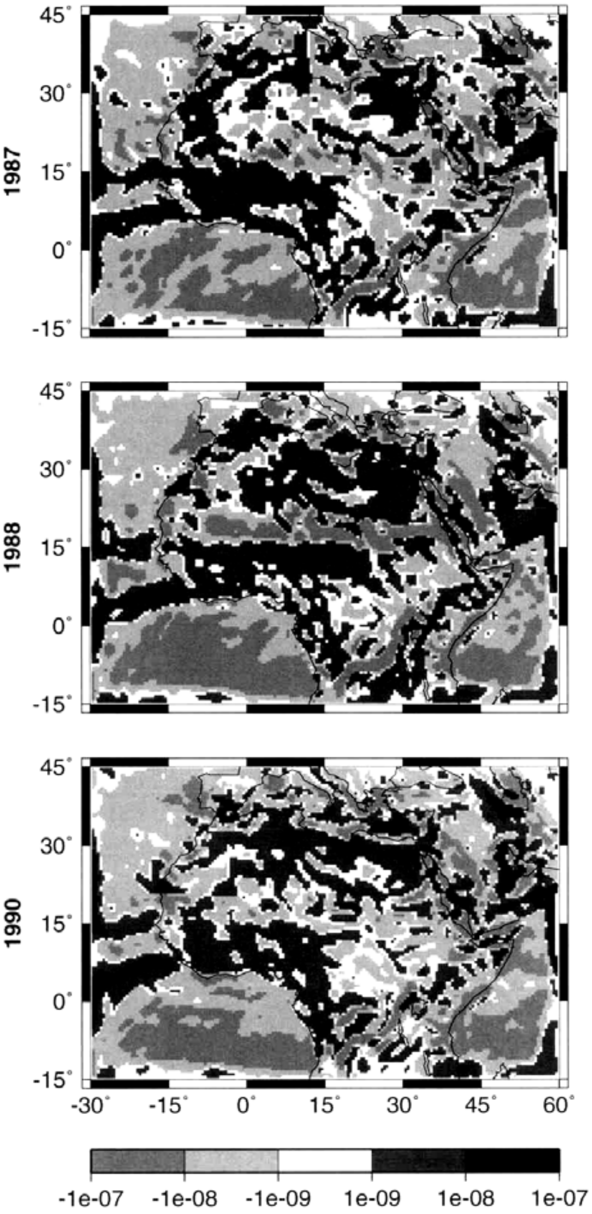


Fig. 17. Anomalies in near-surface moisture convergence in reponse to GHG-induced oceanic heating in three years with different lateral boundary forcing, positive values in 1/s denoting moisture enrichment in a model grid box

The physical idea of the SST-rainfall relationship in tropical Africa, as suggested by Vizy and Cook (2001), has been described in subsection 3.2. In order to show that the simulated rainfall anomalies in Fig. 16 are indeed linked to a change in the near-surface large-scale monsoon circulation, Fig. 17 displays the GHG-SST-related anomalies in near surface moisture advection. It is obvious that REMO simulates moisture enrichment over GCR, while SHZ is subject to moisture divergence due to the dry Harmattan flow. In detail, there are some differences between the three years: The clearest signal occurs under 1988 conditions, when the original SST field was already abnormally warm.

4. Concluding remarks

The present study is dedicated to the major patterns of 20th century West African rainfall variability and its forcing mechanisms. It is found that the leading EOF describes a spatially homogenous drought tendency over the subsaharan part of the subcontinent. Higher EOFs reveal a dipole behaviour with opposing centers in the GCR and the SHZ, altogether accounting for almost 20% of total rainfall variance. This WDR is a basic feature in long-term observational data and global climate model simulations. The interannual variations of WDR are largely affected by SST in the Gulf of Guinea region. At longer time scales, the SHZ precipitation is more closely related to the extratropical North Atlantic, whereas the tropical Atlantic remains the main player in the monsoon dynamics over GCR in all parts of the spectrum. Therefore, the dipole structure is less clearly prevailing in the low-frequency component of West African rainfall variability. Wavelet analysis shows that a significant coherence between WDR and tropical Atlantic SST already occurs at the intra and interseasonal time scale. Soil moisture is no precursor of the WDR anomaly in summer, at least not at the considered monthly-mean time scaJe, which is partly in contradiction with Fontaine *et al.*, (2002).

Regional dynamical downscaling is used in order to gain more insight into the spatial nature of the WDR response to oceanic heating. Forcing REMO gradually with idealized SST anomalies during two summer months leads to a substantial change in rainfall amount and distribution over subsaharan West Africa. A warmer tropical Atlantic is associated with more abundant rainfall amount over GCR and less over SHZ, enhancing the north-south gradient in freshwater input. At this short time scale, WDR is much less affected by subtropical North Atlantic SST anomalies, but in general, the response is of opposite sign. The amplitude and the pattern of the simulated SST-induced rainfall signal is in reasonable agreement with the observed long-term composites of warm and cold SST boundary conditions. The WDR-SST relationship is nonlinear, the rainfall sensitivity increasing with the oceanic heating rate. The systematic SST changes can be made responsible for up to 50% of total rainfall variability over GCR, even with respect to the pronounced day-to-day variations. This impact is statistically significant at the 1% level. A more realistic scenario of oceanic heating is derived from a coupled climate change experiment under enhanced greenhouse conditions. The resulting warming pattern in the tropical and subtropical oceans is used as the lower boundary condition in REMO in order to evaluate the WDR sensitivity to global climate change. It turns out that the radiative forcing, *via* the tropical oceans, enhances the natural rainfall gradient between SHZ and GCR.

So far, most studies have focussed on the prominent long-term trend to a dryer climate over entire West Africa (Nicholson *et al*., 2000). The present study has drawn a more complex picture of rainfall variability: A further important mode describes opposing rainfall anomalies in GCR and SHZ, related to SST changes in the eastern tropical Atlantic. At the end of the 20th century, oceanic heating was coming along with a strengthening of the dipole. Superimposing the dipole anomaly (EOF 2-4) onto the spatially homogenous drought tendency (EOF 1) resulted in a further deterioration of freshwater availability in the Sahel, whereas rainfall reduction over the coastal region of tropical West Africa was partly compensated. Contemporaneously, demographic studies have revealed large-scale migration processes from the Sahel mainly to the southernmost part of West Africa (Findley 1994). It is hypothesized that WDR changes are one of the key factors in this migration, among many socio-economic motivations. For political measurements and various kinds of development plannings, it is of major relevance to anticipate the possible reponse of the north-south gradient in rainfall amount to future radiative forcing. The regional climate model experiments in this study suggest a further intensification of the dipole, probably with negative demographic implications, if the tropical and subtropical ocean surfaces are heating up in a warmer climate.

This main conclusion is still confronted with some uncertainty: (*i*) In the experimental design of the present study, the GHG-induced SST forcing is inconsistent with the lateral boundary conditions from ERA15. In addition, increasing GHG concentrations are not incorporated in the radiation scheme of REMO. Both aspects will be addressed in near future in order to perform more realistic sensitivity studies with respect to anthropogenic climate change. (*ii*) Apart from SST and GHG, West African rainfall fluctuations are related to many competing and interacting factors like vegetation cover, soil moisture, albedo and atmospheric dust loadings. Particularly, vegetation is supposed to modify the climate response to global warming (Douville *et al*., 2000; Zeng and Neelin 2000). Thus, reliable estimates of future rainfall trends should account for all these mechanisms. Future investigations will deal with adequate sensitivity studies, prescribing scenarios of vegetation degradation, albedo changes and reduced soil moisture.

The underlying physical mechanism of the WDR-SST relationship has been suggested by Vizy and Cook

(2001, 2002): A linear Kelvin and Rossby wave response to tropical Atlantic heating is inducing large-scale rainfall anomalies over the West African subcontinent with a contrary behaviour of GCR and SHZ. The simulated anomalies in moisture advection indicate that this mechanism is also active in REMO. Thus, the REMO experiments described in this study represent an excellent data basis to evaluate this linear theory of tropical thermodynamics at the synoptic scale and to distinguish between the linear and nonlinear part of the rainfall response. This issue is currently under consideration.

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