# Influence of soil moisture initial conditions in a Regional Climate Model study over West Africa: Part 1: Impact on the climate mean.

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**Abstract.**

The impact of soil moisture initial conditions on the mean climate over West Africa is examined using the latest version of the Regional Climate Model of the International Centre for Theoretical Physics (RegCM4) at the horizontal resolution of 25 km × 25 km. We performed these sensitivity studies to the initial conditions of soil moisture for June-July-August-September (JJAS) from 2001 to 2005 with a focus on two contrasted years 2003 (above normal precipitation year) and 2004 (below normal precipitation year). The soil moisture reanalysis of the European Centre Meteorological Weather Forecast's reanalysis of the 20th century (ERA20C) were used to initialize the control runs, whereas we initialized the soil moisture at the wilting points and field capacity with dry and wet soil moisture initial conditions respectively (hereafter dry and wet experiments). The impact of soil moisture initial condition on the precipitation in West Africa is homogeneous only over the Central Sahel where dry (wet) experiment lead to rainfall decrease (increase). The strongest impact on precipitation in wet experiments is found over the West Sahel with the peak of change about respectively +40%, while the strongest decrease is found in dry experiments over Central Sahel with a peak of change about -8%. The sensitivity of soil moisture initial condition can persist for three to four months (90-120 days) depending on the region. However, the influence on precipitation is no longer than one month (between 15days and 30 days). Overall, the impact of soil moisture initial conditions is greater on temperature than on precipitation. The strongest impact is located over the Central Sahel with the peak of change of -1.5 °C and 0.5°C respectively in wet and dry experiments. Mechanisms associated with the influence of soil moisture initial conditions on mean precipitation and temperature are highlighted. In the Part II of this study, the influence of the soil moisture initial conditions on climate extremes is investigated.

## 1 Introduction

In the climate system, soil moisture is one of the crucial variables which influence water balance and surface energy components through latent surface fluxes and evaporation. Therefore, soil moisture impacts the development of weather patterns and precipitation production. The strength of soil moisture impact on land-atmosphere coupling is variable according to the place and with the season. Koster et al. (2004) sustained that the atmospheric response simulation to the slow variation of the ocean and land surface states, can accurate the seasonal simulations. The atmosphere response to ocean temperature anomalies is well documented (Kirtman et al. 1998; Rasmusson et al.1982). Another earth system component, potentially useful, that varies slowly is soil moisture. The role of the soils may be comparable to that of the oceans. While in summer, the solar energy received by the oceans is stored (and use it to heat the atmosphere in winter), in winter the precipitation received by the soil is stored (the moistening and cooling is returned to the atmosphere in summer). Through its impact on surface energy fluxes and evaporation, there are many additional impacts on climate process of soil moisture, such as boundary-layer stability and air temperature (Hong and Pan, 2000; Kim and Hong 2006). Several studies have shown that the anomalies of the soil moisture may persist for several weeks or months, however, its impact remains only for a shorter time in the atmosphere, not exceed few days (Vinnikov and Yeserkepova 1991; Liu et al., 2014). The important role of the anomalies in soil moisture in the coupling of land and atmosphere is shown in several studies, using numerical climate models (Jaeger et al., 2011; Zhang et al., 2011) and observation datasets (Zhang et al., 2008a; Dirmeyer et al., 2006).

West Africa is known to be a region where there is a strong coupling between soil moisture and precipitation (Koster et al., 2004). Several previous studies have been conducted over West Africa on a global scale using AGCMs (Atmospheric General Circulation Model) to investigate the impact on the land-atmosphere coupling of soil moisture anomalies (Koster et al., 2004; Douville and al, 2001; Zhang et al., 2008b). However, at the local and regional scales, the land-atmosphere coupling studies with AGCM, present large uncertainties (Xue et al. 2010). Recently, the use of RCMs to simulate the impact on interannual climate variability of anomalies in soil moisture received a lot of attention because of the increase in climate variability associated with extreme weather events that can have greater societal and environmental impacts. In general, these studies have been conducted for Asia, Europe and America (e.g. Seneviratne et al. 2006 for Europe; Zhang et al. 2011 for Asia; Zhang et al. 2008b for America). Overall, the results of these studies show, during summertime, the strong impact of the anomalies of soil moisture in land-atmosphere occurred mainly over the transition zones with a climate between wet and dry climate regimes. The relevance and extent of this potential feedback are still poorly understood over West Africa.

This study will focus on the influence of soil moisture initial conditions anomalies on climate mean and it is based on performance assessment of the Regional Climate model version 4 coupled to the version 4.5 of the Community Land Model (RegCM4-CLM4.5) done by Koné et al. (2018) where the ability of the model to reproduce the climate mean has been validated. This study will help us to understand the impacts of Soil Moisture Initial Conditions on the new dynamical core non-hydrostatic of RegCM4 in the context of land-atmosphere coupling. We attempt, also, in this study to provide the quantification of the sensitivity of the RegCM4 model to initial soil moisture conditions, which could allow the evaluation and development of the RegCM4 model. However, in the part II of the article, the influence of soil moisture on climate extremes will be explored. The descriptions of the model and experiment setup used in this study are presented in Section. 2; in the Section 3, the influence of the anomalies in soil moisture initial conditions on the subsequent climate mean is analyzed and discussed; and in Section 4 the main conclusions close the paper.

## 2. Model and experimental design

### 2.1 Descriptions of the model and the observed datasets

We used in this study, the fourth generation of the Regional Climate Model (RegCM4) of the International Centre for Theoretical Physics (ICTP). Since this release, the physical representations have been submitted to a continuous process of development and implementation. The version used in the present study is RegCM4.7. The MM5 (Grell et al., 1994) non-hydrostatic dynamical core has been ported to RegCM without removing the existing hydrostatic core. The model dynamical core used in this study is non-hydrostatic. RegCM4 is a limited area model using a sigma pressure vertical grid and the finite differencing algorithm of Arakawa B-grid (Giorgi et al., 2012). The radiation scheme used in this version of RegCM4.7 is derived from NCAR (National Center for Atmospheric Research) Community Climate Model Version 3 (CCM3) (Kiehl et al., 1996), the representation of aerosols is from Zakey et al. (2006) and Solmon et al. (2006). The scheme of the large-scale precipitation used is from Pal et al. (2000), the moisture scheme is the SUBEX (SUBgrid EXplicit moisture scheme) takes in account the cloud variability scale sub-grid, and the accretion processes and evaporation for stable precipitation following the work of Sundqvist et al., 1989. In the planetary boundary layer, the sensible heat over ocean and land, the water vapour and the turbulent transports of momentum are calculated according to the scheme of Holtslag et al. (1990). The heat and moisture, the momentum fluxes of ocean surfaces in this study are computed as in Zeng et al. (1998). In RegCM4.7, convective precipitation and the land surface processes can be described by several parameterizations. Based on Koné et al. (2018), we selected the convective scheme of Emanuel (Emanuel, 1991) and the interaction processes between soil, vegetation and atmosphere are parameterized with CLM4.5. In each grid cell, CLM4.5 has 16 different PFTs (Plant Functional Types) and 10 soil layers (Lawrence et al., 2011; Wang et al., 2016). RegCM4 was integrated over the domain of West Africa depicted in Fig. 1 with 25 km (182x114 grid points; from 20°W-20°E and 5°S-21°N) of horizontal resolution and with 18 vertical levels and the initial and boundary conditions are from the European Centre for Medium-Range Weather Forecasts reanalysis (EIN75; Uppala et al., 2008; Simmons et al., 2007). The Sea Surface Temperatures (SST) is from the National Oceanic and Atmosphere Administration (NOAA) optimal interpolation weekly (OI_WK) (Reynolds et al., 1996). The source for the topography is from States Geological Survey (USGS) Global Multi-resolution Terrain Elevation Data (GMTED; Danielson et al., 2011) at 30 arc-second spatial resolution which is an update to the Global Land Cover Characterization (GTOPO; Loveland et al., 2000) dataset.

Our analysis is focused on the precipitation and the 2m air temperature over the West African domain during the summer of June-July-August-September (JJAS) for 2003 and 2004. The uncertainties reduction related to the absence of reliable observation system over the region (Sylla et al., 2013a; Nikulin et al.,2012), we validated the simulated precipitation based on two products: the TRMM datasets (Tropical Rainfall Measuring Mission 3B43V7) at the high-resolution 0.25°, available from 1998 to 2013 (Huffman et al., 2007), and The Climate Hazards Group Infrared Precipitation with Stations (CHIRPS) dataset developed at the University of California at Santa Barbara at the 0.05° high-resolution available from 1981 to 2020. The validation of the simulated 2 m temperature relies on two observational datasets: the global daily temperature from the Global Telecommunication System (hereafter GTS), gridded at 0.5° of horizontal resolution for 1979 to 2020 (Fan and van den Dool, 2008) and the CRU datasets (Climate Research Unit version 3.20) from the University of East Anglia, gridded at the horizontal resolution 0.5°and available from 1901 to 2011 (Harris et al., 2013). To facilitate the comparison with RegCM4 simulations, all products are re-gridded to 0.22° × 0.22° using a method of bilinear interpolation (Nikulin et al., 2012).

**2.2 Experiments setup and analysis methodology**

We set up an ensemble of 3 experiments each with simulations starting from June 1st to September 30th. The difference between these 3 experiments is on the change of soil moisture initial condition during the first day of the simulation (June 1st): For each experiment, we applied (i) a reference initial soil moisture condition, (ii) then a wet initial soil moisture condition, and finally (iii) a dry initial soil moisture condition.

We run the simulations over 5 years (2001 to 2005) during the months of June to September over our West African domain. We choose two extreme years (resp. the wettest and the driest year) among the 5 years to observe the estimates of the limits of the impact of internal soil moisture forcing on the new dynamical core non-hydrostatic of RegCM4. It is in the same context, several previous studies chosen two extreme years for their sensitivity study of initial soil moisture condition on the models. Hong and al. (2000) use in their study only two years (3 months per year) to investigate the impact of initial soil moisture over the North of America (in the Great Plains) during the two summers, May-June-July (MJJ) 1988 (corresponding to a drought in the Great plains) and MJJ 1993 (correspond to a flooding event). Over Asia, Kim and Hong (2006) used two contrasted years 1997 (below normal precipitation year) and 1998 (above normal precipitation year). The first 7 days (Kang et al., 2014) are excluded in the analysis as a spin-up period.

With very little variation in soil moisture in one day, soil moisture initial conditions are given at the first step of June 1$^{st}$ for the two summers JJAS 2003 and JJAS 2004. Except for the geographical location, the experimental setup is the same as that of Hong and Pan (2000). The geographical location of this study is the same as in Koné et al (2018), with four sub-regions (Fig. 1), each with different features of the annual cycle of precipitation: Central Sahel (10°W–10°E; 10°N-16°N), West Sahel (18°W-10°W; 10°N-16°N), and Guinea Coast (15°W-10°E; 3°N-10°N).

For each year, three experiments are conducted; we used the soil moisture from the reanalysis of the European Centre Meteorological Weather Forecast's reanalysis of the 20$^{th}$ century (ERA20C) to initialize the control runs. We initialized the dry and wet soil moisture initial conditions (in volumetric fraction $m^3.m^{-3}$) respectively at the wilting point (=0.117*10$^{-4}$) and the field capacity (=0.489) derived from ERA20C dataset. The wilting point and the field capacity correspond to the minimum and maximum values of soil moisture over our studied simulation studied.

Generally, in several previous studies (Liu et al. (2014), Hong and Pan (2000), Kim and Hong (2006)), the analysis methodology used is the mean biases (MB) averaged over their domains studied to quantify the impact of soil moisture anomalies, while in our study we used the mean biases and the probability density function (PDF, Gao et al. 2016; Jaeger and Seneviratne 2011) by fitting a normal distribution for this purpose to better capture how many grid points are impacted by the soil moisture initial conditions. The pattern correlation coefficient (PCC) is also used as a spatial correlation to reveal the degree of large-scale similarity between model simulations and the observation. We used the two-tailed of the student's t-distribution to investigate the differences which are statistically significant at each grid cell between the control and the sensitivity experiments (wet and dry). For the regional analysis such as MB, PCC and the PDF, both modeled and observed temperature and precipitation values were calculated only over land grid points.

## 3. Results and discussion

### 3.1. Influence of soil moisture initial conditions on precipitation.

In the aim to identify the extreme years (driest and wettest) impacted by the dry and wet experiments among the five years simulations (2001 to 2005), we display Changes in daily soil moisture for 5 years (2001 to 2005) and their climatological mean during JJAS over West African domain, from dry and wet experiments with respect to their corresponding control experiment in Figure 2. The Fig.2 shows that the weakest and strongest impact of the dry experiments is found for 2003 and 2004 respectively. For a wet year, the impact of drying out soil moisture is quickly erased. While for a dry year the impact of the drying of the soil is accentuated. This meaning that 2003 and 2004 are respectively the wettest and driest years in dry experiment. However, for the wet experiments, the weakest impact is found for 2004, and the strongest impact is found for the years 2001, 2002 and 2004. In a dry year, the impact of soil humidification is very quickly erased, while in a wet year the impact of soil humidification is accentuated. The wet experiments confirm the result obtained in dry experiments, 2003 and 2004 are wettest and driest years respectively. To conduct our analyzing to estimate the limits of the impact of internal soil moisture forcing on the new dynamical core non-hydrostatic of RegCM4, we have been used the two extreme years 2003 and 2004 (resp. the wettest and the driest years) among the 5 years. Figure 3 displays the spatial distribution of observed mean rainfall (mm/day) from CHIRPS (Fig.3a, d) and TRMM (Fig.3b, e) for JJAS 2003 and JJAS 2004 and their corresponding simulated from control experiments (Fig.3c, f) initialized with reanalysis soil moisture ERA20C. Table 1 reports the MB and the PCC for the simulations of the model and TRMM observation compared to CHIRPS, computed for the central Sahel, Guinea coast, west Sahel and the entire West African domain. CHIRPS product displays a zonal band of rainfall centered around 10° N decreasing from north to south (Fig.3a, d). The maximum values are located over the mountain regions of Cameroun and Guinea. The TRMM observation (Fig.3b, e) is closer to CHIRPS, and represents quite similarly the North–South gradient of precipitation with PCC up to 0.97 over the entire West African domain for both JJAS 2003 and JJAS 2004 (Table 1). However, although the observation datasets have similar large-scale patterns, they present differences at the local scale. CHIRPS shows a much larger extend of these maxima than TRMM, especially over the Guinea highland and Cameroon mountains, while

TRMM shows a large band of precipitation which extends too far into the Sahel region. The strongest mean biases between the two products are dry about -15.45 % and -16.96 % respectively for JJAS 2003 and JJAS 2004, and are located over the Guinea coast sub-region (Table 1). The control experiments (Fig.3 c and f) initialized with the reanalyze ERA20C soil moisture well reproduce the large-scale pattern of the observed rainfall with PCC 0.72 and 0.77 (Table 1) respectively for JJAS 2003 and JJAS 2004 over the West Africa domain, despite some biases at the locale scale. The spatial extent of rainfall maxima and the North-South gradient are well captured by control experiments; however, their magnitudes are underestimated. In general, the dry mean biases about -49.31% and -50.56% are found respectively for JJAS 2003 and JJAS 2004 over the whole West African domain (Table 1). Figure 4 displays change in mean precipitation (in %) for JJAS 2003 and JJAS 2004, for dry and wet experiments with respect to their corresponding control experiments, the dotted area shows changes with statistical significance of 0.05 level.

Dry and wet sensitivity experiments show that precipitation has been significantly affected by soil moisture anomalies at varying degrees according to the sub-regions (Fig. 4). For the dry experiments (Fig.4a, c), we found a dominant decrease of rainfall over the central Sahel especially in JJAS 2003 (Fig.4a), while the extent of this decrease is smaller in JJAS 2004(Fig.4c) and confined over the southern-west of Mali. On the other hand, we found a dominant increase of rainfall over the Guinea coast and the west Sahel, although there is a sparse decrease, especially over the Guinea coast. For the wet experiments (Fig.4b, d), there is a dominant increase of rainfall over most of the domains studied with a sparse decrease especially along the coastline of Liberia, Sierra Leone and Guinea for both JJAS 2003 and JJAS 2004 (rep. Fig.4a and c). Overall, the impact on the precipitation of the soil moisture initial conditions is homogeneous particularly over the central Sahel, i.e, the dry (wet) experiments with respect to the control exhibits significant decrease (increase) of precipitations (Fig.4a, b).

For a better quantitative evaluation, the PDF distributions of the changes in precipitation in JJAS 2003 and JJAS 2004, over (a) central Sahel, (b) West Sahel, (c) Guinea coast and (d) West Africa derived from dry and wet experiments compared to the corresponding control experiments are shown in Figure 5. The impact on the precipitation of soil moisture initial conditions is not homogeneous over most of the studied domains (Fig.5 b-d) except the central Sahel where the dry (wet) experiments with respect to the control display significant decrease (increase) of precipitation (Fig.5a,). However, the strongest impacts on precipitation in wet and dry experiments are found respectively over west and central Sahel, and the peak mode of change are about respectively 40% and -8%. The impacts on precipitation from wet experiments are greater than from dry experiments.

It is worth to note that, over the West Sahel and Guinea coast, for both dry and wet experiments tend to cause an increase of precipitation. This indicates that the increased precipitation is likely to occur not only for wet experiments but also for dry experiment (Fig. 5b). The lag between the JJAS 2003 and JJAS 2004 PDFs for wet and dry experiments indicates a somewhat significant impact if we compare the two years, this in particular over Guinea and west Sahel (Fig. 5 b and c). The wet year has a greater impact compared to the dry year in most of domains studied (Fig. 5). These results are consistent with previous studies which supported a strong relationship between precipitation and soil moisture in particular over the transition zones with a climate between wet and dry climate regimes (Koster et al., 2004; Liu et al., 2014; Douville et al., 2001).

To better study the influence of soil moisture anomalies on precipitation for the both dry and wet years over the West African domain and its sub-regions, we analyzed changes in the daily domain-average of soil moisture and precipitation (resp. Figure 6 and Figure 7) for JJAS 2003 and JJAS 2004, from dry and wet experiments with respect to their corresponding controls experiments. The second soil layer in CLM4.5 (0 to 2.80 cm) is used in this study, this soil layer corresponds to the top layer soil moisture. In general, soil moisture anomalies persist for three or four months over the domains studied (Fig.6). The anomalies of soil moisture disappear for dry and wet experiments with varying duration, between three to four months from one region to another over the domain studied. The strongest duration and amplitude is found over the west Sahel sub-region, for the both wet and dry experiments, it lasts four months in JJAS 2003 and JJAS 2004, although the signal is rather weak in the wet experiments as compared to the dry ones (Fig. 6b). The weaker change in soil moisture anomalies is found over the Guinea coast for wet experiments and lasts three months (Fig. 6c). While in dry experiments, the weaker change in soil moisture anomalies is found over central Sahel and last three months (Fig.6a).

Figure 7 shows response of the daily precipitation to the soil moisture initial conditions over the different domains studied. In general, the impact of the wet soil moisture anomalies on daily precipitation is larger in magnitude than that of dry anomalies over most of the domains studied (Fig. 7). The strongest daily precipitation response in dry experiment (-4mm.day$^{-1}$) is found over the Guinea coast in the wet year JJAS 2003 (Fig. 7c), while for the wet experiments (more than 8mm.day$^{-1}$, especially in JJAS 2003), it is found over the West Sahel and the Guinea coast (resp. Fig. 7 b and c). However, the impact on daily precipitation of the soil moisture initial conditions has a much shorter-lived than soil moisture change. The significant impact on daily precipitation, greater than 1mm.day$^{-1}$ is only shown in wet experiments, and does not last more than fifteen days for most of the domains studied, except for the Guinea coast where it lasts about 1 month. It is worth to note the peaks in precipitation over West Sahel and Guinea coast (resp. Fig.7b and c) during the two months August and September that coincide with fluctuation in the anomalies of soil moisture (Fig.6b and c). This indicates the soil moisture and precipitation feedback is strong during this period over the Guinea coast and West Sahel regions. The response of the daily precipitation to the anomalies in soil moisture initial conditions is also sensitive to the wet and dry year. This is indicated by the lag between dry and wet experiments for JJAS 2003 and JJAS 2004 years (Fig7). The magnitude of impacts due to contrasting years depends on the location. For example, over Guinea coast, in the dry experiments, the wet year presents a greater impact compared to the dry year (Fig.7 c). This trend is reversed for the central Sahel (Fig. 7a). These results are in line with the previous works which argued that the soil moisture-atmosphere feedback strength and the land memory depend on the place (Vinnikov et al. 1996; Vinnikov and Yeserkepova 1991).

Figure 8 and 9 show the vertical profile change respectively in humidity and temperature for JJAS 2003 and JJAS 2004 from the dry and wet experiments with respect to control experiments over the whole West Africa domain and its sub-region indicated in Fig. 1.

For the dry and wet experiments, the impact on humidity and temperature (Fig.8 and Fig.9) are significant in the lower troposphere. The dry (wet) soil moisture experiments, in the lower and somewhat in the middle troposphere, show drying (moistening) for humidity and warming (cooling) for temperature. This indicates for dry (wet) experiments a weak (strong) dry convection over most of the domains studied (Fig.8 and Fig.9). The strongest impact on humidity and temperature in lower and middle troposphere is found over central Sahel (Fig.8a and Fig. 9a). These results in the lower troposphere are consistent with the precipitation sensitivity, especially over the central Sahel in JJAS 2003 (Fig.4 a, b). However, over the west Sahel and the Guinea coast this impact is somewhat low compared to that of central Sahel. In the dry experiments over the Guinea coast (Fig.8c), these trends are reversed above 500 hPa for humidity, indicating wet convection in this sub-region. These results in the lower atmosphere are consistent with the precipitation sensitivity over the Guinea coast (Fig.4a, c).

On the over hand, in the upper troposphere, the significant impact on humidity and temperature is found only for wet experiments, and exhibits a drying and warming respectively for humidity and temperature over most of the domains studied (Fig.8 and Fig.9). In the wet experiments, the impact on upper tropospheric variability of the anomalies in soil moisture initial conditions is also identified by Hong and Pal (2000). The effect of soil moisture anomalies is mostly confined to the near-surface and somewhat in the upper troposphere. Furthermore, in the upper troposphere, relative humidity responses to the anomalies in soil moisture initial conditions are more sensitive at atmospheric temperature to the contrast of the year, especially, in wet experiments (Fig. 8 and Fig. 9).

To understand the origins of the precipitation changes in Figure 4, we analyzed the lower tropospheric wind (850hpa) and moisture changes for JJAS 2003 and JJAS 2004 from the dry and wet experiments with respect to their corresponding control experiments in Figure 10. In the dry experiments, we found a dominant decrease of moistening over most of domain studied, however the strong wind magnitude change over the Atlantic ocean, tends to bring the increase of moistening from the ocean to Guinea coast and west Sahel, this can explain the increase of precipitation over these sub-region in the dry experiments. While over the central Sahel, a weak change in wind magnitude is found, leading to the strong decrease of precipitation there, especially in JJAS 2003 (Fig.4a). On the other hand, for the wet experiments, an increase in moistening is located over most of domain studied. And the strong change in wind magnitude, tend to shift the moistening from the North to the South, leading to increased precipitation over most of domain studied in wet experiments (Fig.4 b and d). These results are broadly consistent to the dry and wet precipitation changes shown in Figure 4.

Summarizing this section results, the anomalies in soil moisture anomalies persist for three or four months, while the significant impact on precipitation, greater than $1mm.day^{-1}$, of the anomalies in soil moisture is much shorter, no longer than one month. The anomalies in soil moisture initial conditions effect are mostly confined to the near-surface climate and somewhat in the upper troposphere.

### 3.2. Influence on temperature and other surface fluxes.

The spatial distribution of averaged temperature (°C) from CRU (Fig.11 a and d) and GTS (Fig.11 b and e) observations for JJAS 2003 and JJAS 2004 and their corresponding simulated from control experiments (Fig.11 c and f) initialized with reanalysis soil moisture ERA20C are shown in Fig.10. Table 2 resumes the PCC and the MB between the simulation of the temperatures and CRU observation, calculated for the west Sahel, central Sahel, Guinea coast and the whole West African domain.

The CRU temperature displays a zonal distribution over the whole West Africa domain. Maximum values around 34 °C are located over the Sahara, and the lowest temperatures are found on the Guinea coast especially in orographic regions such as Guinean highlands, Cameroon mountains and the Jos Plateau, where the temperature does not exceed 26°C. The two observation datasets GTS and CRU are similar at large spatial scale with PCC about 0.99 over the entire West African domain for both JJAS 2003 and JJAS 2004 (Table 2). However, the extension and the amplitude of these maxima and minima are quite different in the two sets of gridded observations. While GTS (Fig.11b and e) observation displays large (small) areas with maxima (minima) values, CRU (Fig.11a and d) presents small (large) area of these maxima (minima) values. The strongest mean warm biases between the two observation products, about 0.54°C and 0.67°C respectively for JJAS 2003 and JJAS 2004, are located over the west Sahel sub-region compared to the others (Table 2). The control experiments (Fig.11 c and f) show a good agreement in the representation of the large-scale pattern of the observed temperature (CRU) with PCC 0.99 for both JJAS 2003 and JJAS 2004 (Table 2), including the zone of the meridional gradient of the surface temperature between Sahara Desert and Guinea coast which is crucial for the African easterly jet (AEJ) evolution and formation (Thorncroft and Blackburn 1999; Cook 1999). However, some biases are noted at the local scale. The spatial extent of temperature maxima and minima are well reproduced by control experiments, however their magnitude are overestimate. The strongest warm mean biases of control experiments with respect to CRU observation are about 2.68 °C and 2.14 °C respectively for JJAS 2003 and JJAS 2004, are found over the West Sahel sub-region (Table 2).

Figure 12 shows changes in mean temperature (°C) for JJAS 2003 and JJAS 2004, from dry and wet experiments with respect to their corresponding control experiments. The dotted area shows changes that are statistically significant at the 0.05 level. In the dry experiments, for both JJAS 2003 and JJAS 2004, the dominant warm changes are located over most of the area under the latitude 13°N, with maximum values located over the Guinea coast. However, a mixture of warm and cool changes is located around the latitude 13°N (Fig.12a and c). On the other hand, for the wet experiments, we found a dominant cool change over most of the area under the latitude 15°N, with maximum values around the latitude 13°N. Whereas a dominant warm change is located above the latitude 15°N (Fig.12 b and d). Overall, the temperature is more sensitive to soil moisture anomalies than precipitation over most of the domains studied.

For a better quantitative evaluation, the PDF distributions of the changes in mean temperature in JJAS 2003 and JJAS 2004, over (a) the central Sahel, (b) West Sahel, (c) Guinea and (d) West Africa derived from dry and wet experiments with respect to their corresponding control experiments are shown in Figure 13. The temperature impact is homogeneous over the central Sahel and Guinea coast (Fig.13a and c). The strongest homogeneous impacts on temperature of soil moisture initial conditions anomalies are located over the central Sahel, i.e, the dry (wet) experiments display a decrease (an increase) in temperature change with the peak mode of change at -1.5 °C (0.5°C) compared to other sub-regions, for both JJAS 2003 and JJAS 2004. Over the west Sahel, both wet and dry experiments lead to a decrease of temperature. The impact on temperature of the anomalies in soil moisture is somewhat sensitive to the wet and dry year, as

mentioned above, this is indicated by the lag between wet and dry experiments (Fig. 13). The impact on dry and wet years depends on the area and the type of experience dry or wet. Overall, the dry (wet) sensitivity experiments for 2m-temperature show a dominant increase (decrease) of warming (cooling) for both JJAS 2003 and JJAS 2004 over most of the domains studied except for the west Sahel, where both dry and wet experiments lead to an increase of temperature (Fig.13).
We now analyze the influence of soil moisture initial conditions anomalies on land energy balance, particularly on the surface fluxes sensible and latent heat. Figure 14 shows changes in sensible heat fluxes (in $W.m^{-2}$) for JJAS 2003 and JJAS 2004, from dry and wet experiments compared to their corresponding control experiments, and the dotted area shows changes that are statistically significant at the 0.05 level. As can be seen in figure 14, the soil moisture initial conditions anomalies strongly affect the sensible fluxes.
In the dry experiments, the increase of sensible heat flux changes are located under the latitude 15°N, while the decrease of sensible heat flux changes are found over most of area above the latitude 15°N for both JJAS 2003 and JJAS 2004 (Fig.14a, c). Conversely, in wet experiments we have a dominant decrease of sensible heat flux changes, found over almost whole West Africa domain except the orographic and somewhat along Guinea coastline for both JJAS 2003 and JJAS 2004 (see Fig 14b, d).
The PDF distributions of the change in sensible heat flux are displayed in Figure 15. The dry (wet) experiments show an increase (decrease) of the sensible flux in both JJAS 2003 and JJAS 2004 over all the domains studied (Fig. 15). The impact in wet experiments is strong compared to the dry experiments over central and west Sahel except over Guinea coast (Fig. 15). Overall, the impact on sensible heat flux of soil moisture initial conditions anomalies is homogeneous, i.e., dry experiments tend to cause an increase of sensible heat flux while the wet experiments tend to favor a decrease of sensible heat flux over most of the domains studied. The strongest impacts on sensible heat flux in wet and dry experiments are found over respectively west Sahel and Guinea coast, with peak modes about respectively $-40W.m^{-2}$ and $10W.m^{-2}$ (resp. Fig. 15,b and Fig. 15c).
Unlike the case of sensible heat flux, changes in latent heat show opposite patterns, we found a dominant decrease (increase) of latent heat flux in dry (wet) experiment over almost all of the studied domains. Nevertheless, in the dry experiments, we found a sparse increase of latent heat over the Sahara and Senegal (Fig.16b, d), while in wet experiment a sparse decrease is located over the Guinea coast (Fig.16b, d). The PDF distributions of latent heat flux change are shown in Figure 17. It can be seen that the impact on latent heat flux of soil moisture anomalies is homogeneous, i.e. dry experiments result to a decrease in latent heat flux while the wet experiments result in an increase in the latent heat flux over most of the domains studied. The

strongest impact on latent heat flux in wet and dry experiments are found over respectively west Sahel and Guinea coast with peaks mode at 40W.m$^{-2}$ and -15W.m$^{-2}$ (resp. Fig. 17 b and Fig. 17 c). Overall, the impacts in wet experiments on latent and sensible heat flux are strong compared to the dry experiments over most of the domains studied, except over Guinea coast (Fig. 17).

In order to know whether most of the changes in energy go to evaporating water or to heating the environment, we analyzed in Fig. 18 the changes in Bowen ratio for JJAS 2003 and JJAS 2004, from dry and wet experiments with respect to their corresponding control experiments. The dotted area displays differences that are statistically significant at the 0.05 level. The soil moisture anomalies strongly affected the Bowen ratio. The dry experiments show a dominant increase of evaporation energy (Bowen ratio value in the range [0,1]) under the latitude 15°N for both JJAS 2003 and JJAS 2004 (Fig.18a, c). However, above latitude 15° N we found a mixture of increasing and decreasing energy for environment heating (Bowen ratio value more than ±1) (Fig.18a, c). For the wet experiments (Fig.18b, d), we found a dominant decrease of energy for environment heating above the latitude 14°N (Bowen ratio less than -1), while under this latitude, we found a mixture of decrease and increase in evaporation energy (Bowen ratio in the range [-1; 1]). As expected, the areas where most of the energy changes go to water evaporation are generally coincident with areas of temperature changes. The decrease (increase) in evaporation area coincides with decrease (increase) of temperature change.

For a quantitative evaluation, the PDF distribution of the Bowen ratio is shown in Figure 18. Over the Guinea coast, for both dry and wet experiments, most of the energy go to evaporation with decrease in Bowen ratio about, the dry (wet) experiments show an increase (decrease) of water evaporation energy about 0.12 (-0.1) in both JJAS 2003 and JJAS 2004 (Fig. 19c).

On other hand, over the central Sahel (Fig.19 a), for the dry and wet experiments, most of the energy goes to evaporation. The dry (wet) experiments further increase (decrease) the evaporative energy with pic at 0.4 (-0.7) for both JJAS 2003 and JJAS 2004 over the central Sahel. In contrast, in wet (dry) experiments over west Sahel (Fig. 19b), most of the energy goes to heat the environment (to evaporation) with a decrease in Bowen ratio about -3 (-0.1).

We now examine the impact on the stability of planetary boundary layer (PBL) of the anomalies in soil moisture initial conditions. Soil moisture can influence rainfall by limiting evapotranspiration, which affects the development of the daytime planetary boundary layer and thereby the initiation and intensity of convective precipitation (Eltahir, 1998). Figure 20 shows the changes in PBL (in m) for JJAS 2003 and JJAS 2004, from dry and wet experiments with respect to their corresponding control experiments with dotted areas that are statistically significant at the 0.05 level. The soil moisture anomalies impact significantly the PBL. The dry experiments show an increase of the PBL under the latitude 15°N, except a western part of west Sahel, while a dominant decrease of PBL is shown above this latitude for both JJAS 2003 and JJAS 2004 (resp. Fig.20 a and c). For the wet experiments, a decrease of PBL is located over most of the domains studied, however a sparse increase is found above the latitude 15°N. The PDF distribution of PBL changes, computed over the area indicated in Figure1 is shown in Figure 21. The impact on PBL is homogeneous over most of the domains studied (Fig.21). The dry (wet) experiments lead to an increase (decrease) of PBL for both JJAS 2003 and JJAS 2004 over most of the domains studied. The strongest impacts on PBL, in the wet and dry experiments, are found over respectively the west Sahel and Guinea coast, about respectively -300 m and 150m. There is a dry (wet) air above the area where there is increase (decrease) of PBL, which results in warm (cool) and dry (moist) over most of the domains studied (see Fig. 8 and Fig. 9). These results are consistent with the work of Han and Pan 2003.

Summarizing the results of this section, simultaneously the cooling of surface temperature is associated with a decrease in latent heat, and increase in sensible heat and the PBL over most of the domain studied. Conversely the warming of surface temperature is associated with an increase in latent heat and decrease in sensible heat and the PBL height. These results are consistent with previous work of Eltahir et al. (1998). Furthermore, sensible and latent heat fluxes, Bowen ratio and PBL responses to the anomalies in soil moisture initial conditions are somewhat sensitive to the contrast of year and experiments (wet and dry).

## 4. Conclusion

The impact of the anomalies in soil moisture initial conditions on the subsequent summer mean climate over West Africa is explored using the RegCM4-CLM45. Particularly, the aim of this study was to investigate how soil moisture initialization at the beginning of the rainy season may impact the intraseasonal variability of temperature and precipitation mean within the subsequent season (June to September). For this purpose, three (3) experiments each with simulations starting from June 1st to September 30$^{th}$ were set up and runs were performed in JJAS 2003 and in JJAS 2004. The difference between these 3 experiments is on the change of soil moisture initial condition at the beginning of the simulation: For each experiment, we applied (i) a control soil moisture initial condition, (ii) then a wet soil moisture initial condition, and (iii) a dry soil moisture initial condition.

The impact of soil moisture initial condition on precipitation depends on the location, the magnitude and on the persistence of the anomalies of soil moisture initial condition throughout the season. Over the West Sahel and the Guinea coast, both dry and wet experiments lead to an increase of precipitation stronger in the wet experiment with a peak of change of 40% noted in the West Sahel. Over the Central Sahel, the wet experiment lead to an increase of precipitation with a peak of change around 15% while the dry experiments lead to a decrease of precipitation with a peak of change not exceeding 10%. Anomalies of soil moisture initial condition can persist for three to four months (90-120 days) depending the region of West Africa but the impact on precipitation is no longer than 30 days (15 days over the Sahel and 30 days over the Guinea Sahel). Our results indicate that a wet soil moisture initial condition lead in the low levels of the atmosphere to an increase of relative humidity associated with a cooling of temperature and in the upper levels, to a decrease of relative humidity and a warming, while the dry experiment mainly impact the lower levels with a decrease of the relative humidity associated with a warming. However, over the West Sahel and Guinea coast, the increase of precipitation shown in the dry experiments may result from the transport of moisture from the Atlantic Ocean by westerlies. The temperature is more sensitive to the anomalies of soil moisture initial condition than precipitation. The strongest impacts are located over the Central Sahel with the peak of change of -1.5 °C and 0.5°C respectively in wet and dry experiments. Moreover, the soil moisture initial conditions influence the surface fluxes such as the sensible and latent heat, the Bowen ratio and the PBL height.

The main conclusion of our study shows that soil moisture as a boundary condition plays a major role in controlling summer climate variability not only over the transition zone of climate but also over humid zone such as Guinea Coast. This study demonstrates that a good prescription of the initial condition of soil moisture can improve the simulation of the precipitation and air temperature, then would help to reduce biases in climate model simulations. Overall, land surface initialization can contribute to improve subseasonal to seasonal forecast skill, but this needs to be investigated further. We recognize that sensitivity experiments such as "wet" and "dry" ones conducted in this study were not intended to simulate real climate since such extremes are very rare. These kinds of experiments, however, can provide estimates of the limits of the impact of internal forcing of the soil moisture on the new non-hydrostatic dynamical core of RegCM4. Finally, in a context of climate change with projected increase of high impact weather events in the region, there is a need to explore the sensitivity of soil moisture initial conditions on climate extremes.

**Authors contributions**

The authors declare to have no conflict of interest with this work. B. Koné and A. Diedhiou fixed the analysis framework. B. Koné carried out all the simulations and figures production according to the outline proposed by A. Diedhiou. B. Koné and A. Diedhiou, S. Anquetin and A. Diawara worked on the analyses. All authors contributed to the drafting of this manuscript.

**Acknowledgements**

The research leading to this publication is co-funded by the NERC/DFID "Future Climate for Africa" programme under the AMMA-2050 project, grant number NE/M019969/1 and by IRD (Institut de Recherche pour le Développement; France) grant number UMR IGE Imputation 252RA5.

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**Tables and figures:**

| | **Central Sahel** | | **West Sahel** | | **Guinea** | | **West Africa** | |
|---|---|---|---|---|---|---|---|---|
| | **PCC** | **MB (%)** | **PCC** | **MB (%)** | **PCC** | **MB (%)** | **PCC** | **MB (%)** |
| **TRMM 2003** | **0.98** | **7.60** | **0.96** | **-945** | **0.98** | **-15.45** | **0.97** | **-0.57** |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **CTRL_2003** | **0.98** | **-47.97** | **0.87** | **-75.76** | **0.82** | **-47.12** | **0.73** | **-49.31** |
| **TMM 2004** | **0.98** | **-0.62** | **0.99** | **-7.03** | **0.98** | **-16.96** | **0.97** | **-1.56** |
| **CTRL_2004** | **0.98** | **-47.89** | **0.87** | **-68.35** | **0.85** | **-51.97** | **0.77** | **-50.56** |

**Table1:** The pattern correlation coefficient (PCC) and the mean bias (MB) for JJAS precipitation for model simulation and observation TRMM with respect to CHIRPS, calculated for Guinea coast, central Sahel, west Sahel and the entire West African domain during the period 2003 and 2004.

| | **Central Sahel** | | **West Sahel** | | **Guinea** | | **West Africa** | |
|---|---|---|---|---|---|---|---|---|
| | **PCC** | **MB (°C)** | **PCC** | **MB (°C)** | **PCC** | **MB (°C)** | **PCC** | **MB (°C)** |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **GTS 2003** | **0.99** | **0.31** | **0.99** | **0.54** | **0.99** | **0.28** | **0.99** | **0.39** |
| **CTRL_2003** | **0.99** | **1.52** | **0.99** | **2.68** | **0.99** | **-0.34** | **0.99** | **0.85** |
| **GTS 2004** | **0.99** | **0.32** | **0.99** | **0.67** | **0.99** | **0.28** | **0.99** | **0.40** |
| **CTRL_2004** | **0.99** | **1.50** | **0.99** | **2.14** | **0.99** | **-0.57** | **0.99** | **0.51** |

**Table2:** The pattern correlation coefficient (PCC) and the mean bias (MB) for JJAS 2m-temperature for model simulation and observation (GTS) with respect to CRU, calculated for Guinea coast, central Sahel, west Sahel and the entire West African domain during the period 2003 and 2004.

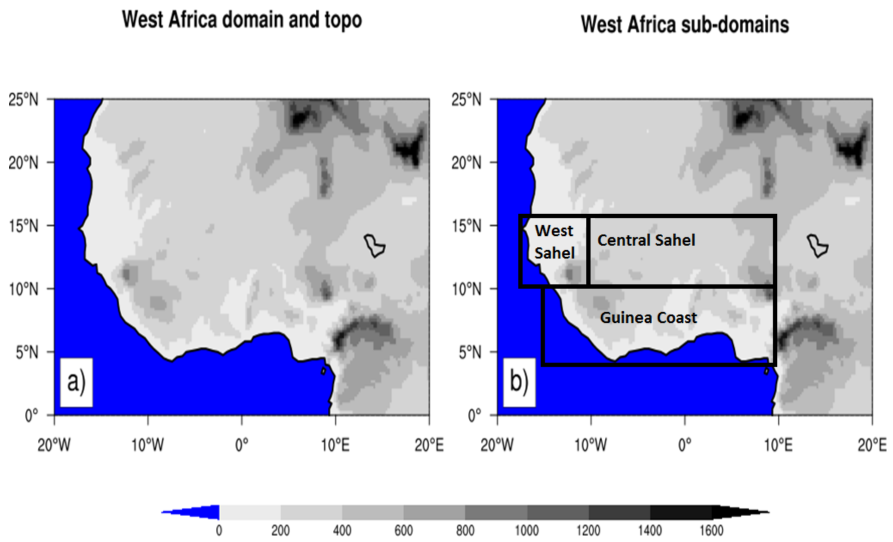


**Figure 1:** Topography of the West African domain. The analysis of the model result has an emphasis on the whole West African domain and the three subregions Guinea coast, central Sahel and west Sahel, which are marked with black boxes.

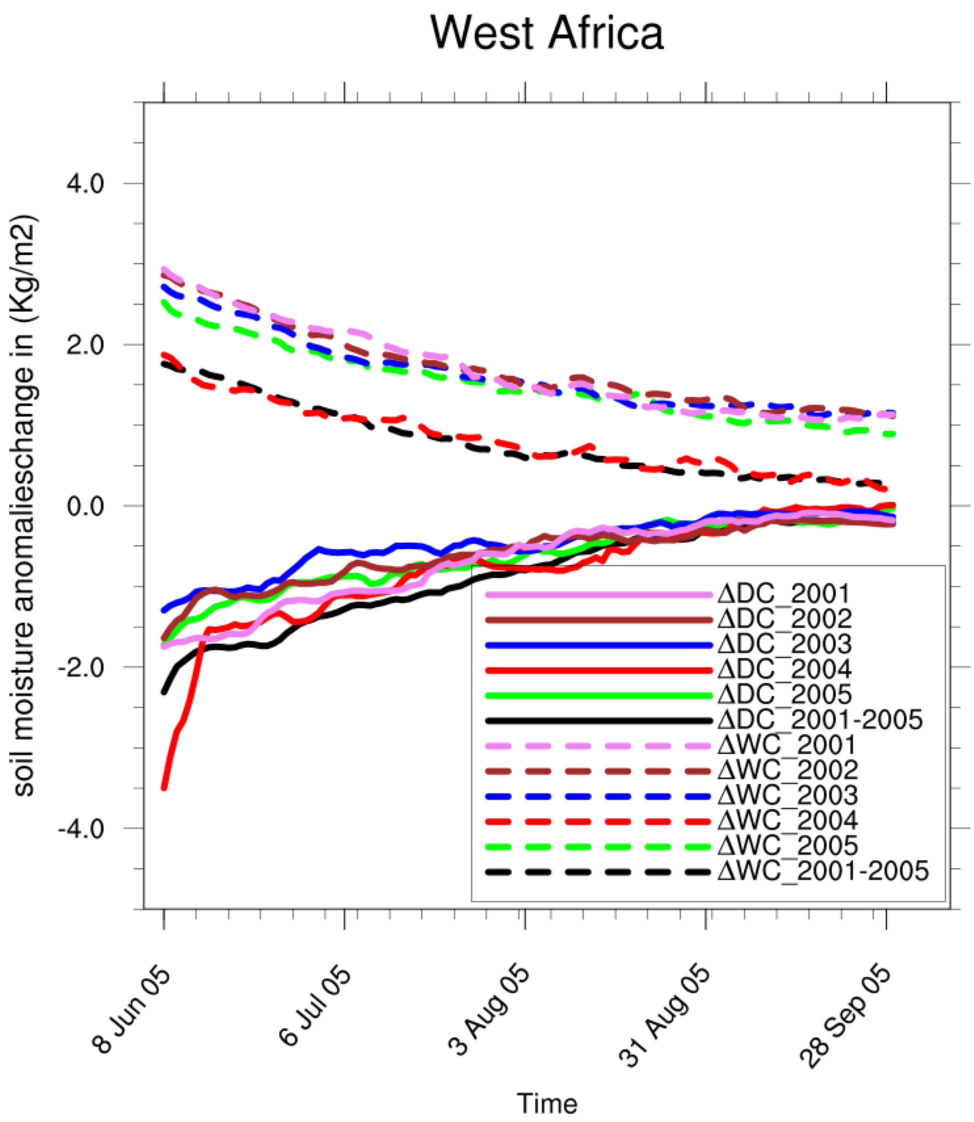


**Figure 2:** Changes in daily soil moisture for 5 years (2001 to 2005) and their climatological mean during JJAS over West African domain, from dry (ΔDC) and wet (ΔWC) experiments with respect to their corresponding control experiment.

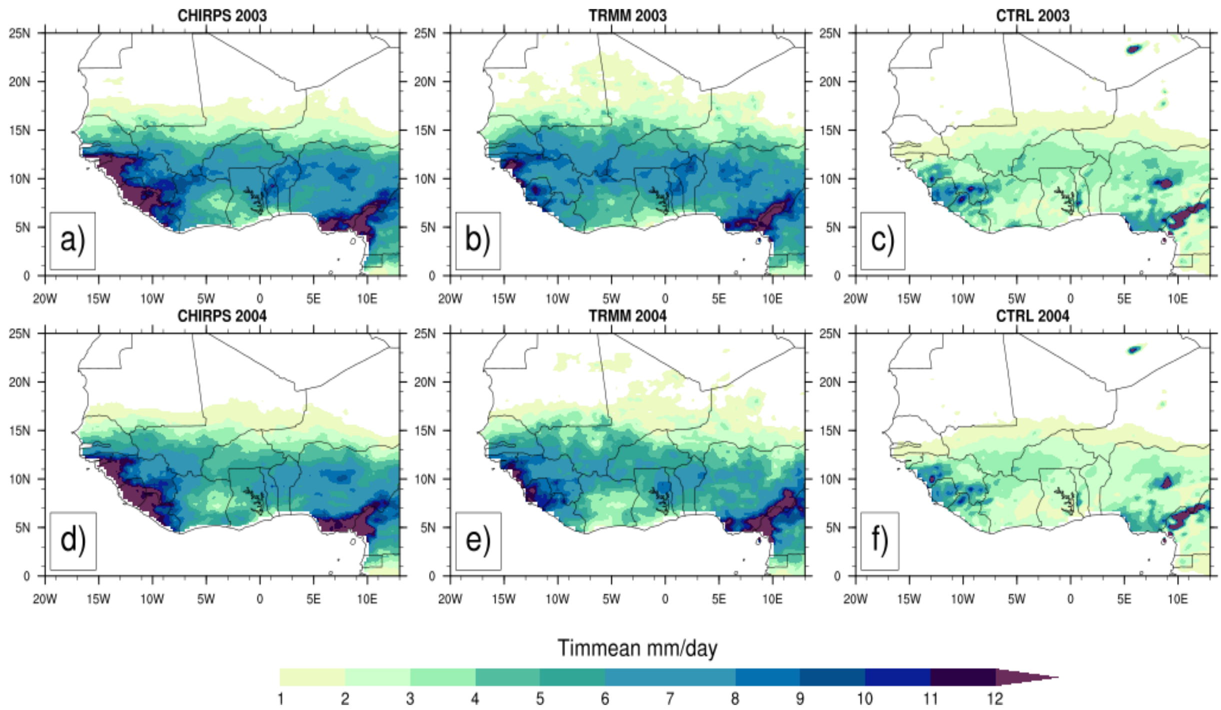


**Figure3:** Observed 4-month averaged (JJAS) precipitation (mm/day) from CHIRPS (a and d) and TRMM (b and e) for 2003 and 2004 and their corresponding simulated control experiments (CTRL) (c and f) with the reanalysis initial soil moisture ERA20C.

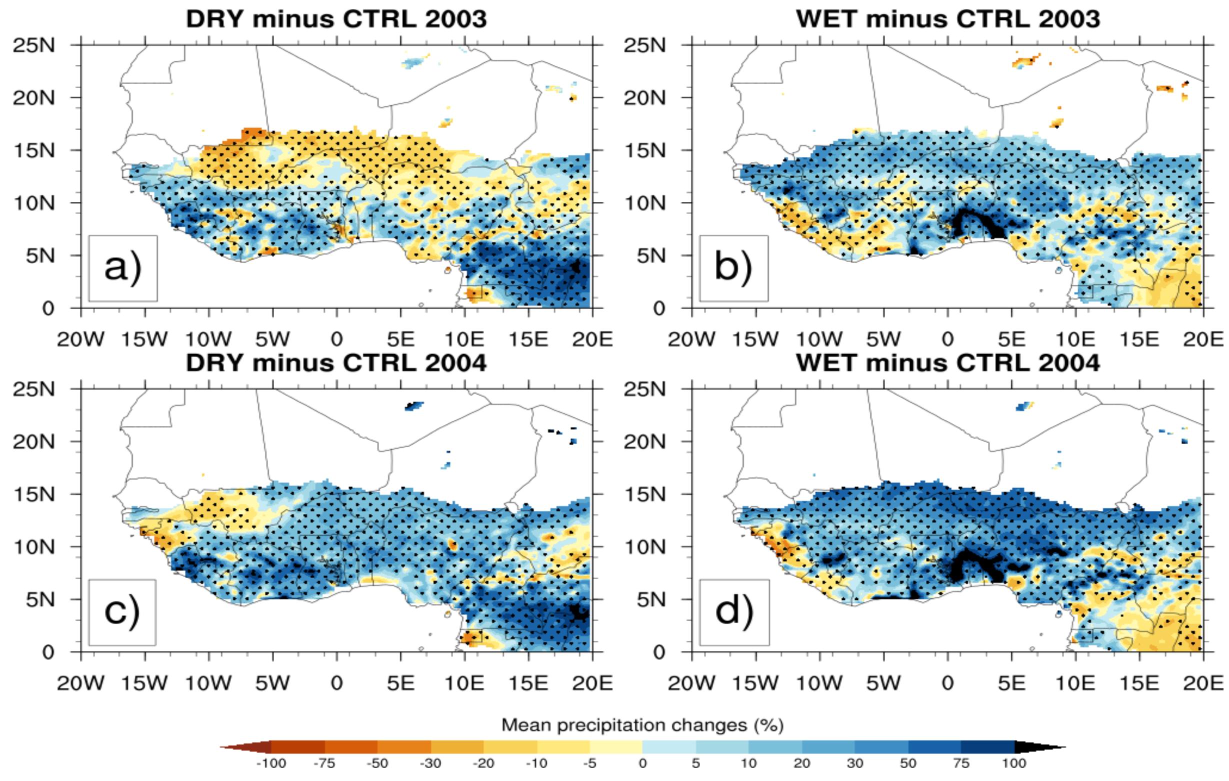


**Figure4:** Changes in mean precipitation (in %) for JJAS 2003 and JJAS 2004, from dry (resp. a and c) and wet (resp. b and d) experiments with respect to their corresponding control experiment, the dotted area shows differences that are statistically significant at 0.05 level.

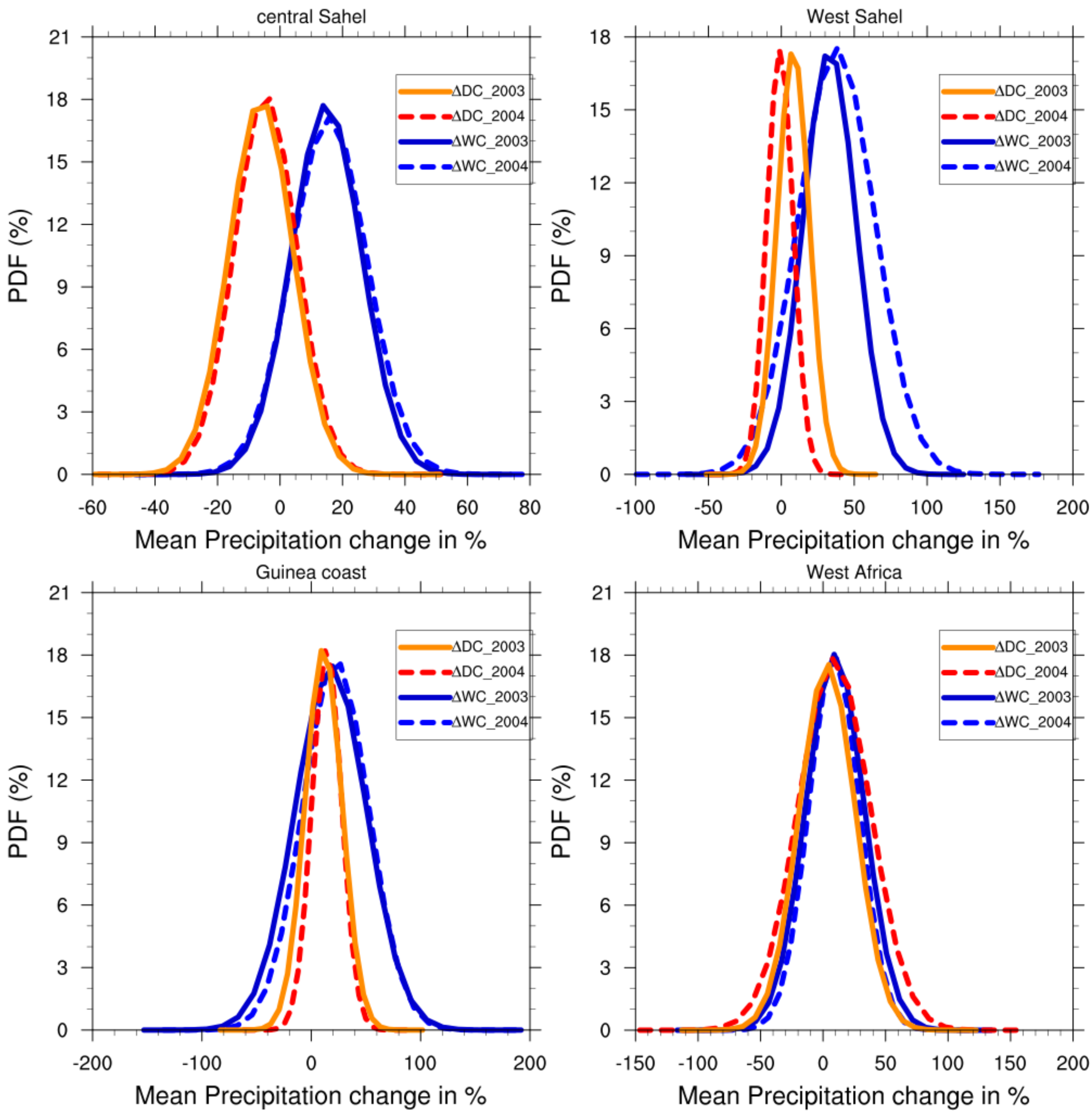


**Figure 5:** PDF distributions (%) of mean precipitation changes in JJAS 2003 and JJAS 2004, over (a) central Sahel, (b) West Sahel, (c) Guinea and (d) West Africa derived from dry (ΔDC) and wet (ΔWC) experiments compared to their corresponding control experiment.

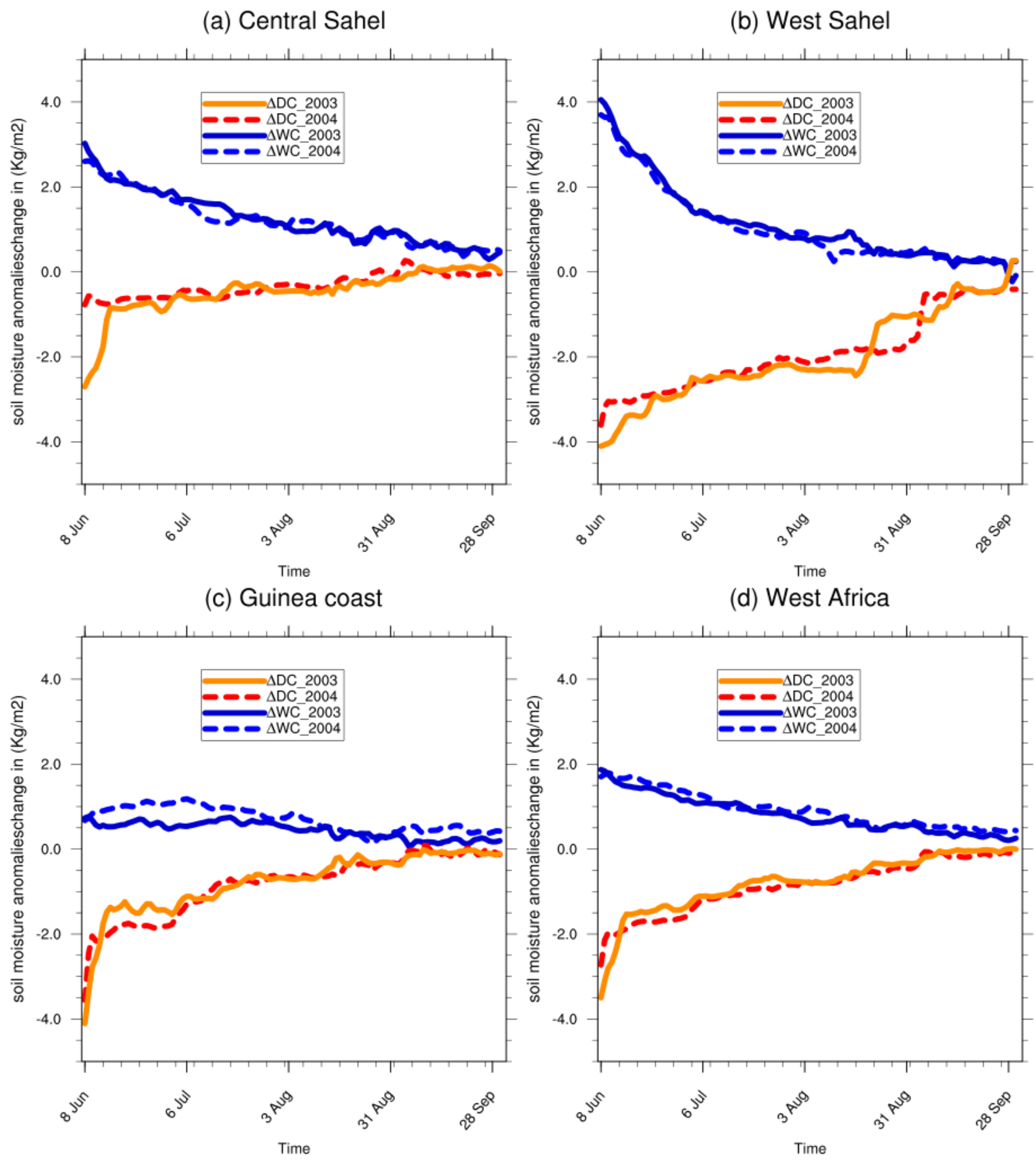


**Figure 6:** Daily domain-average soil moisture changes for JJAS 2003 and JJAS 2004, from dry (ΔDC) and wet (ΔWC) experiments with respect to their corresponding control experiment.

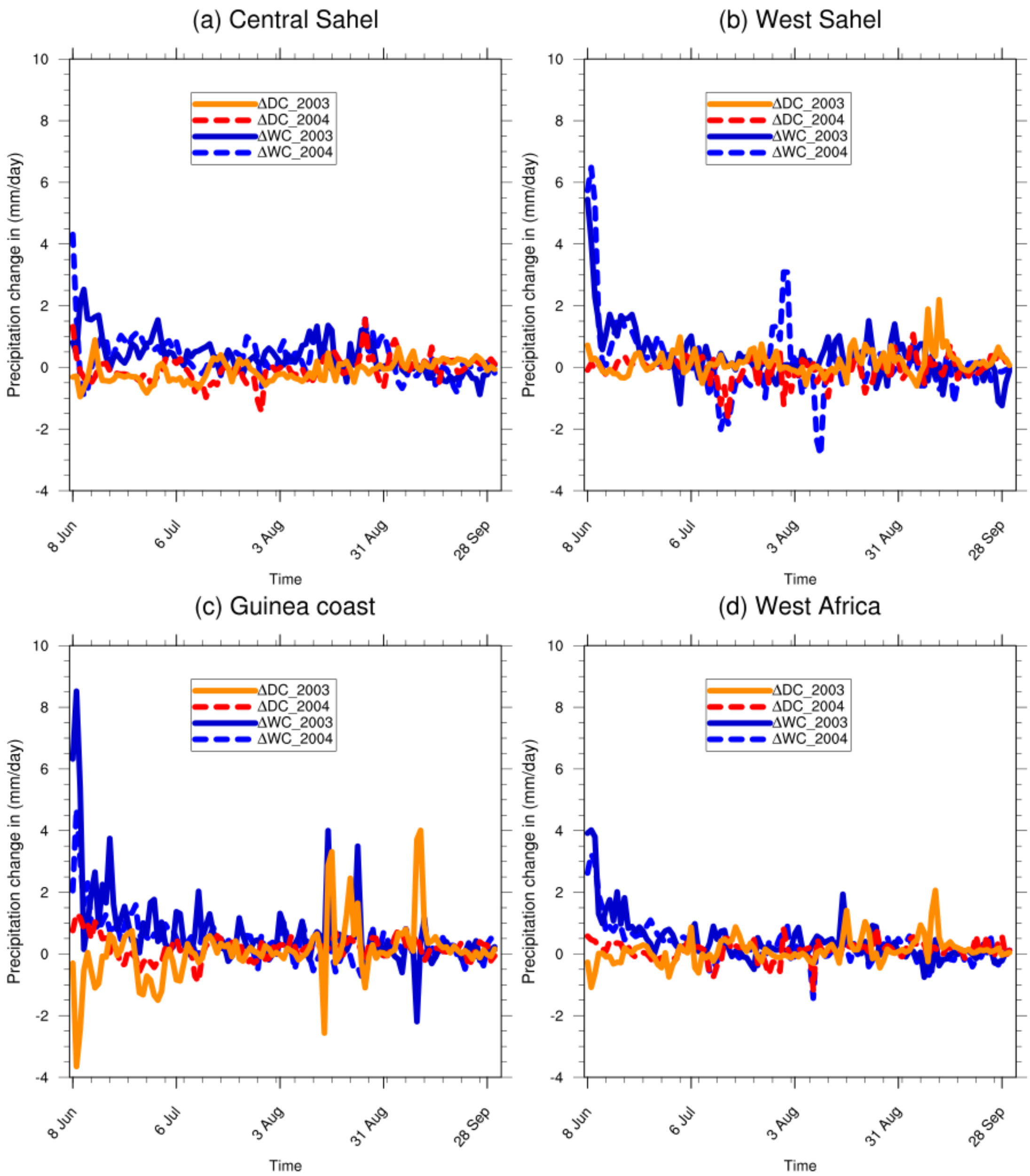


**Figure 7:** Daily domain-average precipitation changes for JJAS 2003 and JJAS 2004, from dry (ΔDC) and wet (ΔWC) experiments with respect to their corresponding control experiment.

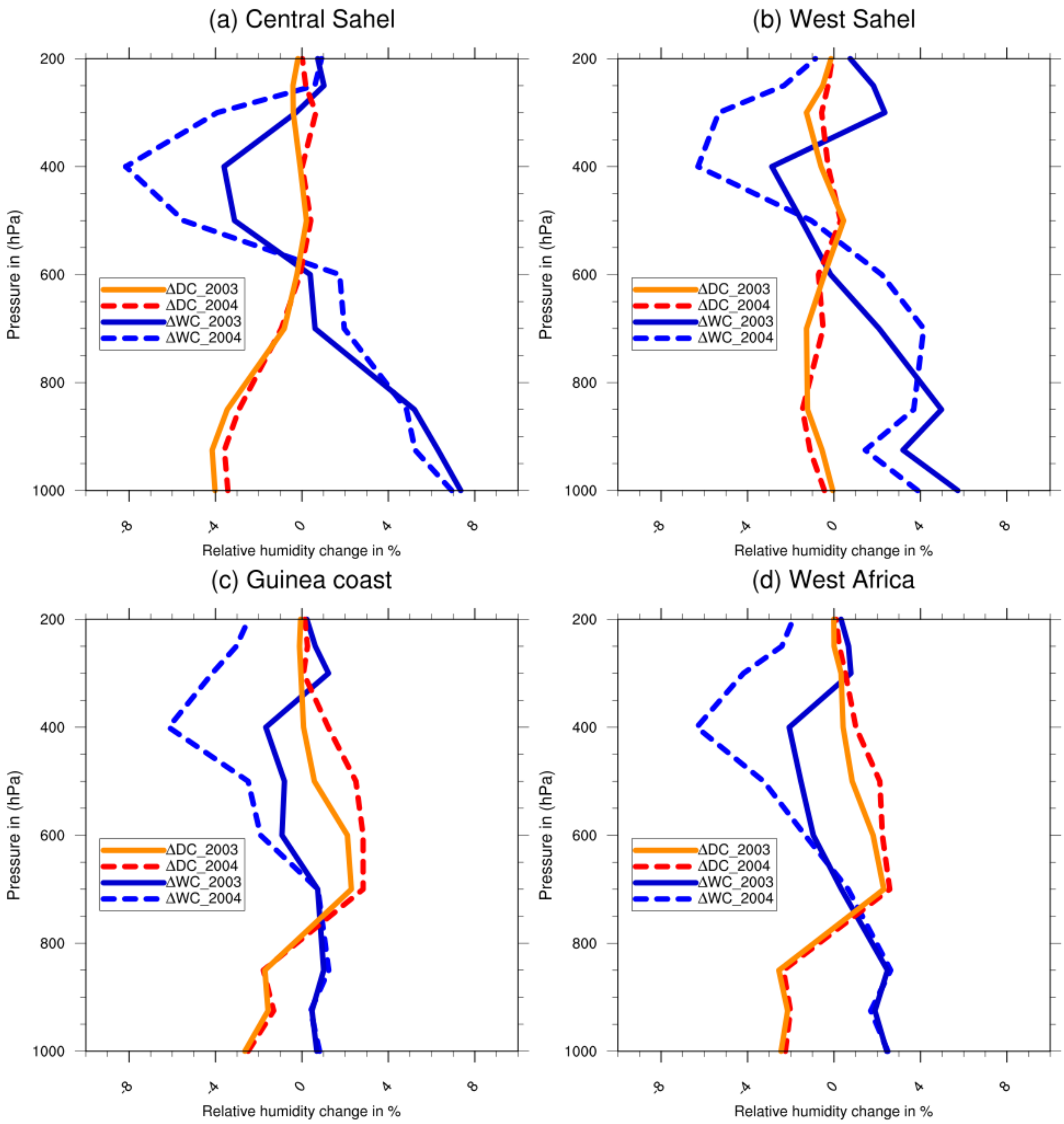


**Figure 8:** Vertical profile changes in Relative humidity for JJAS 2003 and JJAS 2004 from the dry (ΔDC) and wet (ΔWC) experiments with respect to corresponding control experiment over (a) central Sahel, (b) west Sahel, (c) Guinea coast, and (d) West Africa.

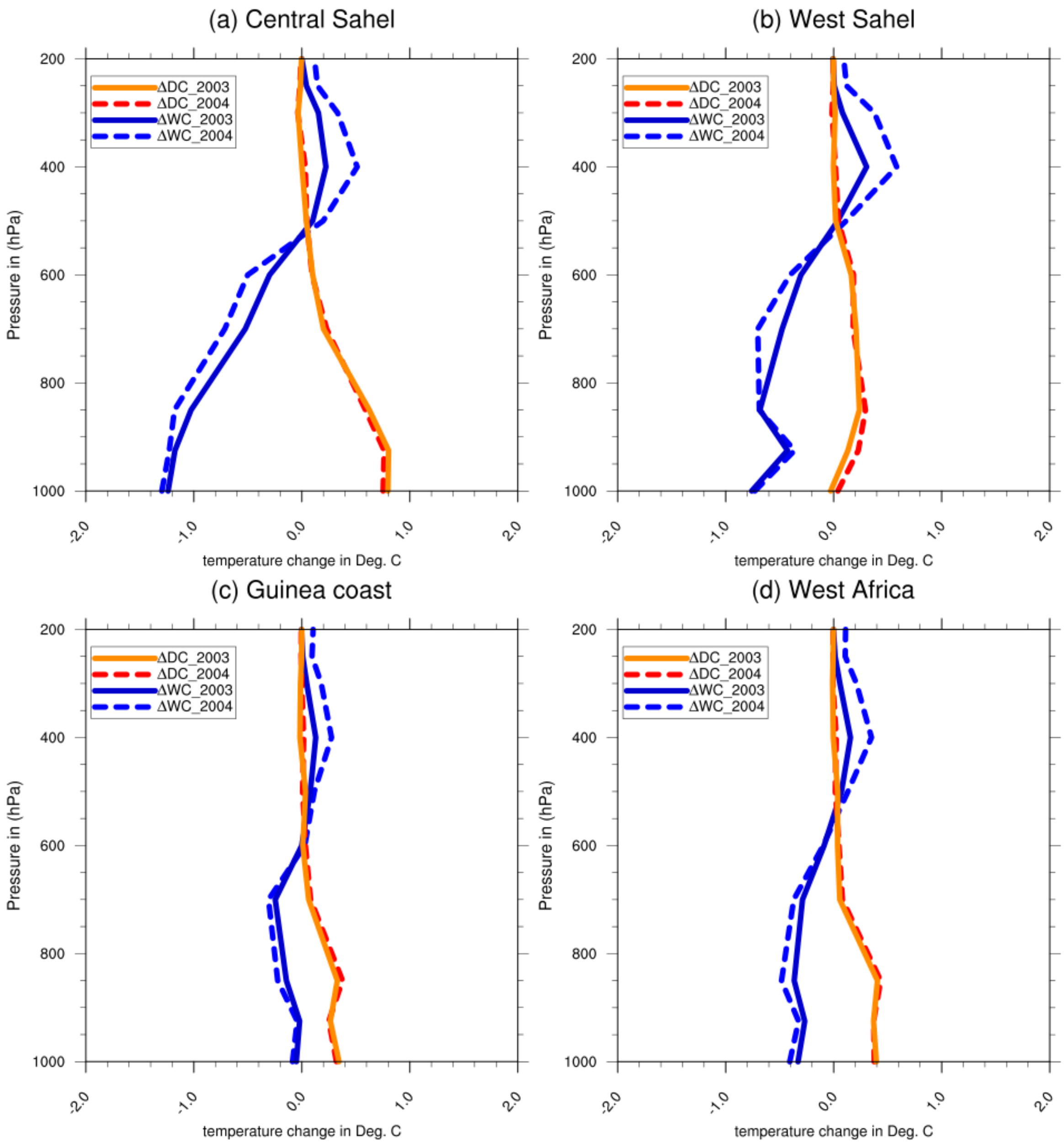


**Figure 9:** Vertical profile changes in temperature for JJAS 2003 and JJAS 2004 from the dry (ΔDC) and wet (ΔWC) experiments with respect to their corresponding control experiment over (a) central Sahel, (b) west Sahel, (c) Guinea coast, and (d) West Africa.

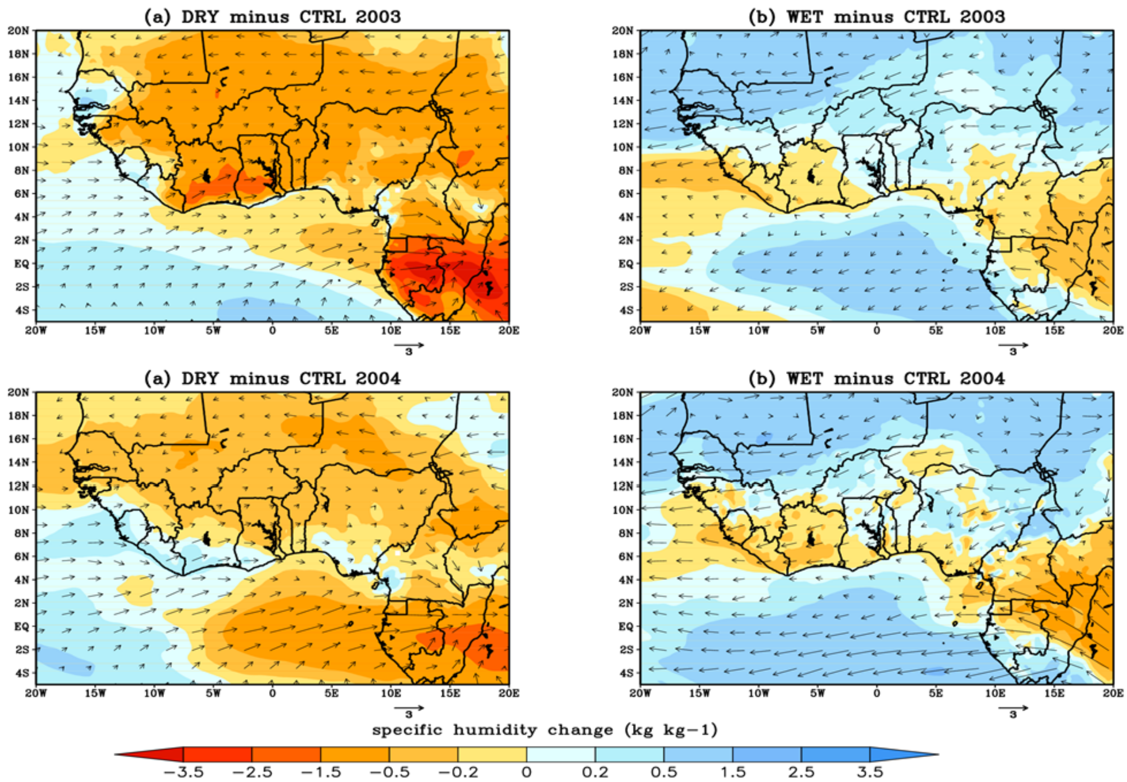


**Figure 10:** The lower tropospheric wind (850hpa) and moisture bias for JJAS 2003 and JJAS 2004 from the dry (a and c) and wet (b and d) experiments with respect to their corresponding control experiment.

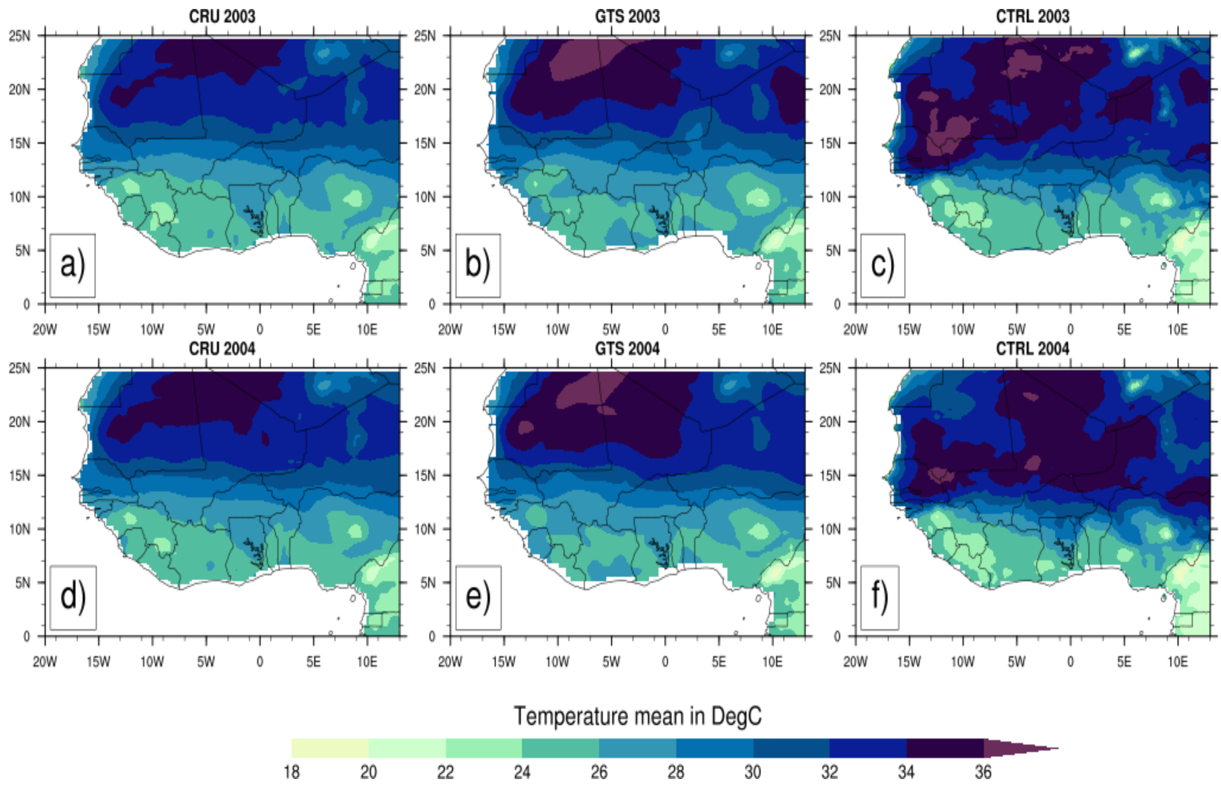


**Figure 11:** Observed 4-month averaged (JJAS) 2m-temperature (°C) from CRU (a and d) and GTS (b and e) for 2003 and 2004 and their corresponding simulated control experiment (c and f) with the reanalysis initial soil moisture ERA20C.

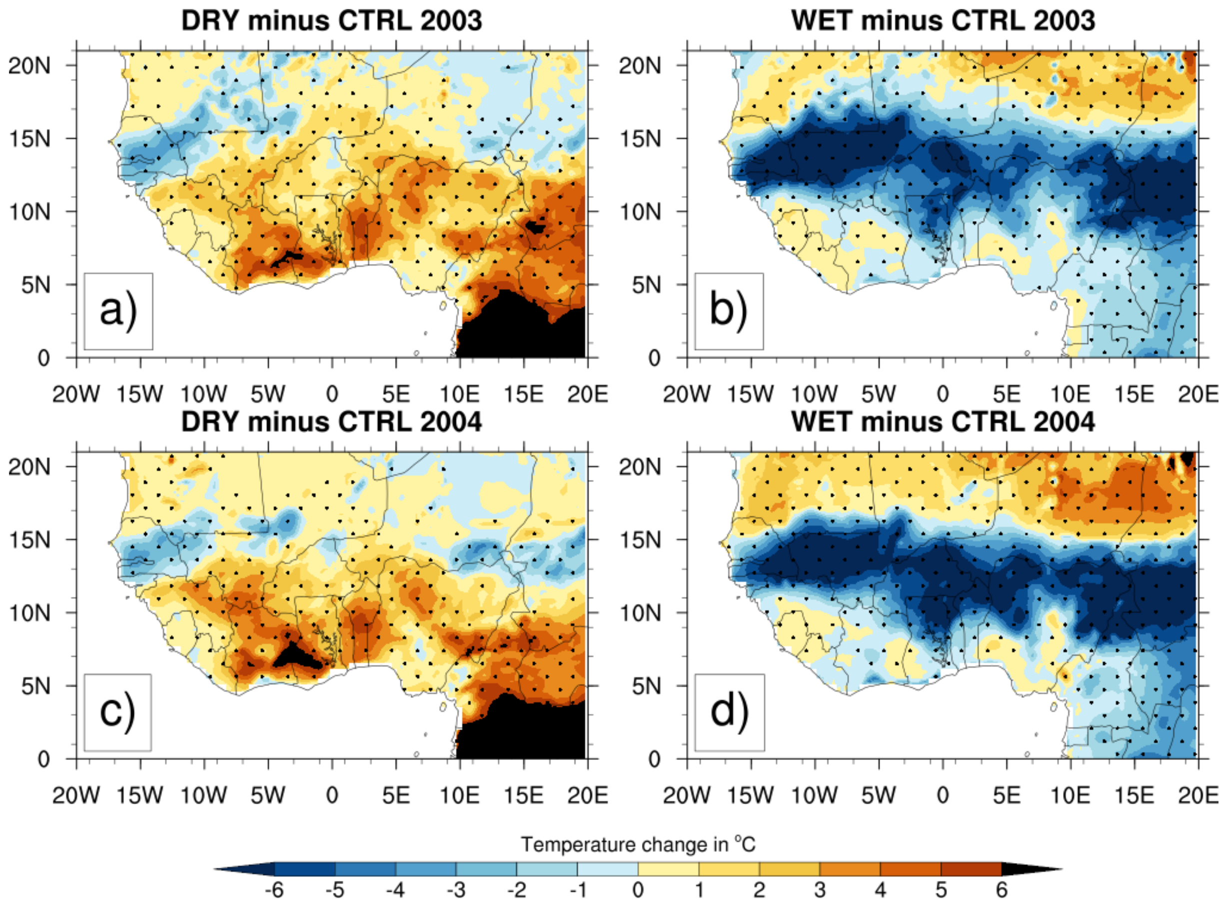


**Figure 12:** Changes in 2m-temperature (°C) for JJAS 2003 and JJAS 2004, from dry (resp. a and c) and wet (resp. b and d) experiments with respect to their corresponding control experiment, the dotted area shows differences that are statistically significant at 0.05 level.

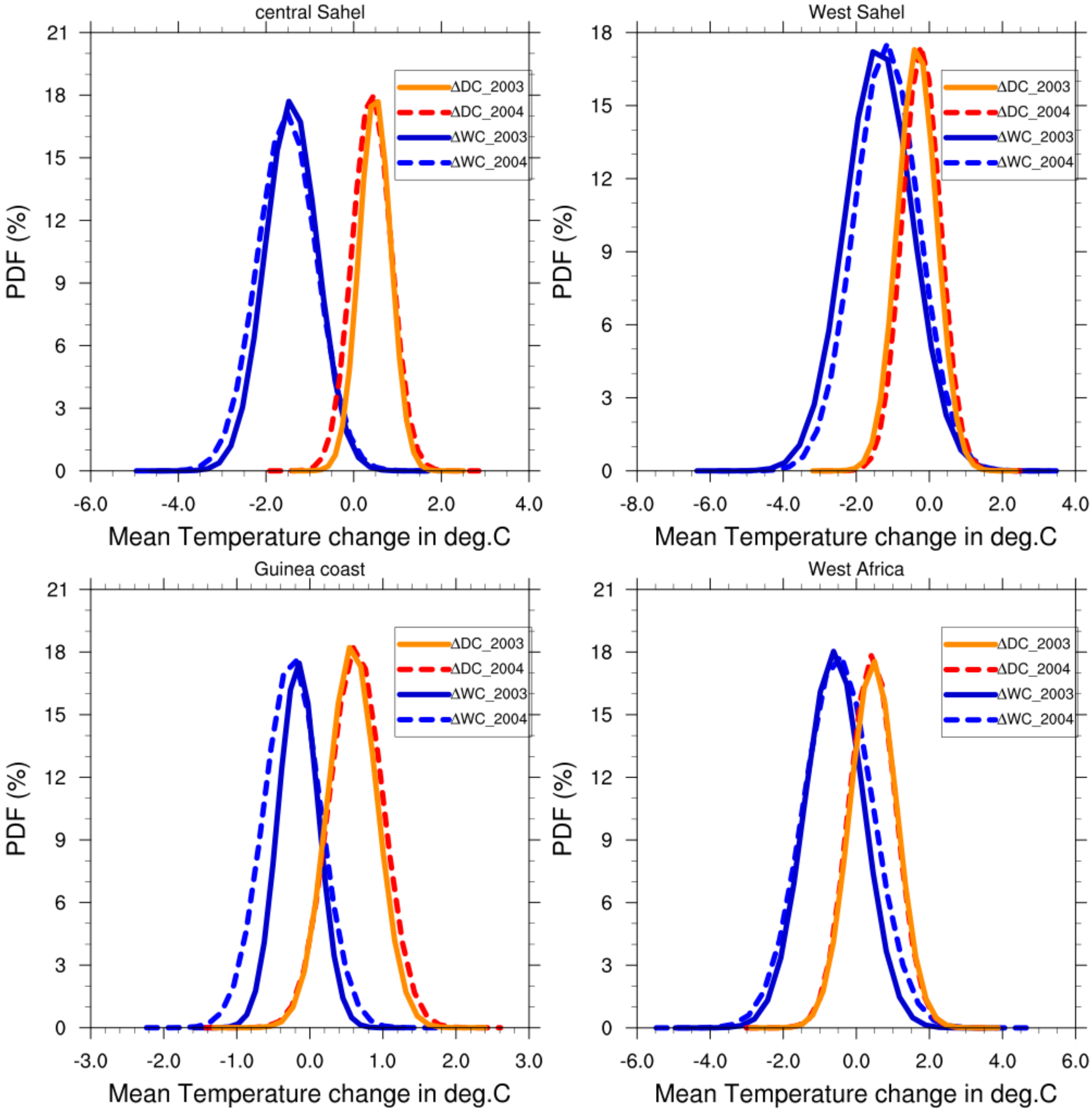


**Figure 13:** PDF distributions (%) of mean temperature changes in JJAS 2003 and JJAS 2004, over (a) central Sahel , (b) West Sahel, (c) Guinea and (d) West Africa derived from dry (ΔDC) and wet (ΔWC) experiments compared to their corresponding control experiment.

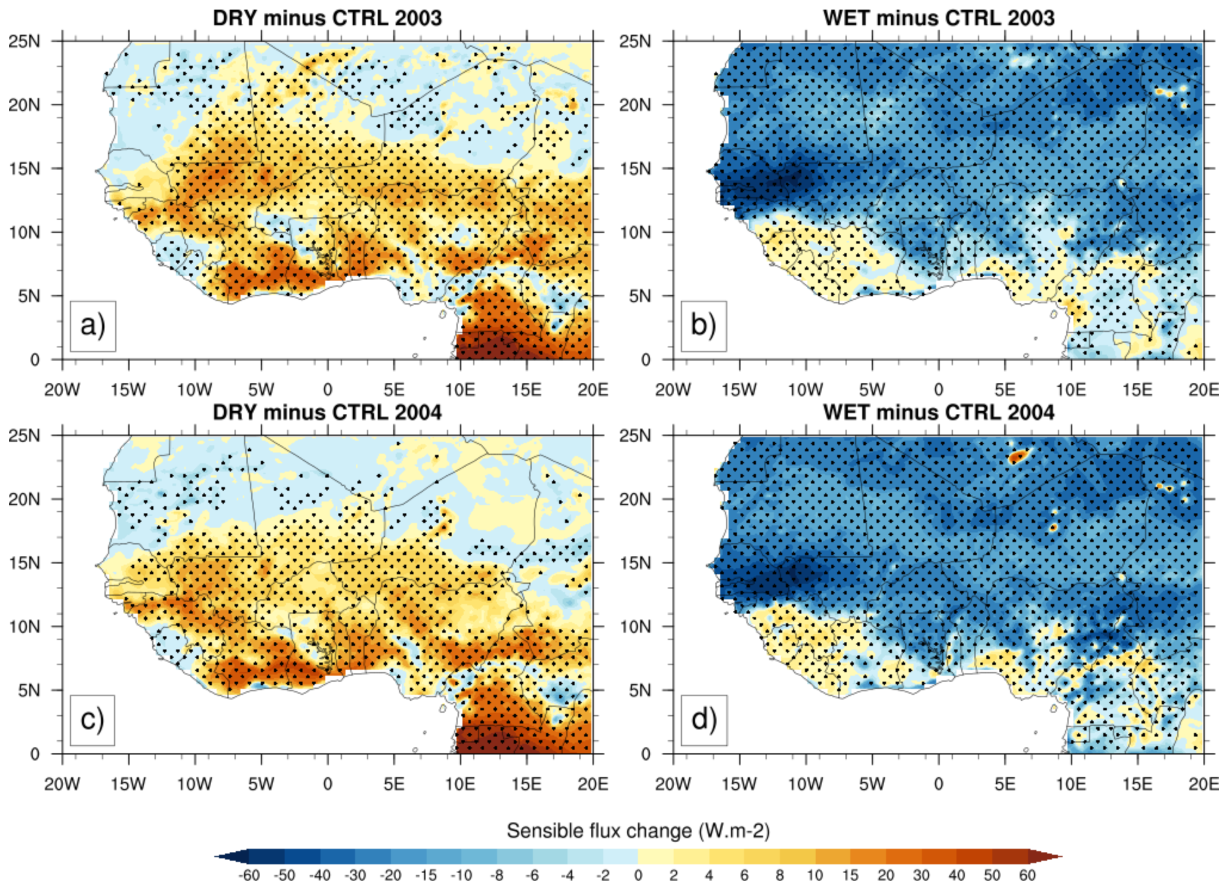


**Figure 14:** Same as Fig.11 but for sensible heat fluxes (in W.m$^{-2}$).

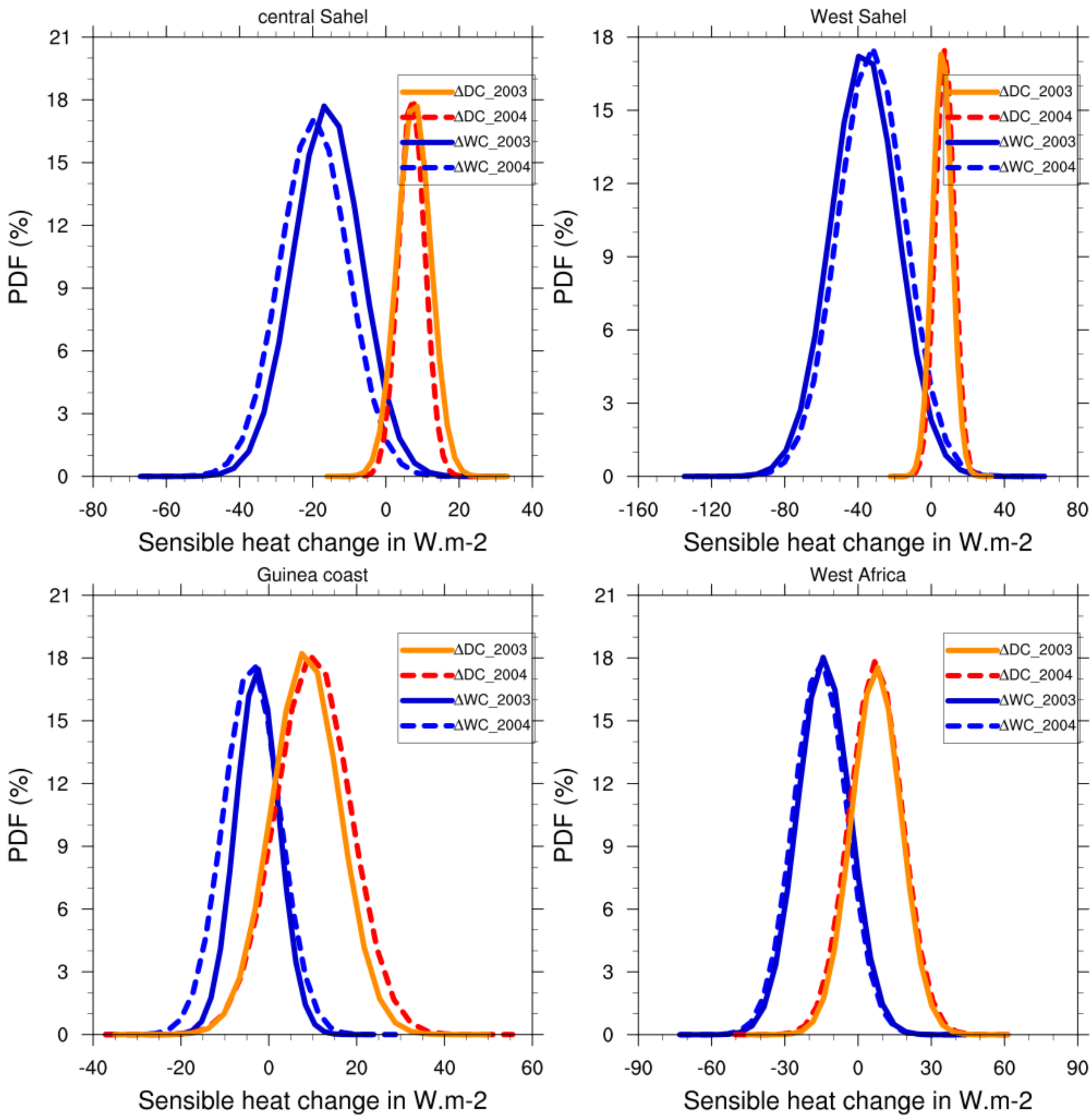


**Figure 15:** Same as Fig.12 but for sensible heat fluxes (in $W.m^{-2}$).

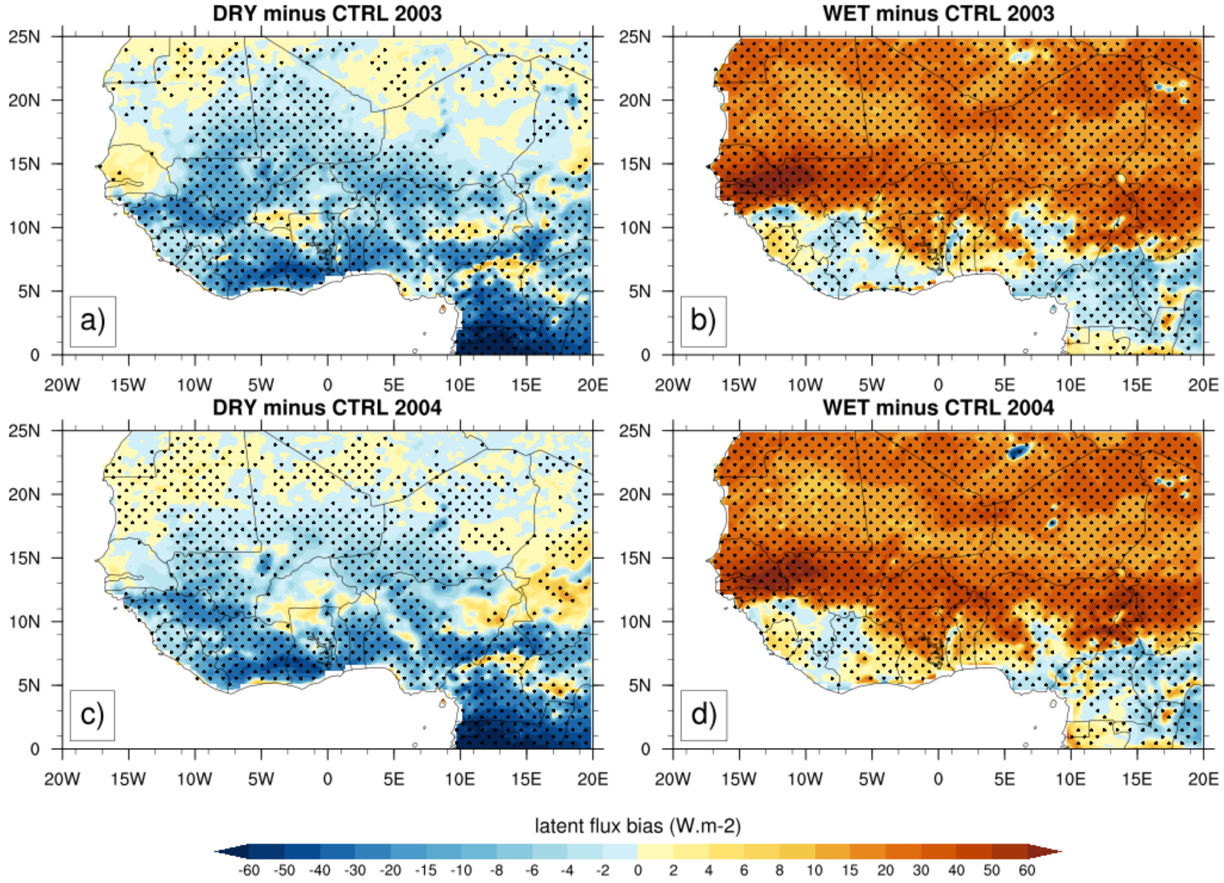


**Figure 16:** Same as Fig.11 but for latent heat fluxes (in W.m$^{-2}$).

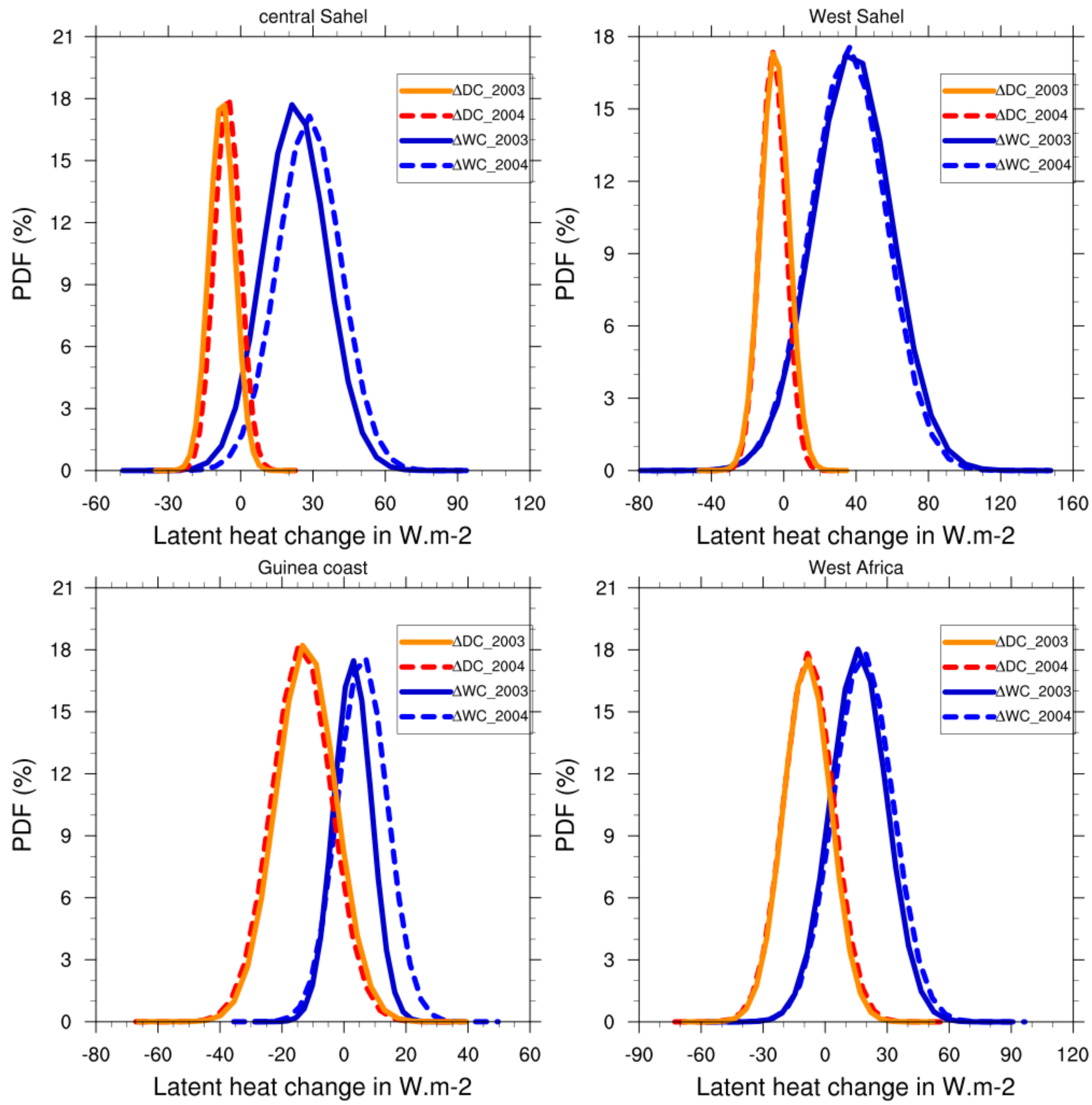


**Figure 17:** Same as Fig.12 but for latent heat fluxes (in W.m$^{-2}$).

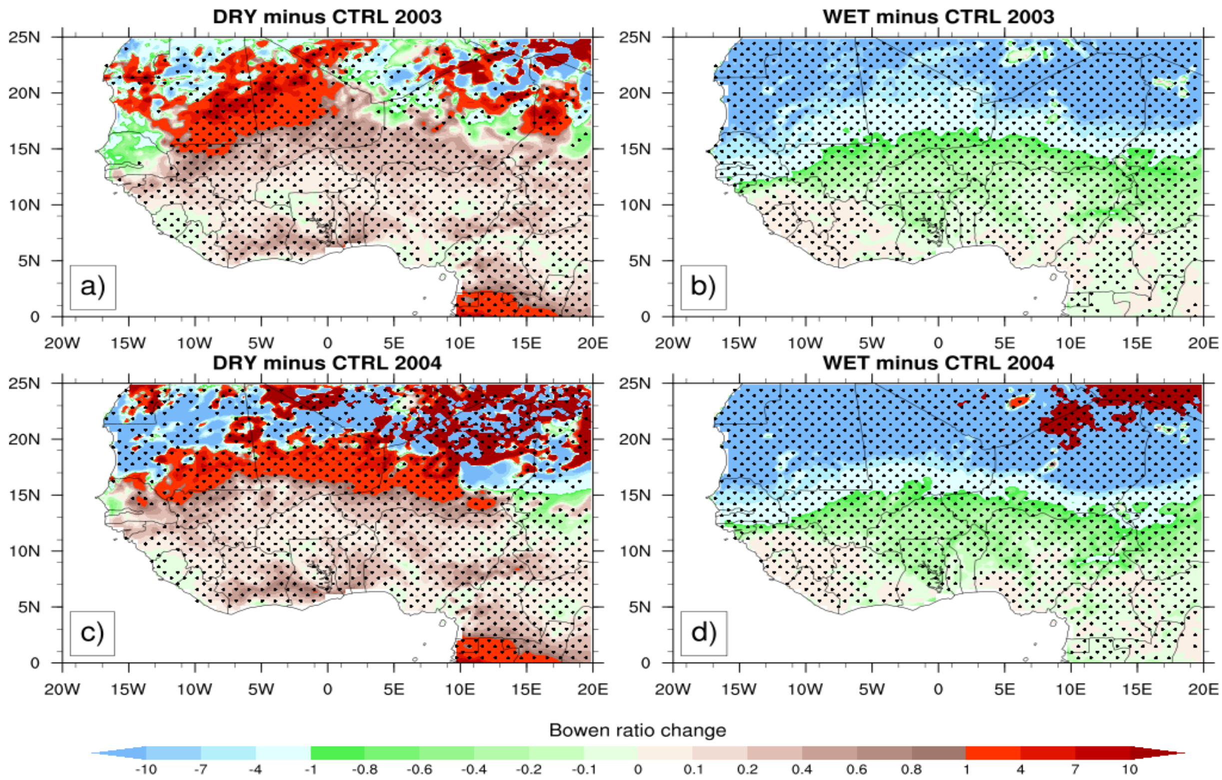


**Figure 18:** Same as Fig.11 but for Bowen ratio.

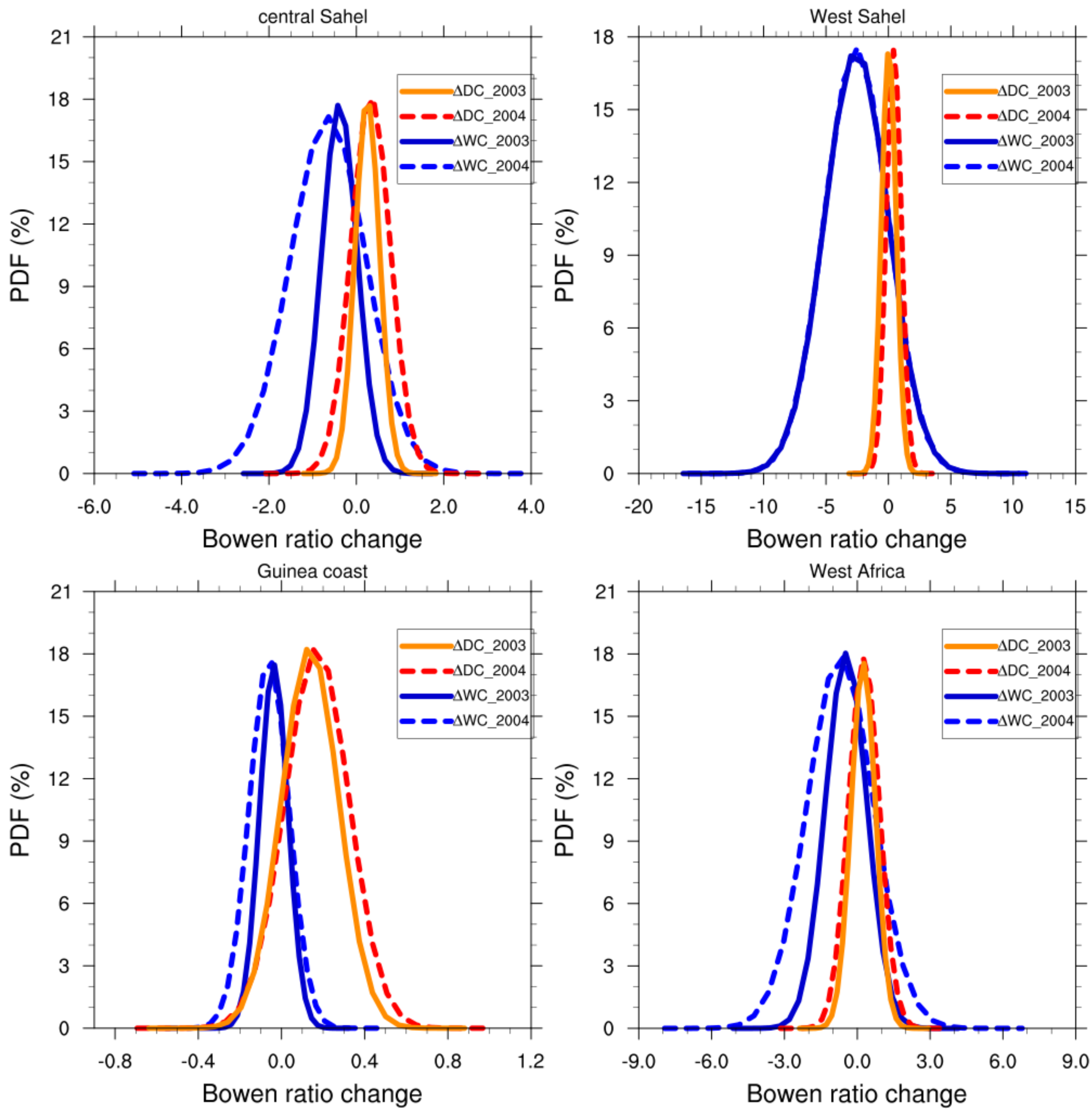


**Figure 19:** Same as Fig.12 but for Bowen ratio.

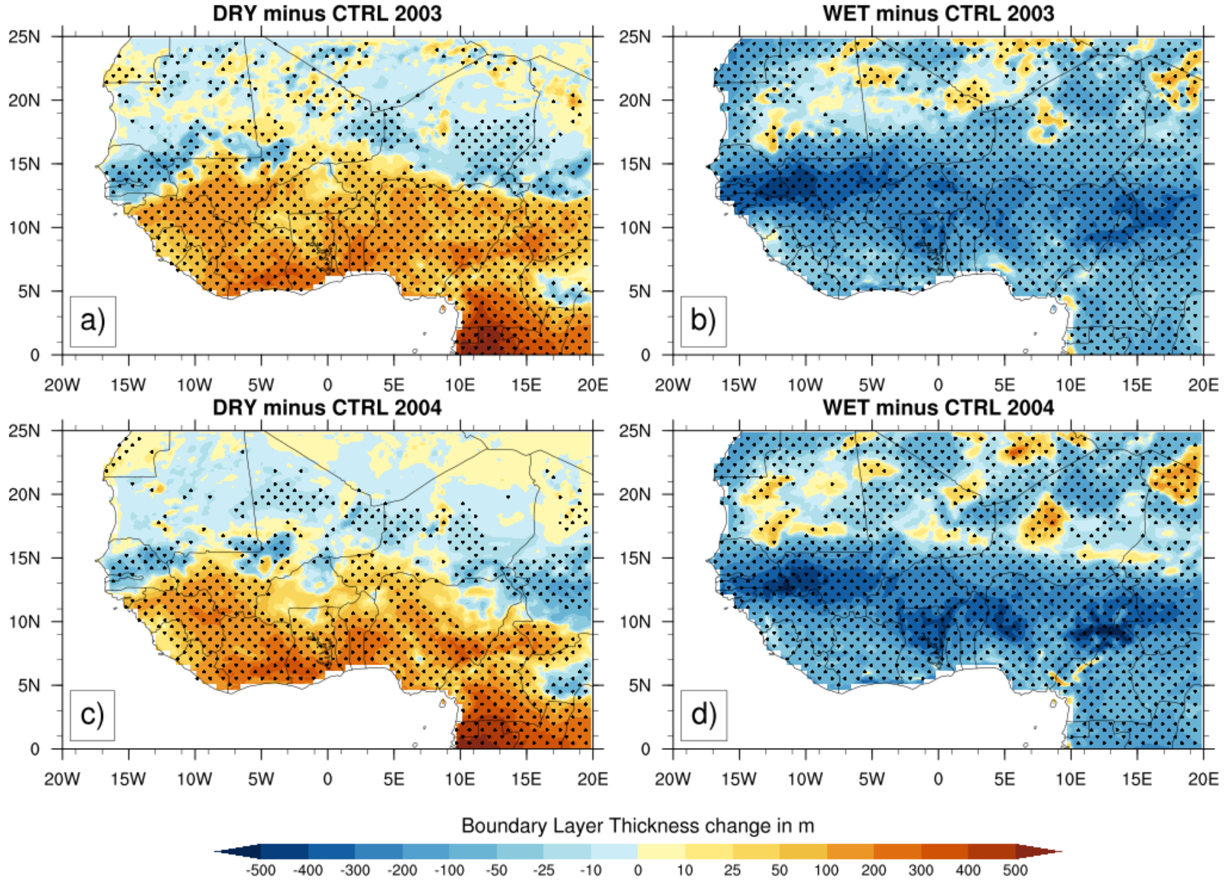


**Figure 20:** Same as Fig.11 but for the change of the height of the planetary boundary layer (in m).

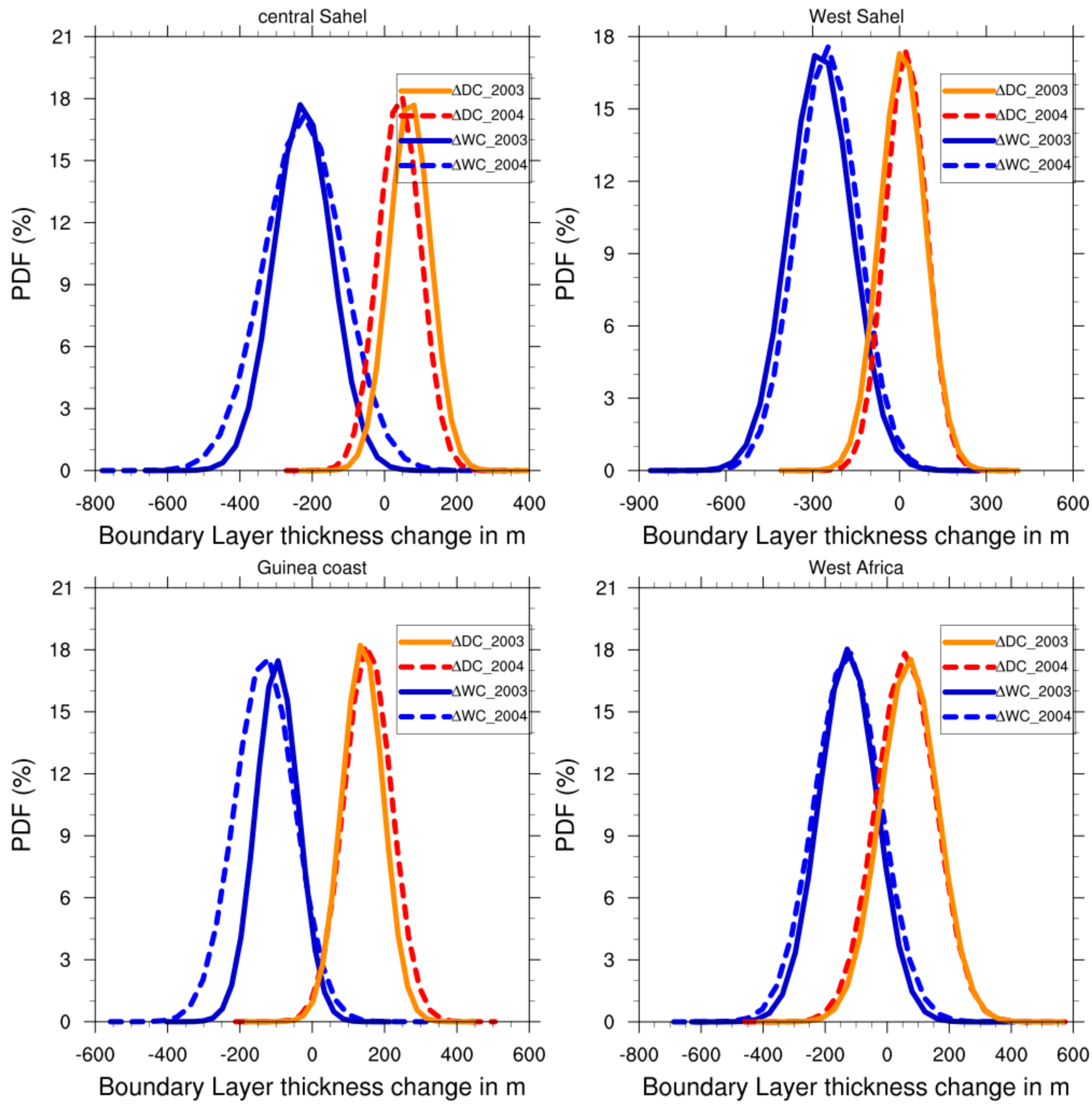


**Figure 21:** Same as Fig.12 but for the height of the planetary boundary layer (in m).