Influence of initial soil moisture in a Regional Climate Model study over West Africa. Part 2: Impact on the climate extremes

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Abstract.
The influence of the soil moisture initial conditions on climate extreme indices over West Africa is investigated using the fourth generation of Regional Climate Model version 4 (non-hydrostatic) coupled to the version 4.5 of the Community Land Model (RegCM4-CLM4.5) at 25 km spatial resolution. We initialized the control experiments with the reanalysis soil moisture of the European Centre Meteorological Weather Forecast's reanalysis of the 20th century data (ERA20C), while for the dry and wet experiments, we initialized the soil moisture at the maximum and minimum value over West Africa domain, respectively. For each experiment, an ensemble of five runs are performed for five years (2001- 2005), with soil moisture initial conditions prescribed on June 1 and simulations performed over four months (122 days) from June to September. The performance of RegCM4-CLM4.5 in simulating the ten extreme rainfall and temperature indices used in this study is presented. Then, the results are discussed for the two idealized simulations most sensitive to the dry and wet soil moisture initial conditions to highlight the impacts beyond the limits of soil moisture internal forcing in the model.

Over the Central Sahel, dry (wet) experiments lead to a decrease (increase) of precipitation extreme indices related to the number of events, not for those related to the intensity of the events. Soil moisture initial conditions unequally affect the daily minimum and maximum temperatures. The strongest impact is found on the maximum temperature. Wet (dry) experiments decrease (increase) maximum temperature in the whole region. Over the Central Sahel, wet (dry) experiments lead to a decrease (increase) of the maximum values of minimum temperature.

1 Introduction

West Africa experienced large rainfall variability during the late 1960s. This variability often leads to flooding events, severe drought, and regional heatwaves, which have major economic, environmental, and societal impacts (Easterling et al., 2000; Larsen, 2003). In recent years, climate extremes have attracted much interest because they are expected to occur more frequently (International Panel on Climate Change (IPCC), 2012) than changes in the mean climate. Yan and Yang (2000) showed that for many cases, the extreme climate changes were five to ten times greater than climate mean change. Many key factors or physical mechanisms could be the cause of the increase in climate extremes (Nicholson, 1980; Le Barbé et al., 2002), such as the effect of increasing greenhouse gases in the atmosphere on the intensification of hot extremes (IPCC, 2007), sea surface temperature (SST) anomalies (Fontaine and Janicot 1996; Folland et al., 1986), and land surface conditions (Philippon et al., 2005; Nicholson (2000)). In addition, smaller-scale physical processes, including the interactions of land–atmosphere coupling, can lead to changes in climate extremes. For the European summer, the influence of soil moisture on land–atmosphere coupling using a regional climate model and focused on the extremes and trends in precipitation and temperature have been studied by Jaeger and Seneviratne (2011). For extreme temperatures, their studies have shown that interactions of soil moisture and climate have a significant impact, while for extreme precipitation, they only influence the frequency of wet days. Over Asia, Liu et al. (2014) studied the impact on subsequent precipitation and temperature of soil moisture anomalies using a regional climate model. They showed that wet (dry) experiences decrease (increase) the hot extremes, decrease (increase) the drought extremes, and increase (decrease) the cold extremes in a zone with strong soil moisture–atmospheric coupling. However, none of these studies examined the impacts of the soil moisture initial conditions on subsequent climate extremes using a regional climate model over West Africa. In part 1, the influence of initial soil moisture on the climate mean was based on a performance assessment of the Regional Climate Model coupled with the complex Community Land Model (RegCM4-CLM4.5) performed by Koné et al. (2018), where the ability of the model to reproduce the climate mean has been validated. However, in Part 2, before starting to study the influence of initial soil moisture on climate extremes, it was necessary to assess the performance of RegCM4-CLM4.5 in simulating the ten temperature indices and extreme rainfall events used in this study. This has never been done before in Africa; therefore, we separated the work in two parts. The manuscript is organized as follows: Section 2 describes the RegCM4 model, experimental design, and methodology used in this study; Section 3 presents the assessment of RegCM4-CLM4.5 in extreme climate simulation and the impacts on climate extremes of the soil moisture initial conditions; and Section 4 documents the conclusions.

2. Model, experimental design and methodology

2.1 Model description and numerical experiments

The fourth generation of the Regional Climate Model (RegCM4) of the International Centre for Theoretical Physics (ICTP) is used in this study. Since this version, physical representations have been subject to a continuous process of implementation and development. The release used in this study was RegCM4.7. The non-hydrostatic dynamical core of the MM5 (Mesoscale Model version 5, Grell et al., 1994) was ported to RegCM4 while maintaining the existing hydrostatic core. RegCM4 is a limited-area model using a vertical grid sigma hydrostatic pressure coordinate and a horizontal grid of the Arakawa B-grid (Giorgi et al., 2012). The radiation scheme is from the NCAR-CCM3 (National Center for Atmospheric Research and the Community Climate Model Version 3) (Kiehl et al., 1996), and the aerosol representation is from Zakey et al. (2006) and Solmon et al. (2006). The large-scale precipitation scheme used in this study is from Pal et al. (2000); the moisture scheme is called the SUBgrid EXplicit moisture scheme (SUBEX), which considers the sub-grid variability in clouds. The accretion and evaporation processes for stable precipitation are from Sundqvist et al. (1989). The sensible heat and water vapour in the planetary boundary layer over land and ocean, as well as the turbulent transport of momentum, is reported by Holtslag et al. (1990). The heat and moisture and momentum of ocean surface fluxes are from Zeng et al. (1998). Convective precipitation and land surface processes in RegCM4.7 are represented in several options. Based on Koné et al. (2018), the convective scheme of Emanuel (1991) is used. The parameterization of land surface processes is from CLM4.5 (Oleson et al., 2013). In each grid cell of CLM4.5, there are sixteen different plant functional types and ten soil layers (Lawrence et al., 2011; Wang et al., 2016). The integration of RegCM4 over the West African domain is shown in Fig. 1 with eighteen vertical levels and 25 km of horizontal resolution (182 × 114 grid points; from 20°W - 20°E and 5°S - 21°N). The European Centre for Medium-Range Weather Forecasts reanalysis (EIN75; Uppala et al., 2008; Simmons et al., 2007) provides the initial and boundary conditions. The sea surface temperatures (SSTs) are derived from the National Oceanic and Atmosphere Administration optimal interpolation weekly (NOAA; OI_WK) (Reynolds et al., 1996). The topography is derived from the United States Geological Survey (USGS) Global Multi-resolution Terrain Elevation Data (GMTED; Danielson et al., 2011) at a spatial resolution of 30 arc-s, which is an update of the Global Land Cover Characterization (GTOPO; Loveland et al., 2000) dataset.

We used the soil moisture from the reanalysis of the European Centre Meteorological Weather Forecast's Reanalysis of the 20th century (ERA20C) to initialize the control runs. Wet and dry experiments were initialized for the soil moisture at the maximum (= 0.489 $m^3.m^{-3}$) and minimum (= $0.117.10^{-4}$ $m^3.m^{-3}$) soil moisture values over West Africa derived from the ERA20C soil moisture dataset. In the part 1 of this study, we designed three experiments (reference, wet, and dry), each with a set of five (5) simulations starting from June 1st to September 30th. The difference between these three experiments is the change in the initial soil moisture condition (reference initial soil moisture condition, wet initial soil moisture condition, and dry initial soil moisture condition) during the first day of the simulation (June 1st, 2001, 2002, 2003, 2004, and 2005) over the West African domain. Then, we selected the two years most affected by the wet and dry initial soil moisture conditions (2003 and 2004) to estimate the limits of the impact of the internal soil moisture forcing on the new non-hydrostatic dynamic core of RegCM4.

For these two years most sensitive to soil moisture initial conditions, the Student t-test is used to compare the significance of changes in climate extreme indices between a wet or dry sensitivity test (sample 1) and the control (sample 2) in assuming that this method performs well for climate simulations (Damien et al., 2014) and knowing that it is extensively used for climatological analysis (Menedez et al., 2019; Talahashi and Polcher, 2019). In this study, the t-test at the 95% confidence level was used to consider statistically significant.

2.2 Validation datasets and evaluation metrics

Our investigation focused on the air temperature at 2 m and the precipitation over the West African domain during JJAS for 2003 and 2004. The simulated precipitation fields are validated with the Climate Hazards Group Infrared Precipitation Stations (CHIRPS) dataset from the University of California at Santa Barbara, available from 1981 to 2020 with 0.05° high-resolution data. We have chosen CHIRPS as reference in this study, mainly because this product has been widely assessed and used for the study of extreme events in West Africa by Bichet et al. (2018a, b) and Didi et al. (2020).

We validated the 2-m temperature using the The National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC) daily maximum and minimum global surface air temperature. The NOAA/CPC global daily surface 2-m air temperature (CPC-T2m) is a land-only gridded global daily maximum (Tmax) and minimum (Tmin) temperature analysis from 1979 to the present, available at two spatial of 10 min × 10 min and 0.5° × 0.5° (latitude × longitude). This product provides an observational T2m estimate for climate monitoring, model evaluation, and forecast verification (Fan Y. and Huug van den Dool, 2008; Pan et al., 2019). In this study, the daily Tmax and Tmin are used at spatial resolution 0.5° × 0.5°. To compare the model simulations with the observation datasets, we re-gridded all the products to 0.22° × 0.22° using a bilinear interpolation method (Nikulin et al., 2012).

The performance of RegCM4-CLM4.5 to simulate the extreme indices is evaluated using four selected sub-regions (Fig. 1) based on the previous work of Koné et al. (2018), which correspond to different annual precipitation cycle features. We used the mean bias (MB), which captures the small-scale differences between the simulation and observation. The pattern correlation coefficient (PCC) is also used as a spatial correlation between model simulations and observations to indicate the large-scale similarity degree.

To quantify the impact of soil moisture initial conditions on climate extremes over Asia, Liu et al. (2014) used the MBs in five subregions. In our study, we used the MBs and the probability density functions (PDF, Gao et al. (2016); Jaeger and Seneviratne (2011)) for this purpose to better capture how many grid points are impacted by initial soil moisture and their highest value.

2.3. Extreme rainfall and temperature indices

In this study, we investigated the changes in precipitation and temperature in terms of duration, occurrence, and intensity of six extreme rainfall and four extreme temperature indices using daily rainfall and daily minimum and maximum temperature data (Table 1). These ten extreme indices are recommended by the Expert Team on Climate Change= Detection and Indices (ETCCDI, Peterson et al., 2001).

3. Results and discussion

3.1. Seasonal extreme rainfall

In this section, we analyzed six extreme rainfall indices based on daily precipitation in RegCM4 simulations over West Africa. All precipitation indices were calculated for JJAS in 2003 and 2004. Table 2 summarizes the PCC and the MB of all precipitation indices studied in this section for simulations obtained from control experiments with respect to CHIRPS observations, calculated for the West Sahel, Central Sahel, Guinea Coast, and the entire West African domain during the runs JJAS 2003 and JJAS 2004

3.1.1 The number of the wet days (R1mm)

Figure 2 shows the mean values of the number of wet days (R1mm, in days) from CHIRPS (Fig. 2a, c) observation and the simulated control experiments (Fig. 2b, d) with the initial soil moisture derived from ERA20C reanalysis. The R1mm index maximum values up to 100 days in CHIRPS observation are found over mountainous regions such as the Cameroon Mountains, Jos Plateau, and Guinea Highlands, while minimum values less than 50 days are found over the Sahel and along the coastline from Liberia to Ghana with the number of wet days decreasing gradually from south to north.

The control experiments (Fig. 2b, d) reproduce well the large-scale pattern of the observed rainfall, with PCC values of 0.96 and 0.95 for runs JJAS 2003 and JJAS 2004, respectively (Table 2) over the entire West African domain, but exhibit some spatial extent and magnitude biases at local scale. The control experiments display a large and quite homogeneous area of maximum values of R1mm index below 12 °N latitude and overestimate the number of wet days over most of the studied domains (Table 2). The largest MBs are found over the Guinea Coast with MB values more than 53.16 and 55.46 days for the runs JJAS 2003 and JJAS 2004, respectively (Table 2). This overestimation of the number of wet days in RegCM4 is also found by Thanh et al. (2017) with RegCM4 for Asia.

Figure 2 (second panel) displays additional changes in the R1mm index for JJAS 2003 and JJAS 2004 from the dry (Fig. 2e and g) and wet experiments (Fig. 2f and h) compared to the control experiments; the dotted area shows changes with statistical significance at the 95% level. The dry experiments (Fig. 2e, g) decrease the R1mm index values, while the wet experiments (Fig. 2h, j) increase them, especially over Central Sahel. However, over the Guinea Coast sub-region, both wet and dry experiments show a significant increase in R1mm index values.

For a better quantitative evaluation, Figure 3 displays the PDF distributions of changes in R1mm over the sub-domains (Fig. 1), during the runs JJAS 2003 and JJAS 2004 while Table 3 summarizes the PDF maximum values. The results essentially confirm the linear impact found over Central Sahel (Fig. 3a). Over West Sahel, the Guinea Coast, and the West African domain (Fig. 3b, c, and d), both dry and wet experiments increase the R1mm index values. The strongest R1mm increase is found in wet experiments over West Sahel, with a maximum change about 12 days in JJAS 2003 (Table 3) while the strongest R1mm decrease is found for dry experiments over Central Sahel, with a maximum change about -5.19 days (Table 3).

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Summarizing the results of this section, RegCM4 overestimated the number of wet days over most of the studied domains. Over the Central Sahel, wet and dry experiments lead both to a linear impact on the R1mm index with an increase and a decrease respectively of the number of rainy days. These results are compatible with previous work that sustained a strong land–atmosphere coupling in transition areas between wet and dry climate regimes (Zhang et al., 2011; Koster et al., 2006).

3.1.2 Simple daily intensity index (SDII).

We analyzed in this section the SDII index (rainfall intensity in $mm.day^{-1}$) which gives the amount of precipitation mean on total wet days (daily precipitation >1mm). Figure 4 (first panel) is the same as figure 2 (first panel) but for the rainfall intensity. Over the coastline of Guinea Coast, CHIRPS observation (Fig.4a, c) depicted the highest values of SDII index, more than 25 $mm.day^{-1}$. While, over the Sahel and Sahara, CHIRPS observation showed large extend SDII index values not exceeding 12 $mm.day^{-1}$ in both runs JJAS 2003 and JJAS 2004.

The control experiments (Fig. 4 b, d) reproduced well the large-scale pattern of CHIRPS with PCC values reaching 0.73 and 0.77 (in the runs JJAS 2003 and JJAS 2004, respectively; Table 2) over the West African domain. However, at the local scale, some biases are found. Over most of the studied domains, the magnitude of the SDII is underestimated and not exceed 10 $mm.day^{-1}$, excepted over the Cameroon Mountains (Fig. 4b, d). The largest MB values were located over the Guinea Coast with MB values greater than −13.62 and −14.65 $mm.day^{-1}$ for the runs JJAS 2003 and JJAS 2004, respectively (Table 2).

Figure 4 (second panel) is the same as figure 2 (second panel) but for the rainfall intensity. Unlike the R1mm index, changes in the SDII index due to soil moisture initial conditions are not linear over most of studied domains. Fig. 4 (second panel) shows that generally, the impact on rainfall intensity of dry and wet experiments presents areas of increase and decrease over most of the studied sub-domains.

Figure 5 displays PDFs of changes in SDII, as in Fig. 3. The PDFs show a maximum change value centered approximately on zero (Table 3), indicating that changes in the rainfall intensity for wet and dry experiments are not significant.

In summary, RegCM4 underestimates the rainfall intensity over the studied domain compared to the observation and the impact on SDII index in wet and dry experiments are not significant.

3.1.3 Maximum number of consecutive dry days (CDD).

The duration of consecutive dry days (CDD, in days), which represents the maximum number of consecutive dry days with precipitation less than 1 mm.day^{-1} is analyzed in this subsection. Figure 6 (first panel) is the same as figure 2 (first panel) but for CDD. CHIRPS observation locates the highest CDD values over the Sahara, with length more than 50 days (Fig. 6a, c). The lowest CDD values are found over the Guinea Coast, with length less than 8 days.

The control experiments (Fig. 6b, d) over the entire West African domain well reproduce the large-scale pattern of the observed rainfall with a PCC values more than 0.85 and 0.89 for the runs JJAS 2003 and JJAS 2004, respectively (Table 1). However, in terms of magnitude, some differences are observed at local scale. In general, the control experiments overestimate the CDD over most of studied subdomains, except over the Guinea Coast (Table 2). The strongest overestimation is found over West Sahel with MB values reaching more than 14.49 and 17.51 days for runs JJAS 2003 and JJAS 2004, respectively (Table 2). The current model parameterization increases the drought extreme over most of the studied domains, except over the Guinea Coast (Table 2).

Figure 6 (second panel) is the same as figure 2 (second panel) but for CDD. The soil moisture initial condition impact on CDD index is linear over the Central and West Sahel (Fig. 6, second panel); Over the Sahel, dry (wet) experiments increase (decrease) the length of dry spells. Over the Guinea Coast, the impacts on CDD are weak for both dry and wet experiments and in average, soil moisture initial conditions seems to decrease the length of dry spells in a central band between Côte d'Ivoire and Nigeria.

Figure 7 is the same as figure 3 but displays the PDF distribution of the changes in CDD. The highest length of CDD increase are found over the Central Sahel in dry experiments with maximum change in length reaching 3.80 days in JJAS 2004 (Table 3), while the highest CDD decrease are found over West Sahel in wet experiments with maximum change in length reaching -12.73 days in the run JJAS 2003 (Table 3).

In summary, RegCM4 overestimated the maximum number of consecutive dry days over most studied subdomains, except over the Guinea Coast. However, the impact of soil moisture initial condition is linear over the Central and West Sahel. Over the Guinea Coast, the dry and wet experiments generally decrease the length of dry spells.

3.1.4 Maximum number of consecutive wet days (CWD).

The duration of wet spells (CWD) which represents the maximum number of consecutive wet days with precipitation ≥ 1 $mm.day^{-1}$ is investigated in this subsection. Figure 8 (first panel) is the same as figure 2 (first panel) but shows the CWD duration. In the CHIRPS observation, the maximum length of CWD lasting longer than 20 days are found over the mountain regions such as Cameroon Mountains, Jos plateau and Guinea highlands. While the minimum length of CWD lasting less than 4 days are found over most of the area above the latitude 17°N (Fig.8a, c).

The control experiments well reproduce the large-scale pattern over the entire West African domain, with PCC values around 0.81 and 0.87 (resp. for JJAS 2003 and JJAS 2004, Table 2). However, at local scale, the control experiments exhibit some biases in the CWD minimum and maximum values, both in terms of magnitude and spatial extent. Control experiments overestimate the CWD length over most of subdomains studied (Fig. 8 b, d). We noted that, areas of overestimation coincide with areas of excessive R1mm values (Fig.2b, d). The strongest overestimation is found over the Guinea Coast, reaching 59.21 and 60.51 days (resp. for JJAS 2003 and JJAS 2004, Table 2).

Figure 8 (second panel) is the same as figure 2 (second panel), but displays changes in CWD. As for R1mm index, over the Central Sahel, the dry (wet) experiments decrease (increase) CWD length for both JJAS 2003 and JJAS 2004. This result confirms the strong influence of soil moisture initial conditions in the Sahel band, as found by Zhang et al. (201) and Koster et al. (2006) over the transition zones with a climate between dry and wet regimes. However, over Guinea and the West Sahel, the changes are not linear, both dry and wet experiments increase the CWD length (Fig. 8e-h).

Figure 9, as in figure 3, but shows the PDF distribution of changes in CWD. The strongest CWD increase is found over Central Sahel with maximum changes reaching 15.58 days in wet experiments, while the strongest CWD decrease is found in the same sub-domain with maximum changes reaching −4.48 days dry experiments.

Summarizing the results of this section, as for R1mm and CDD indices, the impact of wet and dry experiment on CWD is linear over the Central Sahel meaning that dry (wet) experiments decrease (increase) the CWD lengths. The model RegCM4 overestimates the duration of wet consecutive days over most of studied subdomains. This overestimation is associated with the excessive number of wet days in the model as documented by Diaconescu et al. (2014).

3.1.5 Maximum one-day precipitation accumulation (RX1day).

The maximum one-day precipitation accumulation (RX1day) during JJAS 2003 and JJAS 2004 is assessed in this section. Figure 10 (first panel) shows the spatial distribution of RX1day. CHIRPS observation confines the spatial extent of RX1day maximum values greater than 80 mm over the coastline of the Guinea Coast. While, the large extent of RX1day minimum values less than 50 mm are found over the Sahara, Sahel and part of Guinea Coast.

The control experiments capture the spatial pattern of RX1day with PCC values around 0.50 and 0.4 for JJAS 2003 and JJAS 2004, respectively (Table 2). This low coefficient of PCC is also obtained by Thanh et al. (2017) over Asia with RegCM4 (correlation < 0.3). The model simulations fail to capture the magnitude and spatial extent of the RX1day maxima. The control experiments underestimate the RX1day over most of studied subdomains and this seems to be associated with the excessive number of weak precipitation simulated by the model. The largest underestimation is located over the Guinea Coast and the West Sahel. For instance, over the West Sahel, the MB values are −38.07 and −36.67 mm for JJAS 2003 and JJAS 2004, respectively (Table 2).

Figure 10 (second panel) is similar to Figure 2 (second panel), but displays changes in the RX1day. As for the SDII, the impact of the soil moisture initial conditions on RX1day is not linear (Fig. 10, second panel).

Figure 11 is similar to figure 3, but shows the PDF distribution of changes in the RX1day. Increases of RX1day for both dry and wet experiments are found over most of studied subdomains (Fig.11). The strongest increase in RX1day is found over Guinea Coast for wet experiments, with values reaching 26.14 and 14.93 during JJAS 2003 and JJAS 2004, respectively (Table 3).

In summary, RegCM4 underestimates the maximum one-day precipitation accumulation over most of studied domain. Both wet and dry experiments lead to an increase of RX1day.

3.1.6 Precipitation percent due to very heavy precipitation days (R95pTOT)

In this section, we investigated the precipitation percentage due to very heavy precipitation days during JJAS 2003 and JJAS 2004. Figure 12 (first panel) is the same as figure 2 (first panel), but shows the spatial distribution of R95pTOT. CHIRPS observation confines the R95pTOT maximum values greater than 40% over the Guinea Coast. While R95pTOT index minimum values less than 30 % are found over the Central and West Sahel (Fig. 10 a, c). The control experiments (Fig. 12b, d) capture the large spatial pattern with PCC values of 0.59 and 0.55 for JJAS 2003 and JJAS 2004, respectively (Table 2). As with SDII and RX1day indices, the control experiments underestimate the values of the R95pTOT index, while they overestimate the R1mm index. This is also due to the current physical parameterization scheme of the RegCM4 model, which results in a positive bias for the number of wet days with a low precipitation amount (e.g., 1 mm.day^{-1}), and a negative bias in the number of wet days with a higher precipitation threshold (e.g., 10 mm.day^{-1}, not showed here).

The control experiments underestimate R95pTOT over the different studied domains. The highest R95pTOT underestimation is found over the Guinea Coast with MB values more than −43.22 and −46.61 % for JJAS 2003 and JJAS 2004, respectively (Table 2).

Figure 12 (second panel) is similar to figure 2 (second panel), but displays changes in the R95pTOT index. Both dry and wet experiments lead to R95pTOT index increase over the orographic regions. Therefore, the soil moisture initial conditions, whether dry or wet extreme reinforce occurrence of extreme floods events.

Figure 13 is the same as figure 3 but shows the PDF distribution of changes in the R95pTOT. The highest R95pTOT increase is found over the West Sahel and Guinea Coast with maximum change values around 4.03% and 4.33% for JJAS 2003 and JJAS 2004, respectively (Table 3). In summary, RegCM4 underestimates R95pTOT while the soil moisture initial conditions, whether dry or wet, increase the precipitation percent due to very heavy precipitation days. This result is consistent with Liu et al. (2014) work over Asia using RegCM4.

3.2. Temperature extreme indices

In this section, using daily maximum and minimum temperatures, we analyzed four extreme temperature indices (Table 1) in RegCM4 simulations over West Africa. All temperature indices are calculated for JJAS 2003 and JJAS 2004. Table 4 summarizes the PCC and MB of all temperature indices for the control experiments with initial soil moisture from ERA20C reanalysis, with respect to CPC-T2m observation, calculated over the subdomains presented in Fig. 1, during the JJAS 2003 and JJAS 2004.

3.2.1. Maximum value of daily maximum temperature (TXx)

In this section, we analyzed the TXx, which gives the hottest day's temperature during JJAS 2003 and JJAS 2004. Figure 14 (first panel) shows the TXx (in °C) from CPC-T2m observation (Fig. 14a, c) for JJAS 2003 and JJAS 2004 and from the mean control experiments (Fig. 14b, d). The CPC-T2m observation shows that the highest TXx values more than 46 °C are found over the Sahara. The lowest TXx index values less than 32 °C are found over the Guinea Coast (Fig. 14a, d). CPC-T2m observation (Fig. 14a, c) shows the lowest TXx values less than 28 °C along the coastline of the Guinea Coast, while the TXx highest values more than 40 °C are found over Sahara and the northern of Sahel (Fig.14a, c),

The control experiments (Fig. 14c, f) reasonably replicate the large-scale patterns of the TXx values with PCCs up to 0.99 (Table 3) over the entire West African domain; however, they exhibit some biases at local scale. The control experiments are closer to the maximum and minimum values displayed in the CPC-T2m observation. The control simulations overestimate the TXx values over the Central and West Sahel, and underestimate them over the Guinea Coast (Table 4). The greatest overestimation is found over the West Sahel with MB values around 3.02 and 2.02 °C for JJAS 2003 and JJAS 2004, respectively (Table 4). However, the biases obtained for TXx are much lower than those obtained by Thanh et al. (2017), who used RegCM4 over Asia where they reached 8 °C.

Figure 14 (second panel) displays changes in TXx for JJAS 2003 and JJAS 2004 in dry (Fig. 14g, i) and wet experiments (Fig. 14h, j) with respect to the control experiments; the dotted area showed significant changes with a statistical significance of 95%. Dry experiments lead to an increase of TXx values, while the wet experiments decrease them.

The PDF distributions of TXx changes for JJAS 2003 and JJAS 2004 over (a) the Central Sahel, (b) West Sahel, (c) Guinea Coast, and (d) West Africa derived from dry and wet experiments compared to the control experiments are shown in Fig. 15. Table 5 summarizes the maximum values of changes obtained on the PDF of TXx. The strongest decrease (increase) in the TXx index are found over the Central Sahel with a maximum changes around −2.57 °C (more than 1.69 °C) in wet (dry) experiments in JJAS 2004.

In summary, during JJAS 2003 and JJAS 2004, the RegCM4 model overestimates and underestimates the hottest day's temperature over the Sahel and Guinea Coast, respectively. Dry experiments result in an increase of TXx, while the wet experiments lead to a decrease TXx values.

3.2.2. Minimum value of daily maximum temperature (TXn).

In this section, we investigated the TXn index which gives the lowest day's temperature during JJAS 2003 and JJAS 2004. Figure 16 (first panel) is the same as figure 14 (first panel) but presents the spatial distribution of the TXn index. CPC-T2m observation displays maxima (greater than 36°C) and minima (less than 24°C) of TXn over the Sahara and the Guinea Coast respectively (Fig.16a, c).

The control experiments (Fig.16b, d) show a good agreement with the CPC-T2m datasets in the large scale patterns with PCC of approximately 0.99, however, the magnitude of the TXn index over most of studied domain is overestimated. The strongest positive bias was observed over West Sahel domain with MB about 6.56 and 5.44 °C for JJAS 2003 and JJAS 2004, respectively (Table 4). The TXn biases of our study are lower than those obtained by Thanh et al. (2017) in their work over Asia using RegCM4. As for Fig.14 (second panel), the Figure 16 (second panel) displays changes in TXn index. Dry experiments increase TXn index values while the wet experiments decrease them.

Figure 16 (second panel) is similar to figure 14 (second panel) but displays the PDF distribution of changes in TXn. The impact on TXn is rather weak compared to the TXx. The strongest increase of TXn index are found over the Central Sahel reaching 1.03 °C in dry experiments during JJAS 2004 (Table 5). While the strongest decrease are found over the West Sahel about -1.67°C for wet experiments during JJAS 2004 (Table 5).

In summary, RegCM4 overestimates the lowest day's temperature during JJAS 2003 and JJAS 2004 over the whole West African domain. As for TXx index, dry (wet) experiments increase (decrease) the TXn values.

3.2.3. Minimum value of daily minimum temperature (TNn index).

In this section, we examined the TNn index, which gives the lowest temperature at night during JJAS 2003 and JJAS 2004. Figure 18 (first panel) is the same as figure 14 (first panel) but displays the spatial distribution of the TNn index. CPC-T2m observations (Fig. 18 a, c) shows TNn maxima with values not exceeding 27 °C, above 15 °N latitude, while the minima values (less than 17 °C) are found over the mountainous regions such as the Cameroon Mountains, Jos Plateau, and Guinea Highlands.

The control experiments (Fig. 18 b, d) show good agreement with CPC-T2m observations with PCC of approximately 0.99; however, they exhibit some biases at the local scale. The control experiments overestimate the magnitude of the TNn index over most of studied domains.

The strongest positive biases are found over the West Sahel with MB reaching 3.30 °C and 2.55 °C for JJAS 2003 and JJAS 2004, respectively (Table 4). These positive biases obtained for the TXx, TXn, and TNn indices are opposite to the cold bias known from RegCM4 in mean climate simulation (Koné et al., 2018, Klutse et al., 2016). It is difficult to determine the origin of RegCM4 temperature biases, as they can depend on several factors, such as surface energy fluxes and water, cloudiness, and surface albedo (Sylla et al., 2012; Tadross et al., 2006).

Figure 18 (second panel) is the same as figure 14 (second panel), but displays changes in the TNn. Over the Central and West Sahel, both dry and wet experiments decrease the TNn values. Conversely, over the Guinea Coast, they increase the TNn values.

Figure 19 is the same as Figure 15 but shows the PDF distribution of changes in the TNn. Wet (dry) experiments increase (decrease) the TNN values, especially over the Central Sahel. Table 5 shows that the strongest increase in TNn index in wet experiments is found over Guinea Coast, with maximum change around 0.11 °C in JJAS 2004, while the strongest decrease in TNn is found in dry experiments over the West Sahel, with maximum change around −1.15 °C in JJAS 2003.

In summary, RegCM4 overestimates the lowest temperature at night during JJAS 2003 and JJAS 2004. Wet (dry) experiments lead to an increase (a decrease) of the TNN index.

3.2.4. Maximum value of daily minimum temperature (TNx)

In this section, the index TNx which gives the warmest night temperature during JJAS 2003 and JJAS 2004 is analyzed. Figure 20 (first panel) is the same as figure 14 (first panel), but for the TNx index. CPC-T2m observation (Fig. 20a, c) shows the maxima of the TNx index over the Sahara with values reaching 40 °C, while the minima around 24 °C are located over the Guinea Coast.

The control experiments (Fig. 20b, d) well reproduced the general features of the TNx index with a PCC value reached 0.99, but some differences exist at local scale. Unlike the TNn index, control experiments underestimate the TNx over most of the studied domain. The strongest negative biases are found over the Central Sahel, with MB values up to −3.35 °C and −3.32 °C for JJAS 2003 and JJAS 2004, respectively (Table 4). The TNx index underestimation seems to be systematically related to the cold bias in RegCM4 over West Africa, which has been reported in several papers (Koné et al., 2018, Klutse et al., 2016).

Figure 20 (second panel) is the same as figure 14 (second panel) but displays changes in the TNx. Like for TNn index, over the Central Sahel, dry experiments increase the TNx values, while the wet experiments decrease them. However, over the West Sahel, both wet and dry experiments led to a dominant decrease. Conversely, over the Guinea Coast, although the signal is weak, both dry and wet experiments led to a dominant increase.

Figure 21 is the same as figure 15 but displays the PDF distributions of the changes in the TNx. The highest TNx increase (decrease) is found over the Central Sahel in dry (wet) experiments with maximum changes up to 0.25 (−1.67 °C) for JJAS 2003 (JJAS 2004) (Table 5). In summary, RegCM4 underestimates the warmest night temperature and dry (wet) experiments lead to an increase (decrease) of TNx magnitude.

4. Conclusions

The impact of the soil moisture initial conditions on six precipitation extreme indices and four temperature extreme indices over West Africa was investigated using the RegCM4-CLM45. We first evaluated the performance of RegCM4-CLM4.5 in representing these climate extreme indices over West Africa. We then performed sensitivity studies over the West African domain, with a spatial resolution of 25 km. We initialized the control runs using ERA20C reanalysis soil moisture and for dry and wet experiments, we used the maximum and minimum values of ERA20C over the whole domain, respectively. Results have been presented for JJAS 2003 and JJAS 2004 which are the two contrasted runs most sensitive to the effects of dry and wet soil moisture initial conditions.

Compared to CHIRPS observation, the model overestimates and underestimates the number of wet days. RegCM4 also underestimates the simple daily precipitation intensity index (SDII), the maximum 1-day precipitation (Rx1day), and the precipitation percentage due to very heavy precipitation days (R95pTOT). The current physical parameterization scheme of the RegCM4 model used in our study results in a positive bias of the number of wet days with a low precipitation threshold (e. g. 1 $mm.day^{-1}$), and in a negative bias for a higher precipitation threshold (e.g. 10 $mm.day^{-1}$, not shown here). RegCM4 generally overestimates the CWD and CDD indices over West Africa. Most of the temperature extreme indices used in this study (TXx, TXn, and TNn) are also overestimated, except the TNx index, which is underestimated over the West Africa domain.

The impact on extreme precipitation indices of the soil moisture initial conditions is linear over the Sahel central, only for indices related to the number of precipitation events (R1mm, CDD, and CWD indices) meaning that wet (dry) experiments lead to an increase (decrease) of the number of days, and not for those related to the amount or intensity of precipitation (SDII, RX1day, and R95pTOT). However, the dry and wet experiments increase the precipitation percentage due to very heavy precipitation days and the maximum one-day precipitation accumulation (R95pTOT and RX1day indices, respectively) over most of the studied domain.

The soil moisture initial conditions unequally influence the daily maximum and minimum temperatures over the West African domain. The impact on daily maximum temperature extremes are greater than those on the daily minimum temperature extremes. These results are consistent with previous studies (Jaeger and Seneviratne, 2011; Zhang et al., 2009).The wet (dry) experiments lead to TXx and TXn increase (decrease) over West Africa. However, regarding the minimum temperature we showed that dry (wet) experiments lead to a TNx increase (decrease).

This study helped to quantify the impact of the soil moisture initial conditions on precipitation and temperature extreme events in terms of intensity, frequency and duration over West Africa. This study is the first to investigate the impact of soil moisture initial conditions on climate extreme indices over West Africa. These experiments were done in a highly-idealized framework and were intended to show the potential impact of very strong soil moisture initial conditions on climate extremes. Consequently, it should be considered as a first overview of the influence of initial soil moisture on climate extremes with a RCM (RegCM4). In perspectives, this study will benefit from being performed in a multi-model framework with several RCMs within CORDEX-Africa initiative (Coordinated Regional Downscaling Experiment).

Author contribution

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.

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TABLES AND FIGURES.

Extreme indices	Definition	Units

Extreme Rainfall Indices			
1	R1mm	Number of wet days (daily precipitation ≥ 1mm)	day
2	SDII	The amount of precipitation mean on wet days (daily precipitation ≥ 1mm)	$mm.day^{-1}$
3	CDD	Maximum number of consecutive dry days (daily precipitation < 1 $mm.day^{-1}$)	day
4	CWD	Maximum number of consecutive wet days (daily precipitation ≥ 1 $mm.day^{-1}$)	day
5	RX1day	The maximum one-day precipitation accumulation	mm
6	R95pTOT	Precipitation percent due to very heavy precipitation days.	%
Extreme temperature indices			
7	TXn	Minimum value of daily maximum temperature	°C
8	TXx	Maximum value of daily maximum temperature	°C
9	TNn	Minimum value of daily minimum temperature	°C
10	TNx	Maximum value of daily minimum temperature	°C

Table1: The 10 extreme climate indices used in this study.

	Central Sahel		West Sahel		Guinea Coast		West Africa	
	MB	PCC	MB	PCC	MB	PCC	MB	PCC

R1mm	CTRL_2003	33.17	0.98	-5.25	0.96	**53.16**	0.96	22.18	**0.96**
	CTRL_2004	29.50	0.98	1.34	0.96	**55.46**	0.96	23.85	**0.95**
SDII	CTRL_2003	-7.52	0.97	-9.95	0.94	**-13.62**	0.77	-7.67	**0.73**
	CTRL_2004	-7.01	0.97	-9.37	0.94	**-14.65**	0.81	-7.59	**0.77**
CDD	CTRL_2003	0.93	0.90	**14.49**	0.91	**-7.84**	0.66	**2.63**	**0.85**
	CTRL_2004	4.75	0.91	**17.51**	0.95	**-9.43**	0.68	**6.99**	**0.89**
CWD	CTRL_2003	45.56	0.83	18.44	0.75	**59.21**	0.88	31.20	**0.81**
	CTRL_2004	36.78	0.79	20.48	0.78	**60.51**	0.82	29.74	**0.79**
RX1day	CTRL_2003	-26.46	0.78	**-38.07**	0.91	**-30.28**	0.54	-20.08	**0.50**
	CTRL_2004	-22.89	0.46	**-36.67**	0.88	**-42.44**	0.42	-20.23	**0.40**
R95pTOT	CTRL_2003	-27.67	0.67	-33.39	0.77	**-43.22**	0.65	-29.12	**0.59**
	CTRL_2004	-24.38	0.46	-31.75	0.80	**-46.61**	0.60	-27.45	**0.55**

Table 2: The pattern correlation coefficient (PCC) and the mean bias (MB) of R1mm (in day), SDII (in mm.day-1), CDD (in day), CWD (in day), RX1day (in mm) and R95pTOT (in %) indices for control experiments (initialized with initial soil moisture of ERA20C reanalysis) with respect to CHIRPS, calculated over Guinea Coast, Central Sahel, West Sahel and the entire West African domain for JJAS 2003 and JJAS 2004.

Precipitation indices		Central Sahel		West Sahel		Guinea Coast		West Africa	
		ΔWC	ΔDC	ΔWC	ΔDC	ΔWC	ΔDC	ΔWC	ΔDC
R1mm (day)	2003	8.14	**-5.19**	**12.02**	0.69	3.92	2.88	4.67	1.75

	2004	10.01	-3.79	10.14	0.56	4.90	3.57	7.90	2.61
SDII (mm/day)	2003	0.07	0.11	-0.11	0.14	0.70	0.17	0.29	0.31
	2004	0.03	0.09	0.26	-0.07	0.56	0.22	0.24	0.21
CWD (day)	2003	13.25	-3.15	6.61	0.64	12.24	4.05	9.43	1.09
	2004	**15.58**	**-4.48**	7.20	-0.19	6.08	3.18	11.89	-0.37
CDD (day)	2003	-2.80	2.58	**-12.73**	0.83	-0.68	-1.31	-1.53	0.19
	2004	-5.92	**3.80**	-7.75	2.75	-0.93	-1.46	-3.57	-0.44
RX1day (mm)	2003	1.97	3.78	0.11	0.65	**26.14**	4.17	7.16	7.27
	2004	3.35	3.03	7.05	0.19	**14.93**	15.73	6.46	2.28
R95pTOT (%)	2003	1.54	1.77	2.88	1.53	**4.33**	2.37	2.83	2.46
	2004	1.66	0.89	**4.03**	0.43	1.69	0.92	1.37	2.43

Table 3: Summary Table of maximum values of change on PDF's for R1mm, SDII, CDD, CWD, RX-1day and R95pTOT indices.

	Central Sahel		West Sahel		guinea		West Africa	
	MB	PCC	MB	PCC	MB	PCC	MB	PCC

TXx	CTRL_2003	2.10	0.99	**3.02**	0.99	-1.34	0.99	0.32	**0.99**
	CTRL_2004	1.14	0.99	**2.02**	0.99	-1.41	0.99	-0.16	**0.99**
TXn	CTRL_2003	5.12	0.99	**6.56**	0.99	3.76	0.99	**5.65**	**0.99**
	CTRL_2004	3.43	0.99	**5.44**	0.99	2.75	0.99	**4.14**	**0.99**
TNn	CTRL_2003	2.37	0.99	**3.30**	0.99	1.53	0.99	1.45	**0.99**
	CTRL_2004	2.09	0.99	**2.55**	0.99	1.28	0.99	0.71	**0.99**
TNx	CTRL_2003	-1.91	0.99	-2.86	0.99	**-3.35**	0.99	-3.85	**0.99**
	CTRL_2004	-1.90	0.99	-2.54	0.99	**-3.32**	0.99	-3.99	**0.99**

Table 4: The pattern correlation coefficient (PCC) and the mean bias (MB in°C) of TXx, TXn, TNn and TNx indices for control experiments (initialized with initial soil moisture of ERA20C reanalysis) with respect to CPC-T2m, calculated for Guinea Coast, Central Sahel, West Sahel and the entire West African domain for JJAS 2003 and JJAS 2004.

Temperature	Central Sahel	West Sahel	Guinea Coast	West Africa

indices		ΔWC	ΔDC	ΔWC	ΔDC	ΔWC	ΔDC	ΔWC	ΔDC
TXx	2003	-2.54	1.14	-2.11	0.90	-0.34	0.68	-0.89	1.06
	2004	**-2.57**	**1.69**	-1.58	0.98	-0.32	1.01	-0.86	1.27
TXn	2003	-1.37	0.81	**-1.67**	-0.05	-0.06	0.28	-0.50	0.59
	2004	-1.09	**1.03**	-0.93	0.55	-0.04	0.31	-0.38	0.61
TNn	2003	-0.37	-0.20	-0.23	**-1.15**	0.05	0.04	-0.20	0.03
	2004	-0.03	-0.37	0.06	-1.07	**0.11**	-0.03	-0.05	-0.11
TNx	2003	-1.29	**0.25**	-0.94	-1.37	0.12	0.04	-0.49	0.13
	2004	**-1.67**	0.15	-0.62	-1.13	0.02	0.03	-0.51	-0.07

Table 5: Summary Table of maximum values of change on PDF's for TXx, TXn, TNn and TNx indices.

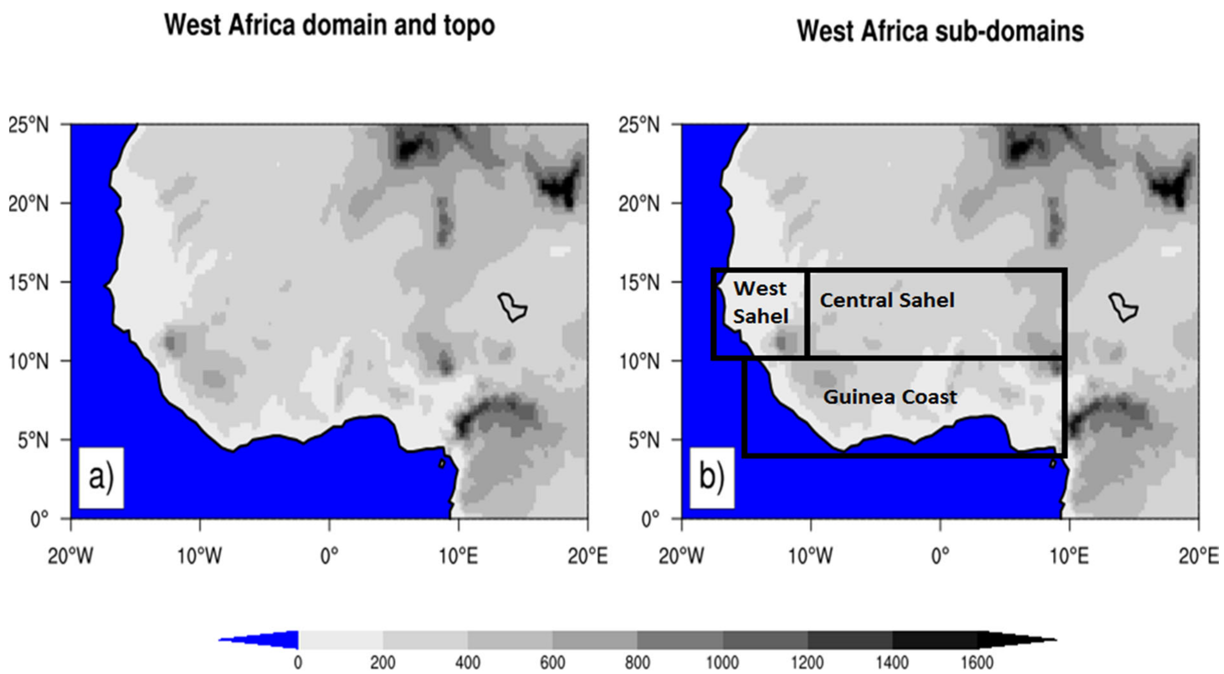

Figure 1: Topography of the West African domain. The analysis of the model result has an emphasis on the whole West African domain and the three subregions Guinea Coast, Central Sahel and West Sahel, which are marked with black boxes.

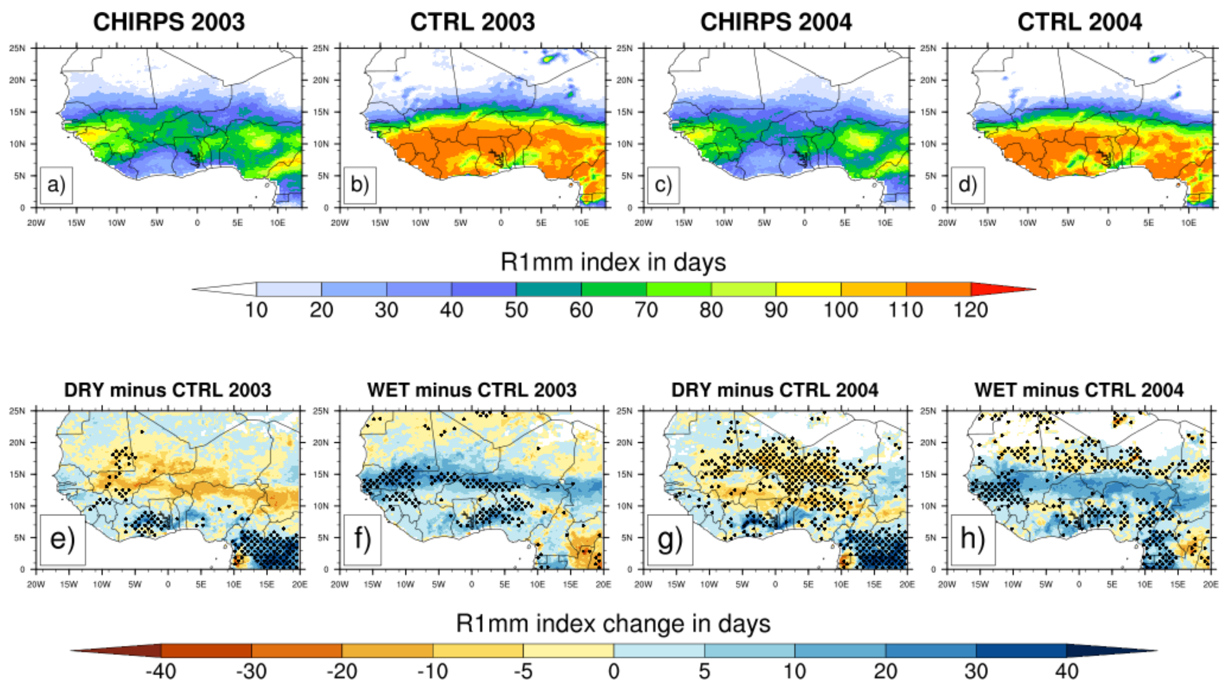

Figure2: Mean values of the number of the wet days (R1mm index in days) from CHIRPS (a and c) observation for JJAS 2003 and JJAS 2004 and the simulated control (CTRL) experiments (b and d) initialized with initial soil moisture of the reanalysis of ERA20C (first panel) and changes in R1mm index in days (second panel) for JJAS 2003 and JJAS 2004, from dry (e and g) and wet (f and h) experiments with respect to the control experiments. Areas with values passing the 95% significance test are dotted.

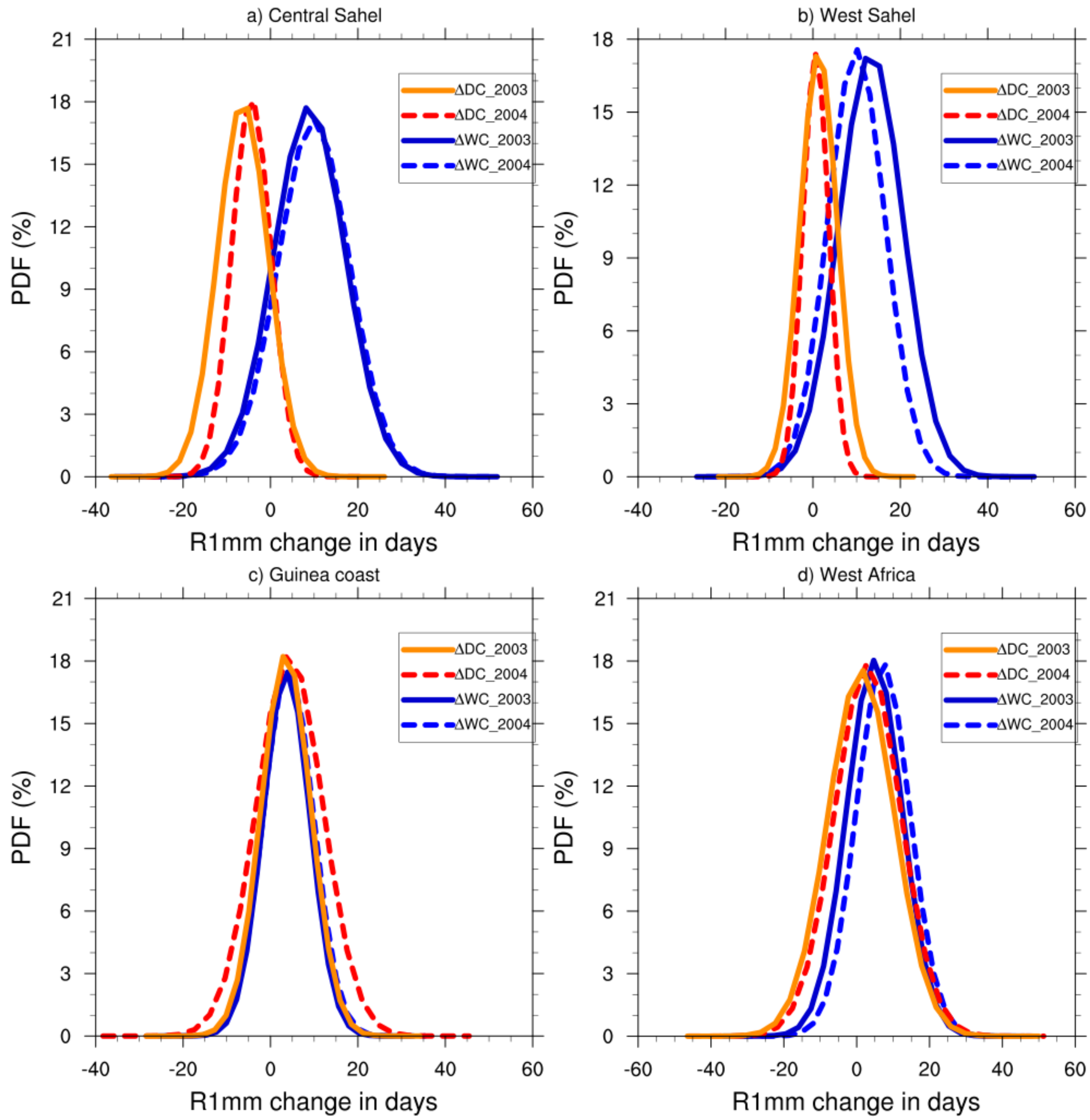

Figure3: PDF distributions (%) of mean values of the number of the wet days change in JJAS 2003 and JJAS 2004, over (a) Central Sahel , (b) West Sahel, (c) Guinea and (d) West Africa derived from dry (ΔDC) and wet (ΔWC) experiments with respect to the control experiment.

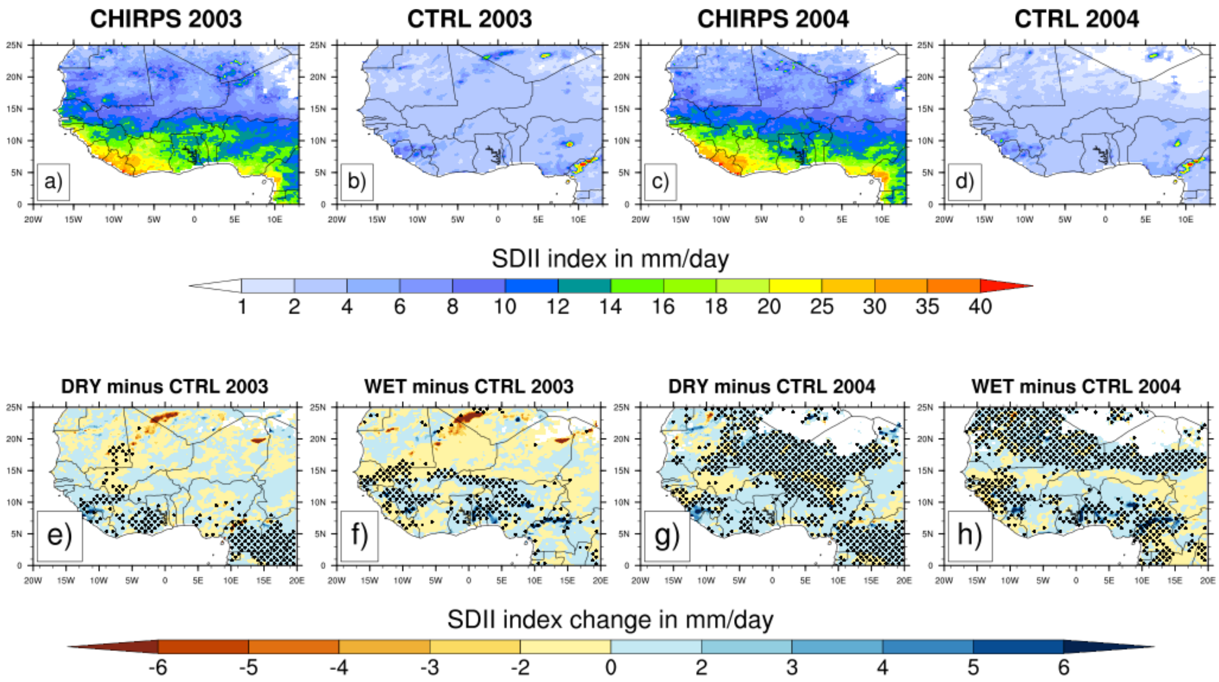

Figure4: Same as Fig. 2 but for the SDII index (in mm.day^{-1}).

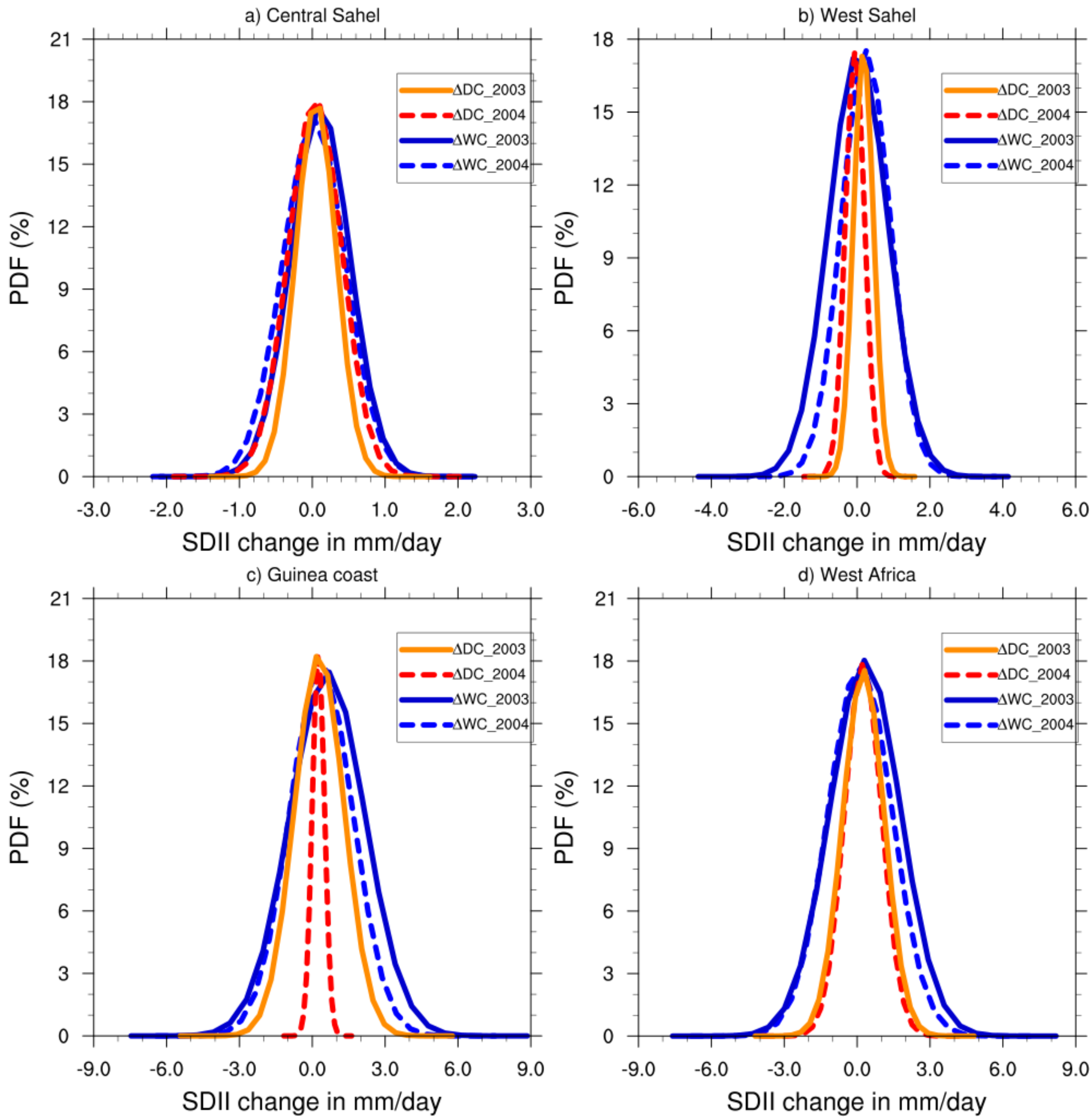

Figure 5: Same as Fig. 3 but for the SDII index (in mm.day^{-1}).

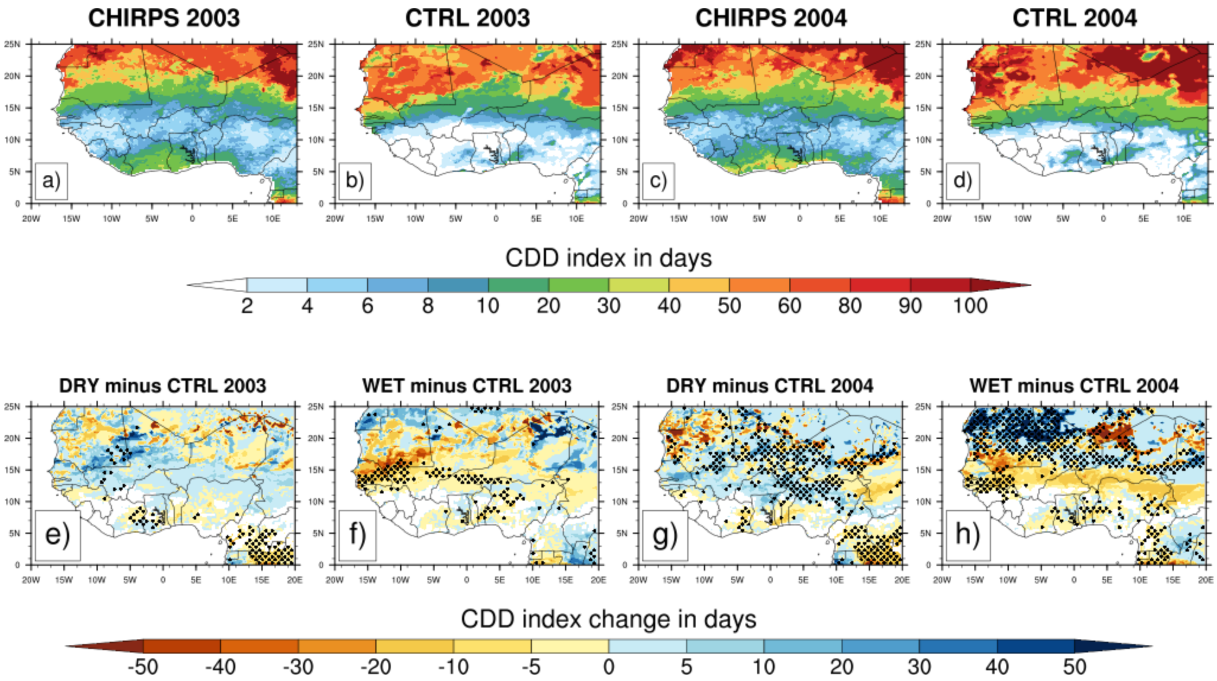

Figure 6: Same as Fig. 2 but for the CDD index (in day).

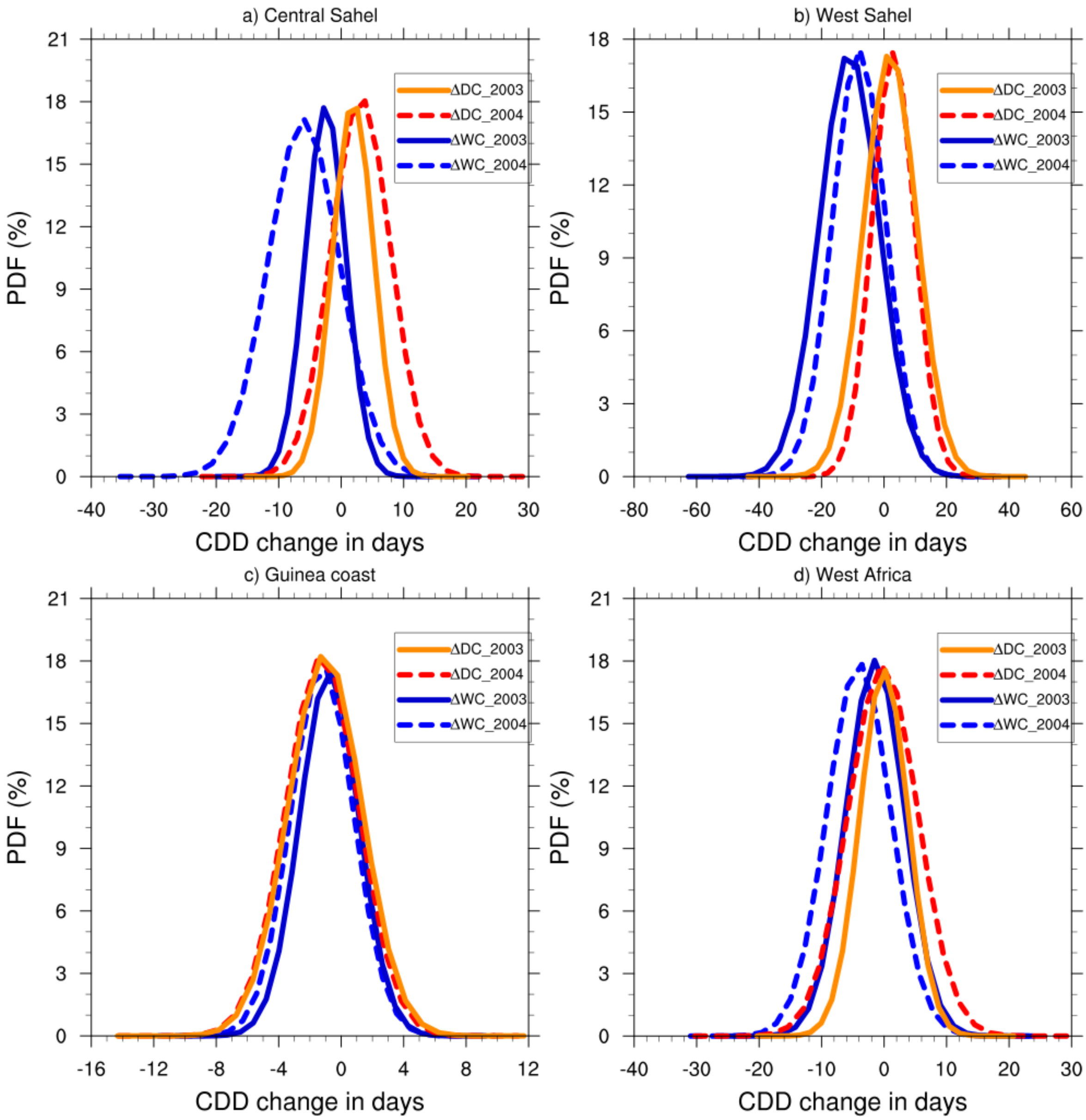

Figure 7: Same as Fig. 3 but for the CDD index (in day).

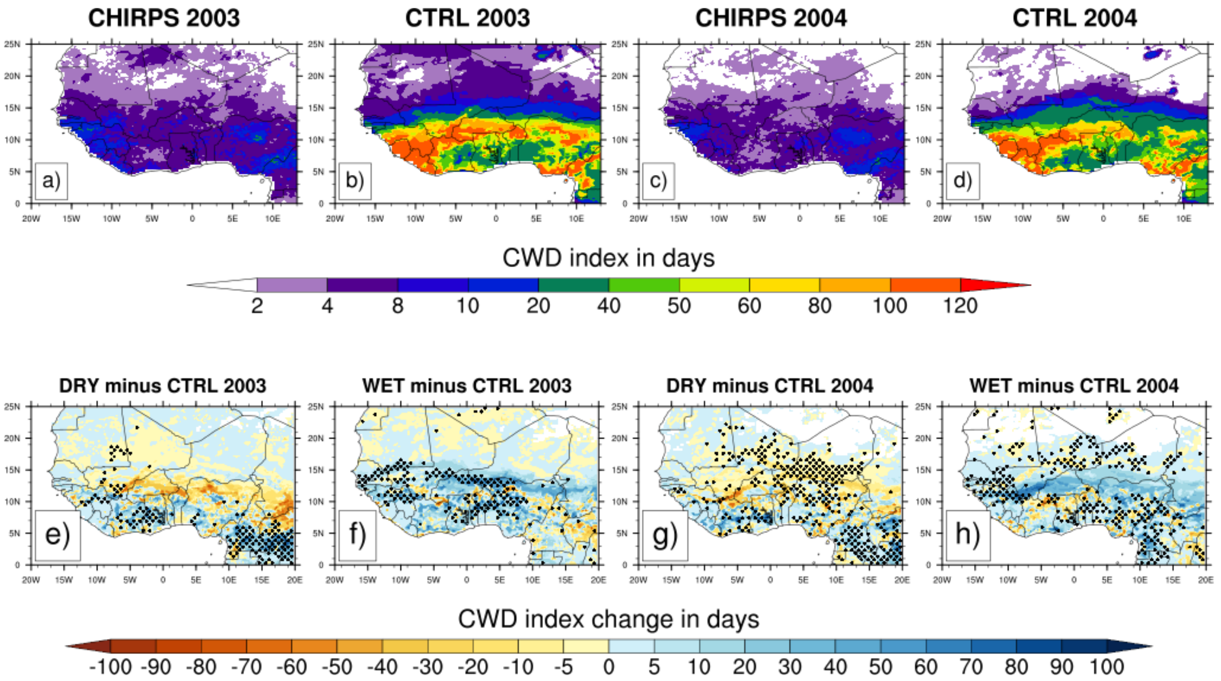

Figure 8: Same as Fig. 2 but for the CWD index (in day).

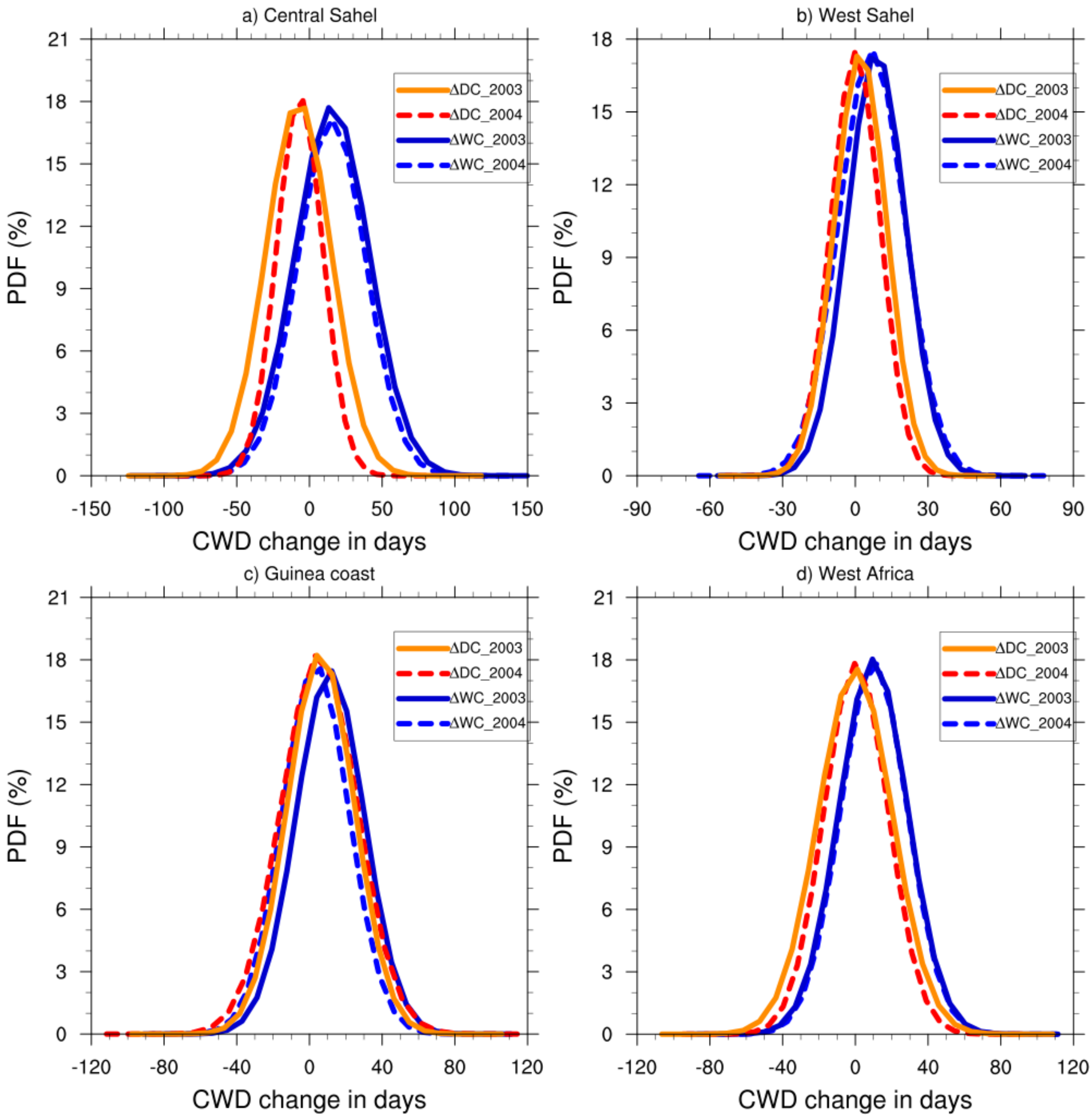

Figure 9: Same as Fig. 3 but for the CWD index (in day).

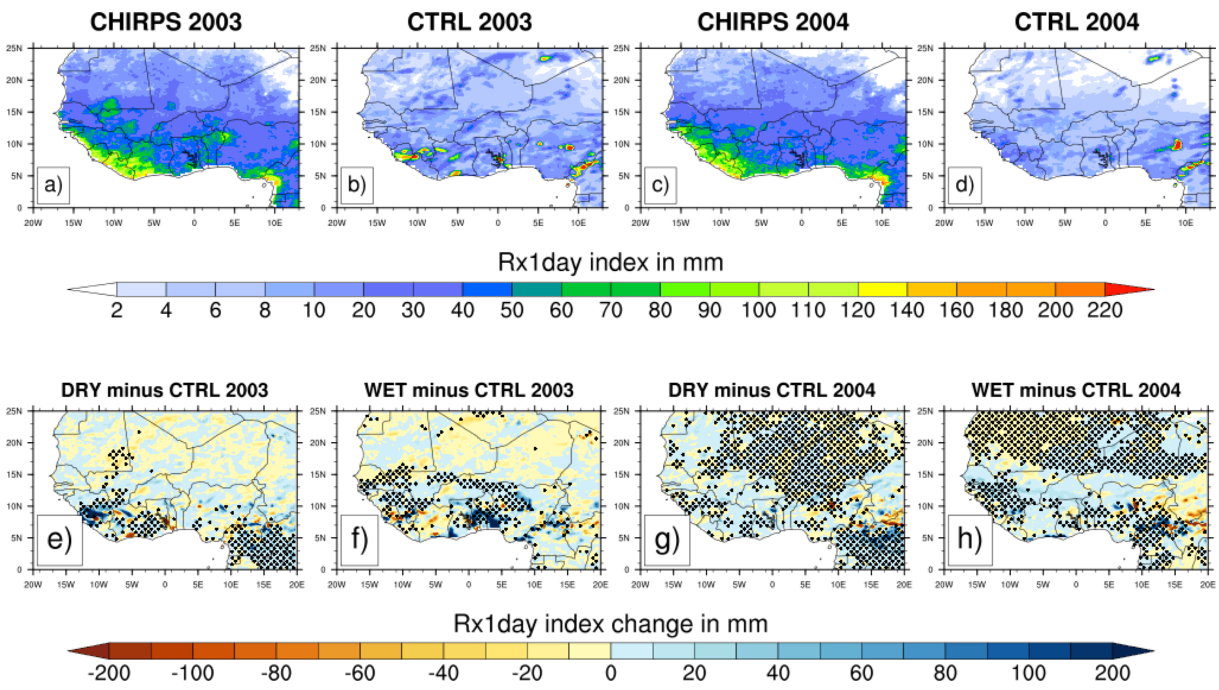

Figure 10: Same as Fig. 2 but for the RX1day index (in mm).

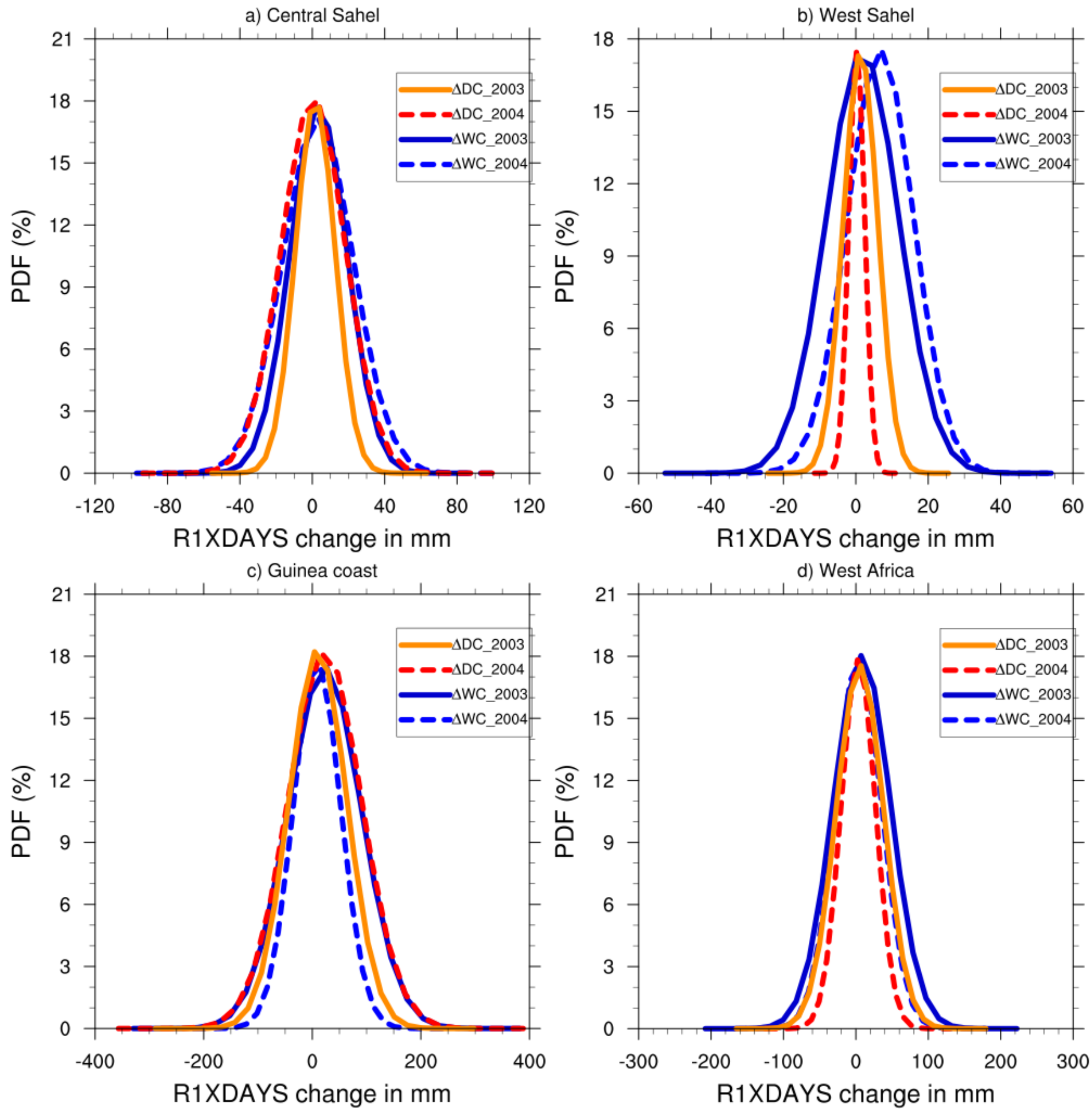

Figure 11: Same as Fig. 3 but for the RX1DAY index (in mm).

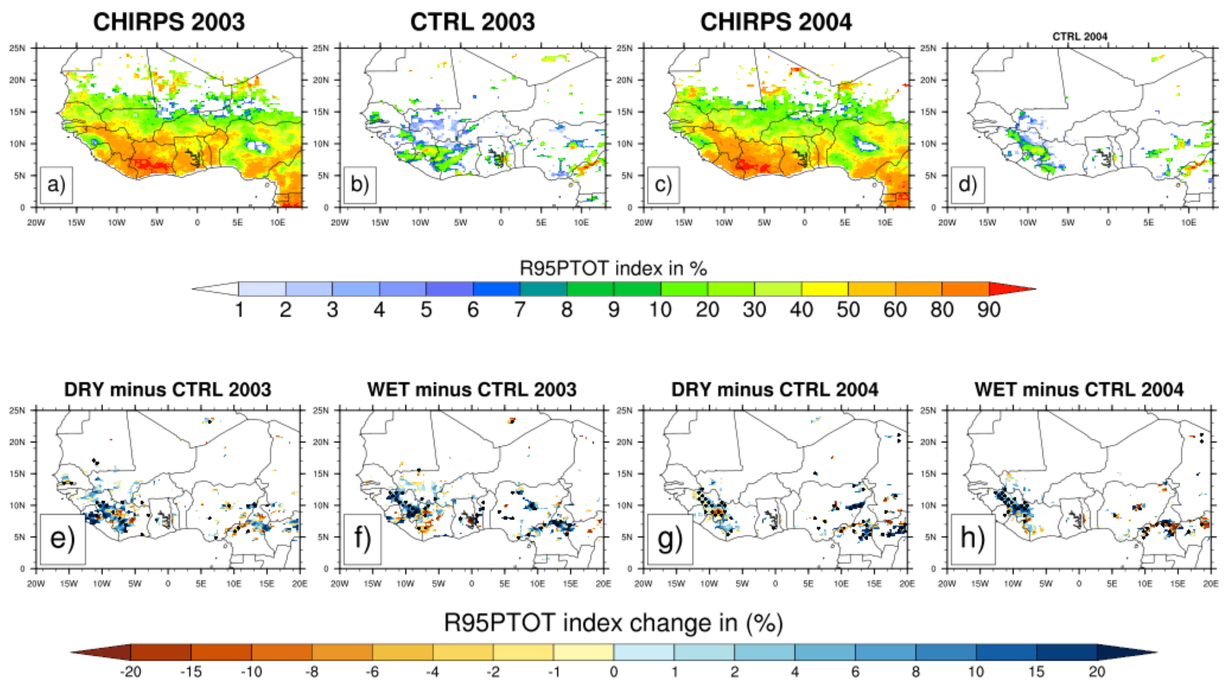

Figure 12: Same as Fig. 2 but for the R95pTOT index (in %).

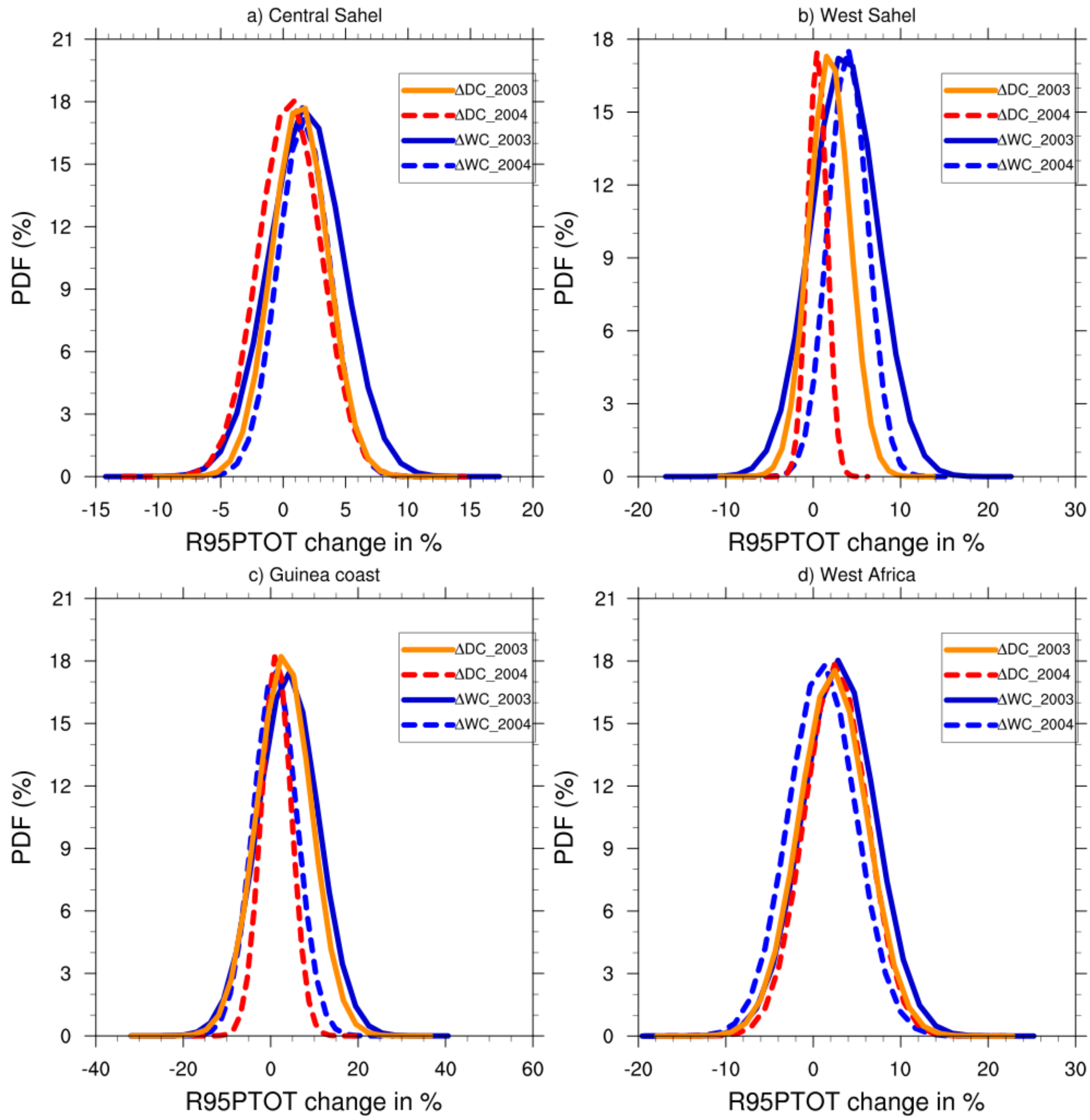

Figure 13: Same as Fig. 3 but for theR95pTOT index (in %).

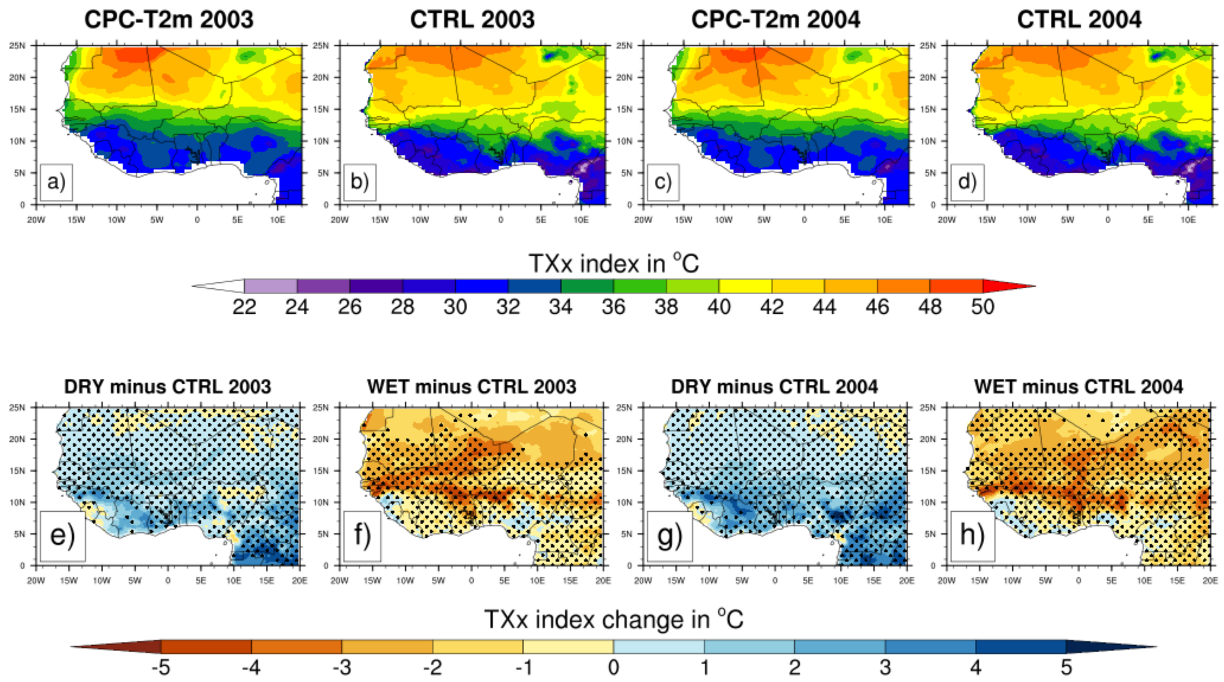

Figure 14: The mean maximum value of daily maximum temperature (TXx index in°C) from CPC-T2m observation (a and c) for JJAS 2003 and JJAS 2004 and the simulated control (CTRL) experiments (b and d) initialized with the initial soil moisture of the ERA20C reanalysis (first panel) and changes in TXx index in°C (second panel) for JJAS 2003 and JJAS 2004, from dry (e and g) and wet (f and h) experiments with respect to the control experiments. Areas with values passing the 95% significance test are dotted.

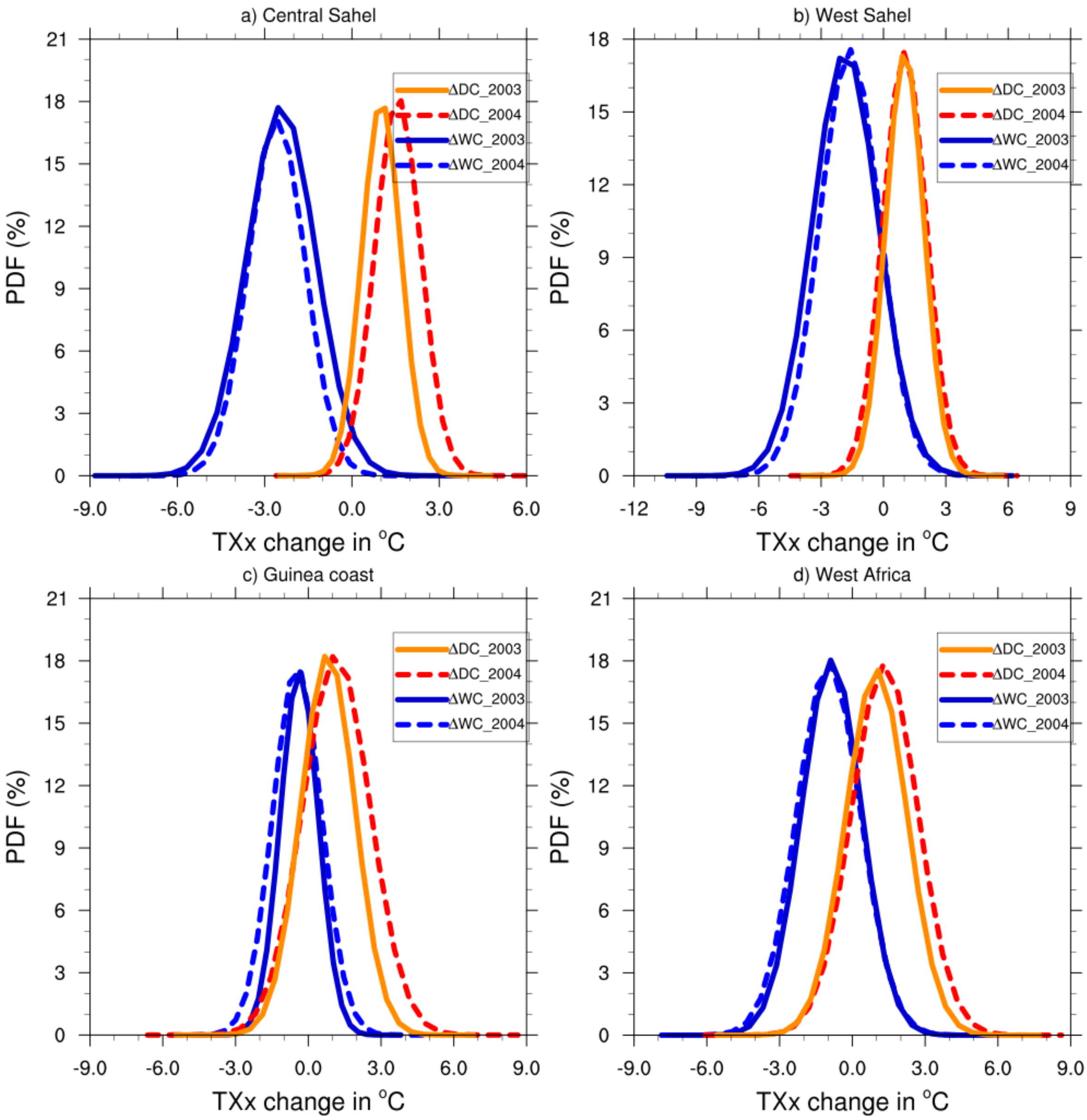

Figure 15: PDF distributions (%) of change in maximum value of daily maximum temperature (TXx index, in°C) for JJAS 2003 and JJAS 2004, over (a) Central Sahel , (b) West Sahel, (c) Guinea and (d) West Africa derived from dry (ΔDC) and wet (ΔWC) experiments compared to the control experiment.

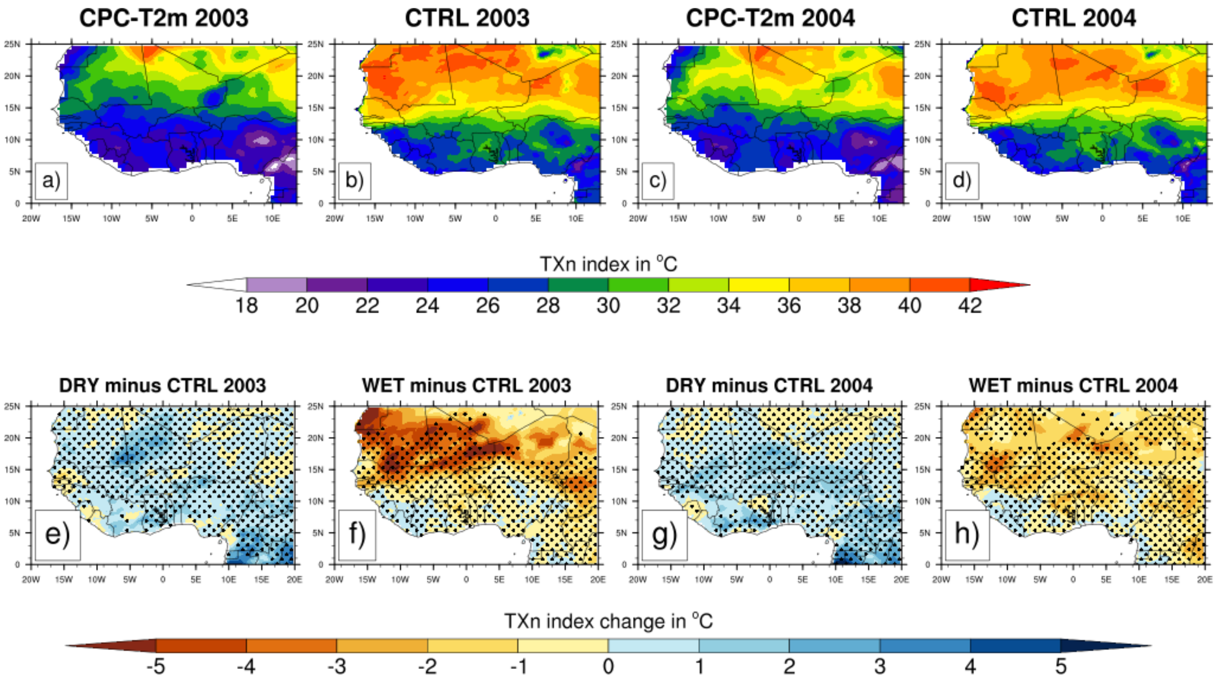

Figure 16: Same as Fig. 14 but for the TXn index

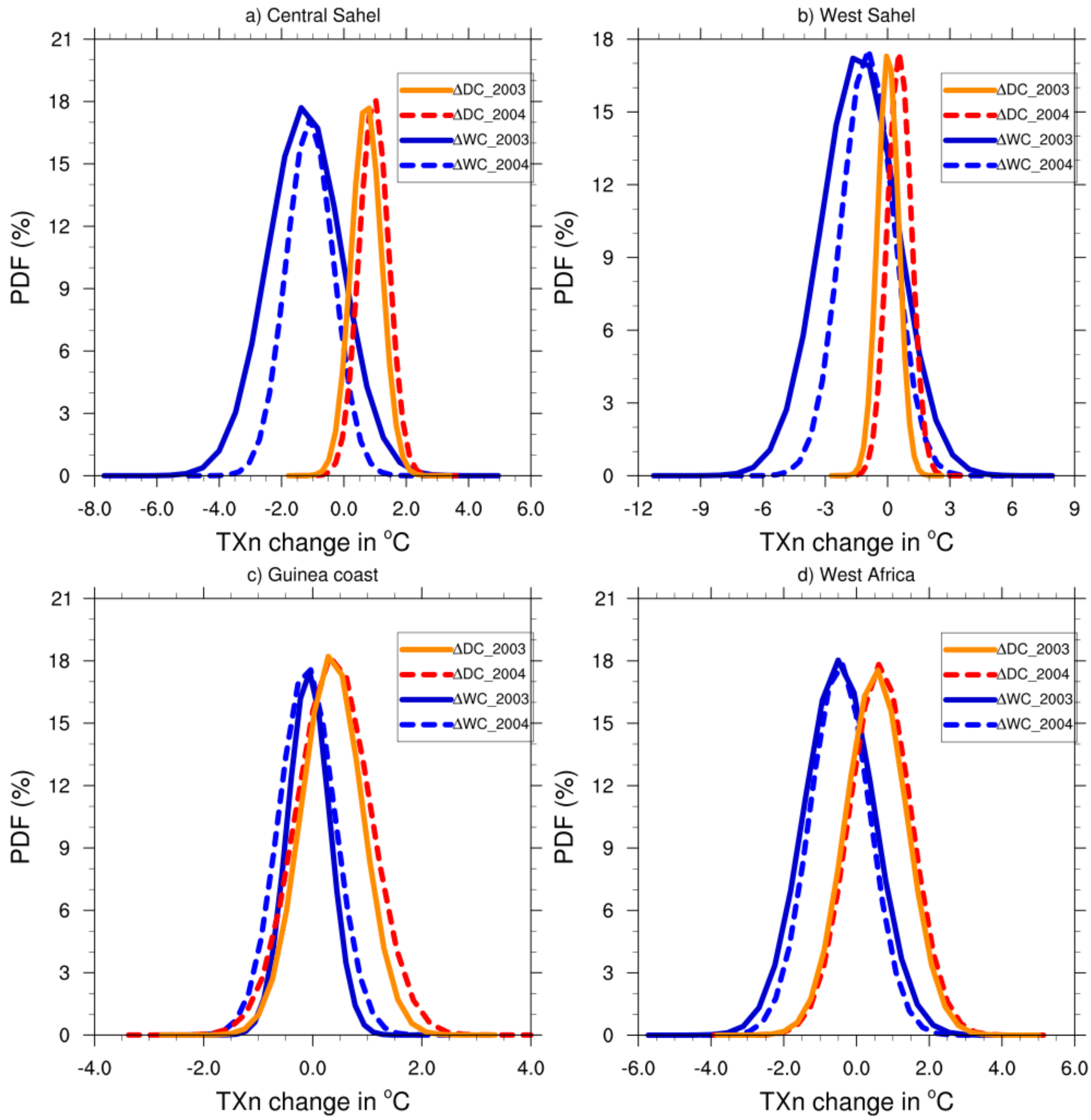

Figure 17: Same as Fig. 15 but for the TXn index.

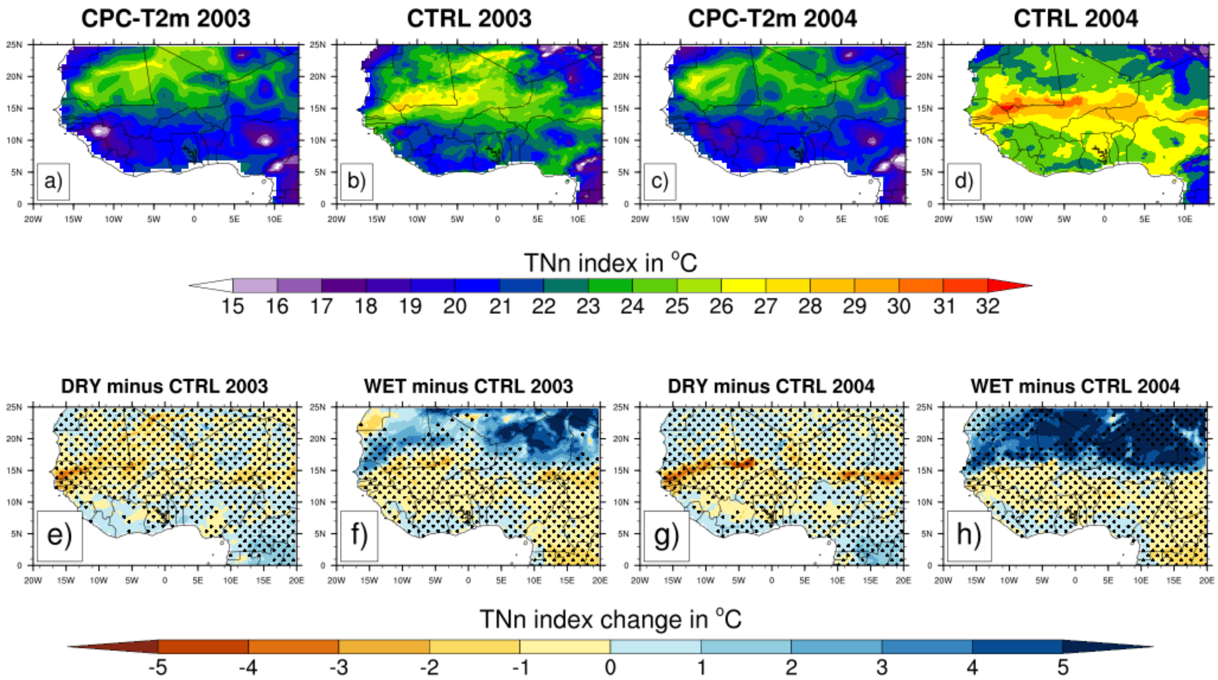

Figure 18: Same as Fig. 14 but for the TNn index.

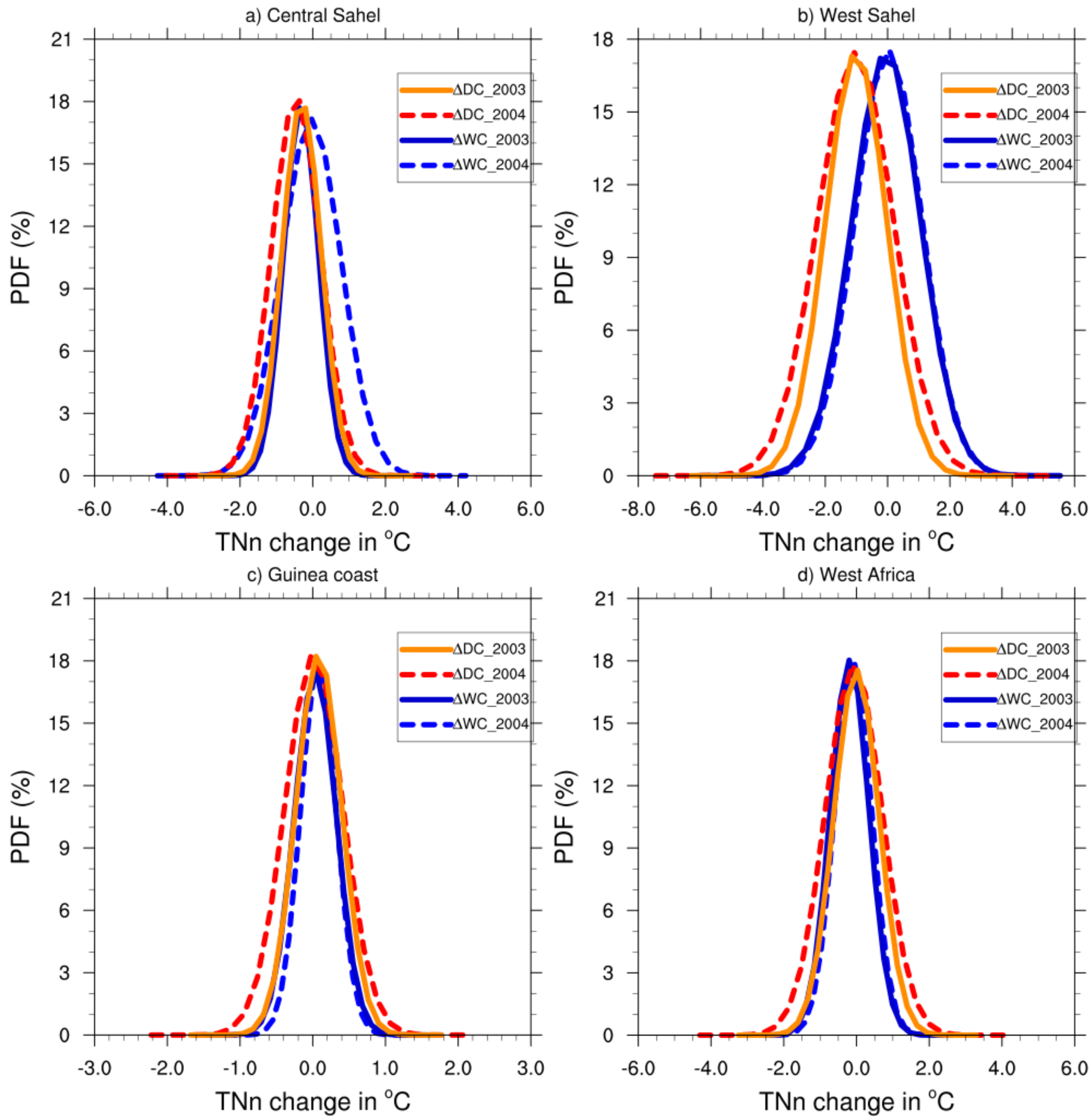

Figure 19: Same as Fig. 14 but for the TNn index.

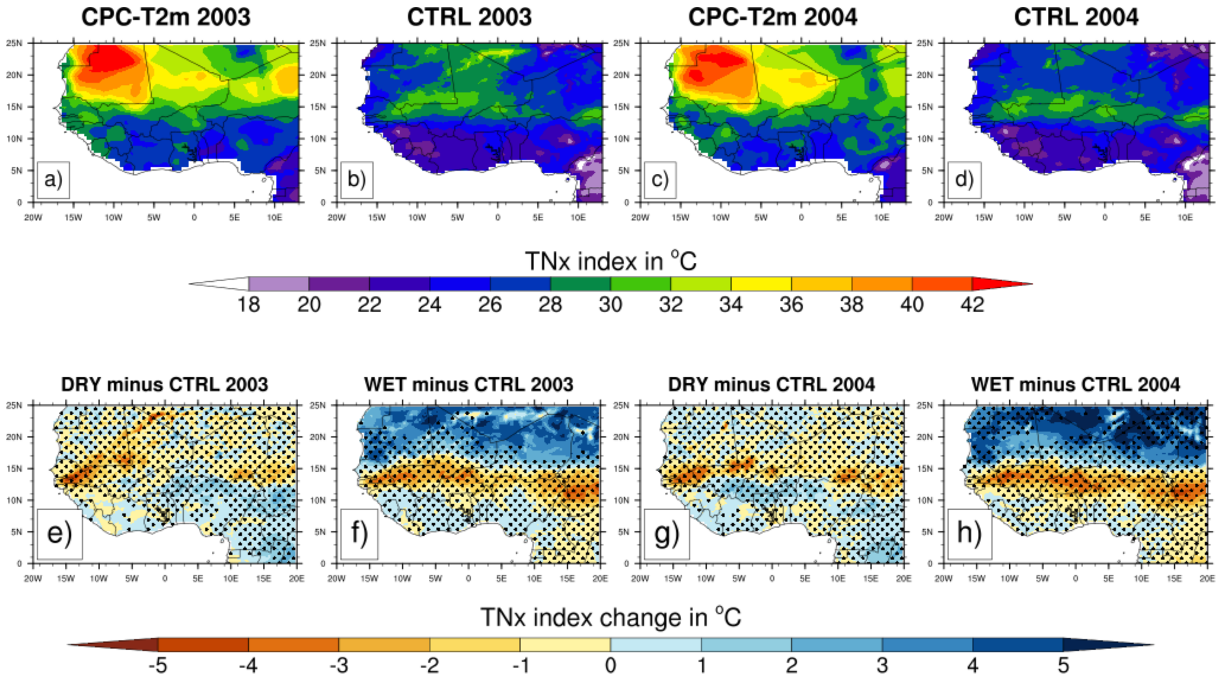

Figure 20: Same as Fig. 14 but for the TNx index

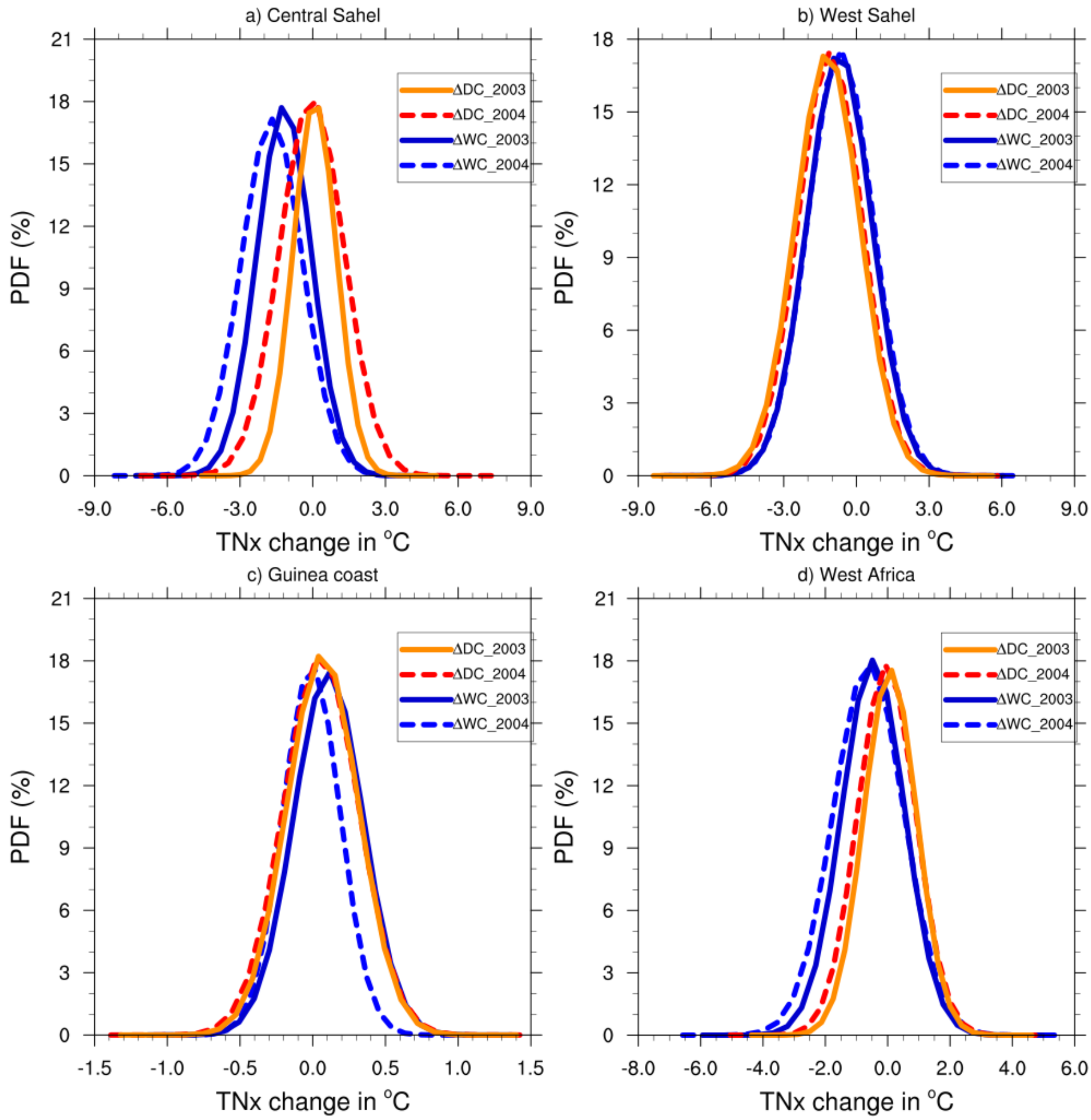

Figure 21: Same as Fig. 15 but for the TNx index.