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 initial soil moisture conditions on the climate extreme 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. Sensitivity studies was carried out during 5 years from 2001 to 2005, with initial soil moisture conditions prescribed on June 1st and simulations performed over 4 months (120 days) from June to September (JJAS). Results have been presented for two extreme years 2003 (above normal precipitation year) and 2004 (below normal precipitation year) in the aim to estimate the limits of the impact of internal soil moisture forcing on the new non-hydrostatic dynamical core of RegCM4. We initialized the control runs with the reanalysis soil moisture of the European Centre Meteorological Weather Forecast's reanalysis of the 20th century (ERA20C), while for the dry and wet experiments, we initialized the soil moisture respectively at the wilting points and field capacity. The impact on extreme precipitation indices of the initial soil moisture, especially over the central Sahel, is linear, i.e. dry (wet) experiments tend to decrease (increase) precipitation extreme indices only for precipitation indices related to the number of precipitation events, not for those related to the intensity of precipitation events. The impact on temperature extremes of the initial soil moisture conditions is more significant compared to precipitation extremes. Initial soil moisture conditions unequally affect daily minimum and maximum temperature. A stronger impact is found on maximum temperature than minimum temperature. Over the entire West African domain, wet (dry) experiments cause a decrease (increase) in maximum temperature. The strongest impacts on minimum temperature indices are found mainly in wet experiments,

on the Sahara where we found the higher values of the maximum and minimum daily minimum temperature indices (resp. TNx and TNn). The performance of RegCM4-CLM4.5 in simulating the ten (10) extreme rainfall and temperature indices used in this study is also highlighted.

1 Introduction

West Africa experienced large rainfall variability during the late 1960s. This variability leads often to flooding events, severe drought and regional heatwaves. Such extreme hydro-climatic events 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 mean climate. Yan and Yang (2000) show that for a large number of cases, the extreme climate changes were 5 to 10 times greater than climate mean change. Many key factors or physical mechanisms could be possible causes 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), the 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 the coupling of land-atmosphere, can lead to changes in climate extremes. For the European summer, the influence of soil moisture in the coupling of land-atmosphere using 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 show that wet (dry) experiences decrease (increase) the hot extremes, decrease (increase) the drought extremes, and increase(decrease) the cold extremes in a zone of strong soil moisture-atmosphere coupling. However, none of these papers intended to examine the impacts of the initial soil moisture conditions on subsequent climate extreme using a regional climate model over West Africa. In part 1, the influence of initial soil moisture on the climate mean was based on performance assessment of the Regional Climate Model coupled with the complex 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. However, in part 2, before starting to study the influence of initial soil moisture on the climate extremes, it was needed to assess first the performance of RegCM4-CLM4.5 in simulating the ten (10) temperature indices and extreme rainfall used in this study. This has never been done before over Africa. That's why we separate in two parts, to ease the reading and to come up with papers of reasonable length. The paper is organized as follows: section 2 describes the model RegCM4, the experimental design and methodology used in this study; section 3 presents the assessment of RegCM4-CLM4.5 in climate extremes simulation and the impacts on climate extremes of the initial soil moisture conditions; and section 4 documents the conclusions.

2. Model, experimental design and methodology

2.1 Model description and numerical experiment

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, the physical representations have been subject to a continuous process of implementation and development. The release used in this study is RegCM4.7. The non-hydrostatic dynamical core of the MM5 (Mesoscale Model version 5, Grell et al., 1994) has been ported to RegCM4 while maintaining the existing hydrostatic core. We selected in this study the non-hydrostatic as the model dynamical core. RegCM4 is a limited-area model using a vertical grid sigma hydrostatic pressure coordinate and a horizontal grid of 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 aerosols 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 is from Sundqvist et al. (1989). The sensible heat and water vapor in the planetary boundary layer over land and ocean, turbulent transports of momentum are from Holtslag et al. (1990). The heat and moisture and the momentum of ocean surfaces fluxes are from Zeng et al. (1998). Convective precipitation and the land surface processes in RegCM4.7 are represented in several options. Based on Koné et al. (2018), the convective scheme of Emanuel (Emanuel, 1991) is used. The parameterization of the land surface processes is from CLM4.5 (Oleson et al., 2013). In each grid cell of CLM4.5, there is 16 different plant functional types and 10 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 18 vertical levels and 25 km (182x114 grid points; from 20°W-20°E and 5°S-21°N) of horizontal resolution. 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 States Geological Survey (USGS) Global Multi-resolution Terrain Elevation Data (GMTED; Danielson et al., 2011) at the spatial resolution of 30 arc-second which is an update of the Global Land Cover Characterization (GTOPO; Loveland et al., 2000) dataset.

The sensitivity of the initial soil moisture does not exceed four months (Hong and Pan., 2000; Kim and Hong, 2006). (Hong and Pan., 2000; Kim and Hong, 2006). As mentioned in Part I, we performed these sensitivity studies to the initial conditions of soil moisture over our West African domain 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 two years 2003 and 2004 (resp. the wettest and the driest years among the 5 years) have been selected in the aim to estimate the limits of the impact of internal soil moisture forcing on the new dynamical core non-hydrostatic of RegCM4. Several previous studies used two extreme years for their sensitivity study of initial soil moisture condition on the models (e.g Hong et al., 2000; Kim and Hong, 2006). We set up an ensemble of 3 experiments each with simulations starting from June 1st to September 30th. 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. Kang et al. (2014) by comparing different land surface schemes (BATS and CLM3) and different periods of spin-up to simulate June – July – August precipitations recommended 7 days as spin-up period. In this study, we used CLM4.5 as land surface scheme (Oleson et al., 2013) which has a more complex design. The first 7 days (Kang et al., 2014) are excluded in the analysis as a spin-up period. 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 (in volumetric fraction $m^3.m^{-3}$) respectively at the field capacity (=0.489) and the wilting point (=0.117.10^{-4}) over the West African derived from ERA20C soil moisture dataset.

2.2 Validation datasets and evaluation metrics

Our investigation is focused on the air temperature at 2 m and the precipitation over the West African domain during the summer of JJAS for 2003 and JJAS 2004. The simulated precipitation fields are validated with two observation datasets: the Climate Hazards group Infrared Precipitation Stations (CHIRPS) dataset is from the University of California at Santa Barbara, available from 1981 to 2020 at the 0.05° high-resolution and the Tropical Rainfall Measuring Mission 3B43V7 (TRMM) dataset with the 0.25° high-resolution available from 1998 to 2013 (Huffman et al., 2007). We validated the 2 m temperature with two observation datasets: the global daily temperature from the Global Telecommunication System (hereafter GTS), gridded at the horizontal resolution of 0.5° for 1979 to 2020 (Fan Y. and Huug van den Dool, 2008) and daily temperature from ERA-Interim (EIN) reanalysis at 0.25° of horizontal resolution available from 1979 to 2020 (Dee et al., 2011). For the comparison of the simulations of the model with observation datasets, we re-gridded all the products to 0.22° × 0.22°. We used an interpolation of the bilinear method for this purpose (Nikulin et al., 2012).
The performance of RegCM4-CLM4.5 to simulate the extreme indices has been carried using four selected sub-regions (Fig. 1) based on the previous work of Koné et al. (2018), they correspond to different features of the annual cycle of precipitation. We used the mean bias (MB), which captures the small-scale differences between the simulation and the observation. The pattern correlation coefficient (PCC) is also used as a spatial correlation between model simulations and the observation to indicate the large-scale similarity degree.
To quantify the impact of soil moisture anomalies on climate extremes Liu et al. (2014) in their work over Asia, used the mean biases in 5 subregions, while in our study we used the mean biases and the probability density function (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.
The statistically significant differences has been tested between the control and the sensitivity experiments, we perform the two-tailed of the student's t-distribution at every grid points as did by Liu et al. (2014) in a similar work over Asia. Due to the multiplicity problem of independent tests and the spatial dependency of neighboring grid points, the significant results can only be seen as a crude estimate. Therefore, we perform the land point's area-weighted

fraction with statistical significance of 10% level and we display the seasonally extreme indices maps during the years 2003 and 2004.

2.3. Extreme rainfall and temperature indices

In this study, to investigate the changes in precipitation and temperature in terms of duration, occurrence and intensity, six extreme temperature and four extreme rainfall indices are examined using daily data of minimum and maximum temperature and daily rainfall (Table 1). These 10 extreme indices are recommended by the Expert Team on Climate Change Detection and Indices (ETCCDI, Peterson et al., 2001). We estimated the monthly values of the indices, which allow investigating of the seasonal variations.

3. Results and discussion

3.1. Seasonal extreme rainfall

In this section, we analyze six extreme rainfall indices based on daily precipitation in RegCM4 simulations over West Africa. All precipitation indices are calculated for JJAS 2003 and JJAS 2004. Table 2 summarizes the pattern correlation coefficient (PCC) and the mean bias (MB) of all precipitation indices studied in this section for TRMM observation and model simulations derived from control experiments with reanalysis initial soil moisture ERA20C with respect to CHIRPS observation, calculated for the west Sahel, central Sahel, Guinea coast and the entire West African domain during the period JJAS 2003 and JJAS 2004.

3.1.1 The index of the number of the wet days (R1mm index)

Figure 2 shows the mean values of the number of the wet days (R1mm index, in days) from CHIRPS (Fig.2a, d) and TRMM (Fig2b, e) observations and their corresponding simulated control experiments (Fig2c, f) with the initial soil moisture derived from ERA20C reanalysis. The two observation datasets CHIRPS (Fig. 2a, d) and TRMM (Fig.2b, e) show a similar large-scale pattern over the West African domain with a PCC up to 0.98 (Table 2). The maximum values of the R1mm index are located over the regions of mountains such Cameroon mountains, Jos plateau and the Guinea highlands, while the minimum values of R1mm index are found over the Sahel with the number of wet days which decrease gradually from South to North. However, although the large-scale patterns are similar, at the local scale some differences are found in term of magnitude and spatial extent of these maxima and minima. The TRMM datasets underestimate the number of the wet days over the central and west Sahel, and they are overestimated over Guinea coast for both JJAS 2003 and JJAS 2004 (Table 2). For instance, over the central Sahel, we observe a strong mean bias (MB) about -6.76 and 7.51 days (resp. for JJAS 2003 and JJAS 2004, Table 2), and over the Guinea coast, the MB reaches 8.89 and 10.44 days (resp. for JJAS 2003 and JJAS 2004, Table 2).

The control experiments (Fig.2c, f) reproduce well the large-scale structure of the observed rainfall with a PCCs values reached 0.96 and 0.95 (resp. for JJAS 2003 and JJAS 2004, Table 2) over the entire West African domain, but do exhibit some biases at the locale scale in term of spatial extent and magnitude. The control experiment display a large and quite homogeneous area of maximum values of R1mm index under the latitude 12°N. The control experiments overestimate the number of wet days over most of the studied domains (Table2). The largest mean biases are found over the Guinea coast with MB more than 53.16 and 55.46 days (resp. for JJAS 2003 and JJAS 2004, Table 2). This overestimation of the number of wet days in RegCM4 has been also found by Thanh et al. (2017) with RegCM4 over the Asia region.

Figure 2 (second panel) displays also changes in the R1mm index for JJAS 2003 and JJAS 2004, for dry (Fig.2g and i, resp. for JJAS 2003 and JJAS 2004) and wet experiments (Fig.2h and j, resp. for JJAS 2003 and JJAS 2004) compared to their control experiments associated, the dotted area shows changes with statistical significance of 10% level. The dry experiments (Fig.2g, i) tend to decrease the R1mm index while the wet experiments (Fig.2h, j) tend to favor an increase of the R1mm index, especially over the central Sahel and a small part of west Sahel. However, over the Guinea coast sub-region, both wet and dry experiments show a significant increase of R1mm, although weaker in the dry experiments.

For a better quantitative evaluation, Figure 3 shows the PDF distributions of the changes in R1mm index over the studied domains (Fig.1), during JJAS 2003 and JJAS 2004. The results essentially confirm the linear impact found over the central Sahel (Fig.3a). The strongest impact on the R1mm index for the dry (wet) experiments is located over the central (west) Sahel, with a decrease (an increase) of R1mm index and with a peak at -5 days (10 days) for JJAS 2003 and JJAS 2004. Over the West Sahel, the Guinea coast and the West African domain (resp. Fig.3b, c and d), both dry and wet experiments lead to an increase of R1mm index. For instance, over Guinea coast, a peak is found at 3 days for both wet and dry experiments. The sensitivity of R1mm index to the contrast of year is shown by the lag between the peaks of PDFs in wet and dry experiments. The strongest impact of contrast years is found over the west Sahel (Fig.3b) reached 3 days, especially in wet experiments. The wet year (2003) is more sensitive to R1mm index changes than the dry year (2004).

Summarizing the results of this section, RegCM4 overestimates the number of wet days over most of the domain studied. The strongest linear impact on the R1mm index for the dry (wet) experiments is found over the central (west) Sahel, with a decrease (an increase) of R1mm index. The peak is found at -5 days and 10 days, respectively for dry and wet experiments. This result is in line with previous work which sustained a strong coupling of land and atmosphere in areas between wet and dry climate regimes (Zhang et al., 2011; Koster et al., 2006). The impact of the contrast of year is significant on the number of wet days in wet and dry experiments over west and central Sahel respectively.

3.1.2 The simple daily intensity index (SDII index)

We analyzed in this section the SDII index which gives the amount of precipitation mean on wet days (daily precipitation >1mm). Figure 4 (first panel) is the same as Fig.2 (first panel) but shows the amount of precipitation mean on wet days (SDII index, in mm.day^{-1}). Over the entire West African domain, the two observations products CHIRPS (Fig.4a, d) and TRMM (Fig.4b, e) present a similar large-scale pattern with a PCC about 0.86 for both JJAS 2003 and JJAS 2004 (Table 2). However, the maxima SDII index values are quite different in term of spatial extension and magnitude. Over the coastline of the Gulf of Guinea, CHIRPS datasets (Fig.4a, d) depict the highest values of SDII index, more than 25 mm.day^{-1} and located. While the SDII index values, in TRMM datasets not exceed 12 mm.day^{-1} over most part of this region. Over the central and west Sahel, TRMM datasets show large sparse values of SDII index up to 20 mm.day^{-1}, while CHIRPS datasets not exceed 12 mm.day^{-1} for both JJAS 2003 and JJJAS 2004. The largest biases of TRMM with respect to CHIRPS are found over the Guinea coast sub-region with MB more than 13 and 14 mm.day^{-1} (resp. for JJAS 2003 and JJAS 2004, Table2). This shows a quite discrepancy among the observation datasets over West African domain. We have chosen CHIRPS because of its high resolution and mainly because this product has been widely assessed and used for study of extremes events in West Africa by Bichet et al. (2018a, b) and Didi et al. (2020).

The control experiments (Fig.4 c, f) well reproduce the large-scale pattern of observation products with a PCC reached 0.73 and 0.77 (resp. in JJAS 2003 and JJAS 2004, Table 2) over West African domain. However, at the locale scale, some biases are shown. Over most of the domain studied, the magnitude of SDII index is quite underestimated, not exceed 10 mm.day^{-}

^{1}, except over the Cameroon mountains (Fig.4c, f). As a result, precipitation events are less extreme in the control experiments. The largest mean biases are located over the Guinea coast with MB more than -13.62 and -14.65 mm.day^{-1} (resp. for JJAS 2003 and JJAS 2004, Table 2).

Figure 4 (second panel) is the same as Fig. 2 (second panel), but displays changes in the amount of precipitation mean on wet days. Unlike for R1mm index, a change in SDII index is not linear over all the domains studied. In general, a similar mixture of both increase and decrease is shown for dry and wet experiments over most of the domains studied (Figure 4, second panel).

Figure 5 displays PDFs of changes in SDII index, as in Fig.3, The PDFs show the peak centered approximately on zero, this means shows that changes in the amount of precipitation mean on wet days for wet and dry experiments is not significant. The SDII index is also not sensitive to the contrast of the year in both wet and dry experiments over the different domains studied (Fig.5).

In summary, the RegCM4 underestimates the amount of precipitation mean on wet days over all the domain study. It is worth to note that precipitation events simulated by RegCM4 with the current parameterization are less extreme, the SDII index not exceeding 10 mm.day^{-1} over the entire West African domain. The impact on precipitation amount on wet days of the dry and wet experiments is not significant and not sensitive to the contrast of year over the entire domain studied.

3.1.3 The maximum number of consecutive dry days (CDD index).

The duration of dry spells (CDD index) which represents the maximum number of consecutive dry days with precipitation less than 1 mm.day^{-1} is analyzed in this section. Figure 6 (first panel) is the same as Fig.2 (first panel) but shows the maximum number of consecutive dry days (CDD index, in day). CHIRPS datasets located the largest values of CDD index over the Sahara, more than 50 days (Fig.6a, d). While the lowest values are found over the Guinea coast, with CDD index values less than 8 days. Over the West African domain, both CHIRPS and TRMM datasets show quite similar large scale features over the entire West African domain with PCC more than 0.92. However, at the local scale, the observations datasets exhibit some disparities. In general, these disparities relate only on spatial extent, especially over the Sahel region. In JJAS 2003, the band of CDD index values is in the range of [10; 20] days and extended too far into Sahel region for TRMM than

CHIRPS. For JJAS 2004, TRMM observation (Fig.6b, e) presents a narrower band of minimum CDD index values over the Guinea coast around the latitude 10°N than CHIRPS which extends it over Guinea coast. TRMM observation underestimates the CDD index over the entire West African domain, with MB about -2.29 and -1.75 days (resp. for JJAS 2003 and JJAS 2004, table2).

The control experiments (Fig.6c, f), over the entire West African domain, well reproduce the large-scale pattern of the observed rainfall with a PCC more than 0.85 and 0.89 (resp. for JJAS 2003 and JJAS 2004, Table 1). However, in term of magnitude, some differences are shown at the locale scale. In general, the control experiments overestimate the CDD index over the most of the domain studied, except over the Guinea coast (Table2). For instance, over the West African domain, the control experiments overestimate the CDD index with MB more than 2.63 and 7 days (resp. for JJAS 2003 and JJAS 2004, table2). The current parameterization of the model tends to increase the drought extreme over most of the domain studied, except over Guinea coast where it is too wet.

Figure 6 (second panel) is the same as Fig.2 (second panel) but shows changes in the maximum lengths of consecutive dry spells (CDD index). The initial soil moisture impact on the consecutive dry spell is linear over the central and west Sahel (Fig 6, second panel), the dry (wet) experiments tends to increase (decrease) the maximum lengths of consecutive dry spell (CDD index). However, particularly over Guinea coast, the dry and wet experiments lead to a decrease.

Figure 7 is the same as Fig.3 but displays the PDF distribution of the changes in the CDD index. The impact on CDD index is linear over the central and west Sahel. For instance, over the central Sahel, peaks are obtained at -6 and 2 days respectively for dry and wet experiences (Fig.7a). The weaker and non-linear impact is found over the Guinea coast and the West African domain. For instance, over the Guinea coast, a decrease in CDD index values is found with a peak not exceeding 2 days for both wet and dry experiments (Fig.7c). The impact of the contrast of year on CDD index is significant over the west and central Sahel for both wet and dry experiments. However, the strongest impact of the contrast of year is found in wet experiments over the central Sahel reached 4 days (Fig.7a). The impact on CDD index in the dry year is strong than wet year.

In summary, RegCM4 overestimates the maximum number of consecutive dry days over most of the domain studied, except over the Guinea coast. The strongest linear impact on the CDD index for the dry (wet) experiments is found over the west Sahel with a peak around -6 days (2 days). The maximum number of consecutive dry days is sensitive to the contrast of year over the west and central Sahel.

3.1.4 The maximum number of consecutive wet days (CWD index).

The persistence of wet spells (CWD index) which represents the maximum number of consecutive wet days with precipitation ≥ 1 $mm.day^{-1}$ is investigated in this section. Figure 8 (first panel) is the same as Fig.2 (first panel) but shows the maximum number of consecutive wet days (CWD index, in day). The observation products TRMM (Fig.8b, e) and CHIRPS (Fig.8a, d) depict a similar large-scale pattern with the PCCs reached 0.90 and 0.87 (resp. for JJAS 2003 and JJAS 2004, Table 2). CHIRPS observation located the maximum of CWD index over the mountain regions such as Cameroon mountains, Jos plateau and Guinea highlands and it is more than 20 days. While the minimum values of CWD index are found over most of the area above the latitude 17°N and not exceed 4 days (Fig.8a, d). In general, the differences between TRMM and CHIRPS observation concern the maxima magnitude and its extent, which are more pronounced in TRMM than CHIRPS. Generally, TRMM underestimates the CWD index over most of the domains studied compared to CHIRPS. The largest mean bias is found over the Guinea coast region with MB more than 2.47 and 2.38 days (resp. for JJAS 2003 and JJAS 2004, Table 2).

The control experiments well reproduce the large-scale pattern over the entire West African domain, with PCCs values about 0.81 and 0.87 (resp. for JJAS 2003 and JJAS 2004, Table 2). However, at the local scale the control experiments exhibit some biases in maxima and minima CWD index values in term of magnitude and spatial extent. Control experiments overestimate the CDD index over the different domains studied (Fig. 8 c, f). We noted that, this overestimation area coincides with the excessive values of R1mm index (Fig.2c, f). The strongest mean bias is found over the Guinea coast, more than 59.21 and 60.51 days (resp. for JJAS 2003 and JJAS 2004).

Figure 8 (second panel) is the same as Fig.2 (second panel), but displays changes in CWD index. As for R1mm index, over the central Sahel, the impact is linear, the dry (wet) experiments tends to decrease (increase) the maximum number of consecutive wet days (CWD index) for wet and dry years (resp JJAS 2003 and JJAS 2004). This result confirms the strong soil moisture impact over the transition zones with a climate between dry and wet regimes (Zhang et al., 2011; Koster et al., 2006). However, over Guinea and the west Sahel, the changes are not linear, both dry and wet experiments lead to cause an increase, in JJAS 2003 and JJAS 2004 (Fig. 8B, c).

Figure 9, as in Fig.3, but shows the PDF distribution of changes in CWD index. The impact on CWD index found over the central Sahel are linear. The dry (wet) experiments tend to decrease (increase) the CWD index with peaks at -10 days (15 days) for both JJAS 2003 and JJAS 2004. However, for the other sub-regions studied, particularly over the Guinea coast, wet and dry experiments tend to increase the CWD index, with peaks 10 and 2 days respectively (Fig. 9c). The CWD index is not sensitive to the contrast of the year over the different domains studied (Fig 9).

Summarizing the results of this section, as in R1mm and CDD indices, the CWD index is only linear over the central Sahel, the dry (wet) experiments tends to decrease (increase) of the CWD index. The model RegCM4 overestimates the duration of wet days over all the domains studied. This overestimation is linked with an excessive number of wet days as documented by Diaconescu et al. (2014).

3.1.5 The maximum one-day precipitation accumulation (RX1day index).

The maximum one-day precipitation accumulation during the period JJAS 2003 and JJAS 2004 is assessed in this section. Figure 10 (first panel) is the same as Figure 2 (first panel), but shows the spatial distribution of the RX1day index. The observations datasets TRMM (Fig.10b, e) and CHIRPS (Fig.10 a, d) present quite differences in term of the spatial extent of the maximum values of RX1day index, although their large-scale pattern is similar with PCC more than 0.84 for both JJAS 2003 and JJAS 2004 (Table 2). Over the Guinea and Sahel regions, the spatial extends of RX1day index maxima values more than 80 mm is large on TRMM, while CHIRPS datasets they are confined over the coastline of the Gulf of Guinea. TRMM observation overestimates the maximum one-day precipitation accumulation over the entire domain studied compared to CHIRPS. The largest maximum one-day precipitation is found over the central Sahel with MB reached 35.78 and 31.66 (resp. for JJAS 2003 and JJAS 2004, Table 2).

The control experiments capture the spatial pattern with PCC values 0.50 and 0.4 (resp. JJAS 2003 and JJAS 2004, Table2). This low coefficient of PCC has been also obtained by Thanh et al. (2017) over Asia with RegCM4 (correlation <0.3). The model simulations failed to capture the magnitude and the spatial extent of RX1day index maxima values. The control experiments underestimate the RX1day index over all the domains studied. The RX1day index is underestimated over the entire domain studied, this is also due to the excessive light precipitation, simulated by the current physical parameterization of RegCM4. The largest underestimation is located over the Guinea coast and the west Sahel. For instance, over the west Sahel, the MB is about -38.07 and -36.67 mm (resp. JJAS 2003 and JJAS 2004, Table 2).

Figure 10 (second panel) is similar to Fig. 2 (second panel), but displays changes in maximum one-day precipitation. As for SDII index, the initial soil moisture anomalies impact on the RX1day index is not linear, a similar mixture of increase and decrease of RX1day index is shown for dry and wet experiments over most of the domains studied (Figure 10 second panel).

Figure 11, as in Fig.3, but shows the PDF distribution of changes in RX1day index. The impact of the contrast of years on RX1day index is significant, only over the west Sahel in wet experiments about 7 mm.

In summary, RegCM4 underestimates the maximum one-day precipitation accumulation over the entire domain studied. A non-linear trend is identified over the different domains studied. As for SDII index, RX1day index is related to precipitation intensity and the impact of wet and dry experiments on the maximum one-day precipitation accumulation is not significant. The maximum one-day precipitation accumulation is sensitive to the contrast of years, especially over the west Sahel in wet experiments.

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

We investigated in this section, the precipitation percent due to very heavy precipitation days during the period JJAS 2003 and JJAS 2004. Figure 12 (first panel) is the same as Fig.2 (first panel), but shows the spatial distribution of R95pTOT index. TRMM (Fig.12b, e) and CHIRPS observations (Fig.12a, d) present a similar spatial pattern over the entire West African domain with PCC value reached 0.91 for both JJAS 2003 and JJAS 2004 (Table 2). However, some biases are noticed for R95pTOT index maxima in term of spatial extent. As for RX1day index, TRMM observation extends maxima of R95pTOT index more than 60 % over the Guinea and the Sahel region (Fig.10), while CHIRPS confine them over the Guinea coast. Overall, TRMM shows a dominant overestimation than CHIRPS over the West African domain about 16.54 and 18.54 % (resp. JJAS 2003 and JJAS 2004, Table2). The control experiments (Fig.12c, f) capture the spatial pattern with PCC values 0.59 and 0.55 (resp. JJAS 2003 and JJAS 2004, Table2). As with SDII and RX1day indices, the control experiments underestimate the values of the R95pTOT index, while they overestimated the R1mm index. This is also due by 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 threshold (e. g. 1 mm.day^{-1}), while results in negative bias for the indices of the number of wet days with a higher precipitation threshold (e. g. 10 mm.day^{-1}, not shown here). The control experiments underestimate the R95pTOT index over the different domains studied. The largest underestimation of R95pTOT index is located over the Guinea coast with MB more than – 43 and - 46 % (resp. for JJAS 2003 and JJAS 2004, Table2).

Figure 12 (second panel) is similar to Fig.2 (second panel), but displays changes in R95pTOT index. Both dry and wet experiments tend to cause an increase of R95pTOT index over the orographic regions. This means that the initial soil moisture conditions, whether dry or wet, tend to reinforce extreme floods.

Figure 13 is the same as Fig.3, but shows the PDF distribution of changes in R95pTOT index. An increasing in R95pTOT index for both wet and dry experiments is shown over most of the domains studied. The largest change is found over the west Sahel with the peak around 5 % and 2 % respectively for wet and dry experiments (Fig.13 b). The impact of the contrast of the wet and dry years on R95pTOT index is significant about reached 2 % (resp. JJAS 2003 and JJAS 2004), especially over west Sahel (Fig. 13a). The impact on R95pTOT index in the wet year is strong over the different domains studied compared to dry year.

In summary, RegCM4 underestimates the precipitation percent due to very heavy precipitation days over the West African domain. The initial soil moisture conditions, whether dry or wet, tend to accentuate the precipitation percent due to very heavy precipitation days. This result is in line with Liu et al. (2014) work over Asia using RegCM4. The precipitation percent due to very heavy precipitation days is sensitive to the contrast of years over the west Sahel in the wet experiments.

3.2. Seasonal temperature extreme indices

In this section, using daily maximum and minimum temperature, we analyze four extreme temperature indices (Table 1) in RegCM4 simulations over West Africa. All temperature indices are calculated for JJAS 2003 and JJAS 2004. Table 3 summarizes the pattern correlation coefficient (PCC) and the mean bias (MB) of all temperature indices studied in this section for EIN reanalysis and model simulations derived from control experiments with initial soil moisture from ERA20C reanalysis, with respect to GTS observation, calculated over the domains presented in Fig 1, during the period JJAS 2003 and JJAS 2004.

3.2.1. Maximum value of daily maximum temperature (TXx index)

In this section, we analyzed the TXx index which gives the hottest day's temperature during JJAS 2003 and JJAS 2004. Figure 14 (first panel) shows TXx index in °C) from GTS observation (Fig14.a, d) and EIN reanalysis (Fig.14b, e) for JJAS 2003 and JJAS 2004 and their corresponding simulated control experiments (Fig.14c, f) with the initial soil moisture of the reanalysis ERA20C. The GTS observation shows the highest values of the TXx index observed over the Sahara, more than 46° C. While the lowest values (less than 32°C) are found over the Guinea coast (Fig.14a, d). The EIN reanalysis have similar large-scale patterns with PCC value 0.99 over the entire West African domain (Table 3). However, some biases are shown at the local scale in terms of magnitude and spatial extent of these maxima and minima. The reanalysis of the EIN (Fig.14b, e) shows lower values (less than 28°C) of the TXx index over a large area along the Guinea coastline compared to GTS datasets. Conversely, GTS observation presents higher values of TXx index (up to 48°C) over a large area as compared to EIN reanalysis. The reanalysis of the EIN shows a negative bias of the TXx index over most of the domains studied (Table 3).

The control experiments (Fig.14c, f) reasonably well replicate the large-scale patterns of TXx index values with PCCs up to 0.99 over the entire West African domain, but they exhibit some biases a local scale. The control experiments are closer to the maximum and minimum values display in GTS observation. The control simulations overestimate the TXx values over the central and west Sahel and over the Guinea coast they are underestimated (Table 3). For instance, the greatest overestimation is found over the west Sahel with MB about 3.02 and 2.02°C (resp. for JJAS 2003 and JJAS 2004, Table3). However, these biases obtained for TXx index in this study are much lower compared to Thanh et al. (2017) work using RegCM4 over the Asia where it reached 8° C.

Figure 14 (second panel) displays changes in TXx index for JJAS 2003 and JJAS 2004, for dry (Fig.14g, i, resp. for JJAS 2003 and JJAS 2004) and wet experiments (Fig.14h, j, resp. for JJAS 2003 and JJAS 2004) with respect to their corresponding control experiments, the dotted area shows changes with statistical significance of 10% level. The impact of the initial soil moisture conditions on TXx index is linear over the entire West African domain, i.e. the dry experiments lead to an increase of TXx index values while the wet experiments favor a decrease of TXx index values. We noted that this linear impact is more pronounced in dry and the wet experiments over the Guinea coast and the central Sahel respectively (Fig.14, second panel).

The PDF distributions of TXx index changes for 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 compared to the corresponding control experiments are shown in Figure 15. As mentioned, the results confirm the linear impact on TXx index of the initial soil moisture conditions over all the domains studied. The strongest impact is found over the central Sahel (Fig.15a) with a decrease (increase) of TXx index and the peak is around -2.5°C (more than 1°C) in wet (dry) experiments. The impact of the contrast years on TXx index is found particularly in dry experiments over the central Sahel reached 0.8°C (Fig.15a). The impact of the dry year (JJAS 2004) is strong than the wet year (JJAS 2003).

In summarizing this section, during the JJAS 2003 and 2004, the model RegCM4 overestimates and underestimates the hottest day's temperature respectively over the Sahel (west and central) and Guinea coast. The impact on TXx index is linear over all the different domains studied, i.e. the dry (wet) experiments decrease (increase) the TXx index. The TXx index is sensitive to the contrast of year, particularly in dry experiments over the central Sahel.

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

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 Fig.14 (first panel) but presents the spatial distribution of the TXn index. GTS observation (Fig.16a, d) and EIN reanalysis (Fig.16b, e) display similar features with PCC reached 0.99 (for JJAS 2003 and JJAS 2004, Table 3). The maxima and minima values of TXn index are located over the Sahara and the Guinea coast respectively. However, there are some differences at the local scale in terms of spatial extent and magnitude. The EIN reanalysis presents a larger spatial extent of the maxima (greater than 36°C) and minima (less than 24°C) compared to GTS observation. The EIN reanalysis show a negative bias value over Guinea coast and west Sahel (for both JJAS 2003 and JJAS 2004 Table3). For instance, over the Guinea coast with MB about -0.70 and -1.38°C (resp. for JJAS 2003 and JJAS 2004, Table 3).

The control experiments show a good agreement with the GTS datasets in the large scale patterns with PCC about 0.99, however, the magnitude of the TXn index over all the domains studied are overestimated. For instance, over the West African domain, the MB is about 5.65 and 4.14°C (resp. JJAS 2003 and JJAS 2004, Table 3). The biases obtained in this study are lower compared to a similar study carried out by Thanh et al. (2017) over Asia using RegCM4,

As for Fig.14 (second panel), the Figure 16 (second panel) displays changes in TXn index. The impact on TXn index of the initial soil moisture anomalies are linear over the entire West African domain, i.e. the dry experiments lead to an increase of TXn index values while the wet experiments favor a decrease of TXn index values. The strongest impact on TXn index is found in wet experiments above the latitude 15 °N, especially for JJAS 2003.

Figure 17 is the same as Fig.15 but displays the PDF distribution of changes in TXn index. The impact on TXn index of initial soil moisture conditions is linear over most of the domain studied, although this impact is rather weak as compared to the TXx index. The strongest impact on TXn index for wet experiments are found over the wet Sahel about -2°C, while in dry experiments, it is found over the central Sahel not exceed 1° C. Moreover, the changes in TXn index are sensitive to the contrast of year, especially in dry experiments over west Sahel reached 0.8°C (Fig. 13b). The impact on TXn index in the dry year is strong than the wet year over the west Sahel.

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, the impact on TXn index to soil moisture anomalies is linear, i.e. the dry (wet) experiments tend to cause an increase (decrease) of TXn index values over most of the domain studied. The impact on TXn index of the initial soil moisture conditions is low compared to the TXx index. The TXn index is sensitive to the contrast of year, especially in dry experiments over west Sahel.

3.2.3. The 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 Fig.14 (first panel) but displays the spatial distribution of the TNn index. GTS observation (Fig.18 a, d) shows the maxima of TNn index values above the latitude 15° N not exceeding 27° C, while the minima values are less than 17°C and located over the mountain regions such as Cameroon mountain, Jos Plateau and Guinea Highland. The EIN reanalysis shows a similar spatial pattern with GTS observation, with PCC value about 0.99 over the whole West African domain (Table 3) despite some biases at the local scale. The EIN reanalysis (Fig.18 b, e) displays the highest value of TNn index (exceeding 27°C) than GTS observation and they are located over a large area above the latitude 15° N. The EIN reanalysis also shows the lowest values (less than 21°C) of TNn index than GTS observation, located over the orographic regions. The EIN reanalysis overestimates the TNn index values over most of the domain studied. For instance, over the West African domain, the MB reaches 3.15 and 3.11°C (resp. for JJAS 2003 and JJAS 2004, Table 3).

The control experiments (Fig.18 c, f) show a good agreement with GTS observation with PCC values about 0.99 but do exhibit some biases at the local scale. The control experiments overestimate the magnitude of the TNn index over all the domains studied. For instance, over the West African domain, the MB is about 1.45 °C and 0.71°C (resp. for JJAS 2003 and JJAS 2004, Table 3). These positive biases obtained in simulating the TXx, TXn and TNn indices are opposite with the cold bias known with RegCM4 in mean climate simulation (Koné et al., 2018, Klutse et al., 2016). It is very difficult to know the origin of RCM temperature biases, as they can depend on several factors, such as surface energy fluxes and water, cloudiness, surface albedo (Sylla et al., 2012; Tadross et al., 2006).

Figure 18 (second panel) is the same as Fig.14 (second panel), but displays changes in TNn index. The impact on TNn index of the initial soil moisture conditions is linear over the Sahara region, i.e. the wet experiments lead to an increase of TNn index values while the dry experiments favor a decrease of TNn index values. We noticed this linear impact coincides with the area of highest TNn index values over the Sahara (Fig.18, first panel). However, over the central and west Sahel, both dry and wet experiments lead to a decrease. Conversely, over the Guinea coast, we found an increase.

Figure 19 is the same as Fig.15 but shows the PDF distribution of changes in TNn index. The impact on changes in TNn index, are not linear over all the domains studied. However, although this impact is weak, over central and west Sahel it tends to decrease, while over the Guinea coast it increases. The strongest impact is found over the west Sahel, where the wet and dry experiments lead to a decrease in TNn index, with the peaks around - 1°C and - 0.2°C respectively. The impact of the contrast years on TNn index is not significant over all the different domains studied.

In summary, RegCM4 overestimates the lowest temperature at night during JJAS 2003 and JJAS 2004 over the different domains studied. The impact on TNn index of the soil moisture conditions is linear only over the Sahara, i.e. the dry (wet) experiments tend to decrease (increase) the TNn index values. The TNn index is not sensitive to contrast years.

3.2.4. The Maximum value of daily minimum temperature (TNx index)

In this section, we turned our attention to TNx index which gives the warmest night temperature during JJAS 2003 and JJAS 2004. Figure 20 (first panel) is the same as Fig.14 (first panel), but for TNx index. GTS observation (Fig.20 a, d) shows the maxima of TNx index values over the Sahara reached 40° C, while the minima values around 24°C are located over the Guinea coast sub-region. The EIN reanalysis (Fig.20 b, e) shows similar large scale patterns with PCC value reached 0.99, but some biases can be noticed between GTS and EIN datasets. The EIN reanalysis underestimates the maxima (not exceeds 38°C) and the minima (less than 22°C) located respectively over the Sahara and the orographic regions such as Cameroon mountains, Jos plateau and Guinea highlands. The strongest negative mean bias is located over the Guinea coast with MB about -3.11°C and -3.14°C (resp. JJAS 2003 and JJAS 2004, Table 3).

The control experiments (Fig.20 c, f) well reproduce the general features of TNx index with a PCC value reached 0.99 but some differences are shown at the local scale. Unlike the TNN index, the control experiments underestimate the TNx index, over most of the domains studied. The maxima of TNx index values are quite underestimated over the Sahara. For instance, over the central Sahel, the MB is about -3.85°C and -3.99°C (resp. for JJAS 2003 and JJAS 2004, Table 3). This underestimation of TNx index seems to be systematic related to the cold bias in RegCM4 over West Africa which is shown by several papers (Koné et al., 2018, Klutse et al., 2016).

Figure 20 (second panel) is the same as Fig.14 but displays changes in TNx index, as in Fig.14 (second panel). As for TNn index, the impact on TNx index of initial soil moisture conditions is somewhat linear over the Sahara, i.e. the dry experiments lead to an increase of TNx index values while the wet experiments favor a decrease of TNx index values. However, over the central and west Sahel, although the signal is weak, both wet and dry experiments lead to a dominant decrease. Conversely, over the Guinea coast, the impact on TNx index leads to a dominant increase.

Figure 21 is the same as Fig.15, but displays the PDF distributions of the changes in TNx index. As for TNn index, the impact on TNx index changes is not linear over the different domains studied. We noticed that TNx index is more sensitive to the wet and dry experiments over the central Sahel than the other sub-regions studied. The strongest impact in the wet experiments is found over the central Sahel (Fig. 21 a) and it's about -1.3°C, while in dry experiments it's found over the west Sahel and it is more than -1°C (Fig. 21 b). The sensitivity of TNx index to the contrast of years is significant over the central Sahel about -1°C In wet experiments.

In summary, RegCM4 underestimates the warmest night temperature during JJAS 2003 and JJAS 2004 over the different domains studied. As for TNn index, the impact on TNx index of the initial soil moisture conditions is linear only over the Sahara, i.e. the dry (wet) experiments tend to decrease (increase) the TNn index values. The impact on TNx index of initial soil moisture conditions is greater compared to TNn index, The TNx index is sensitive to the contrast years over central Sahel in wet experiments

4. Conclusions

The impact on the subsequent summer extreme climate of the initial soil moisture conditions over West Africa is investigated using the RegCM4-CLM45. In addition, the performance of RegCM4-CLM4.5 in representing six extreme indices of precipitation and four extreme indices of temperature over West Africa was also evaluated. Results have been presented for JJAS 2003 (wet year) and JJAS 2004 (dry year). We performed sensitivity studies over the West African domain, with 25 km of spatial resolution. We initialized the control runs by ERA20C reanalysis soil moisture, and at its wilting points and the field capacity respectively for dry and wet experiments.

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

The impact on extreme precipitation indices of the initial soil moisture conditions is linear only for indices related to the number of precipitation events (R1mm, CDD and CWD indices), and not for those related to the amount of precipitation (SDII, RX1day and R95pTOT). The dry and wet experiments accentuate the precipitation percent due to very heavy precipitation days (R95pTOT index) over most of the domain studied. In addition, among all the precipitation indices studied, the contrast of years impacts significantly only the CDD index on the central Sahel in particular for wet experiments.

Generally, the impact on extreme temperatures of the initial soil moisture conditions is great compared to extreme precipitation. Overall, the initial soil moisture conditions unequally affect the daily maximum and minimum temperature over the West African domain. There is a greater impact on daily maximum temperature extremes than on the daily minimum temperature extremes. These results are in line with previous works (Jaeger and Seneviratne, 2011; Zhang et al., 2009).

The wet (dry) experiments result in an increase (decrease) in the TXx and TXn indices over most of the areas studied. The impact of initial soil moisture conditions on the indices related to the minimum temperature (TNx and TNn indices) is not linear over most of the domains studied. The strongest impact on minimum temperature indices (TNn and TNx indices) is somewhat linear over the Sahara. The dry (wet) experiments tend to cause an increase (a decrease) in the TNn and TNx indices over the Sahara.

This study helps to understand the impact of the initial soil moisture conditions on extreme events of precipitation and temperature in terms of intensity and duration over West Africa. It is a contribution to the improvement of extreme events forecasts in West Africa in highlighting the crucial role of initial soil moisture. For a proper assessment of the dependence of the model in our results, it would be appropriate to repeat the investigation using different RCMs in a multi-model framework.

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.

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.

References:

Bichet, A., & Diedhiou, A. (2018a). West African Sahel has become wetter during the last 30 years, but dry spells are shorter and more frequent. Climate Research, 75(2), 155-162.

Bichet, A., & Diedhiou, A. (2018b). Less frequent and more intense rainfall along the coast of the Gulf of Guinea in West and Central Africa (1981 2014). Climate Research, 76(3), 191-201.

Danielson J.J., and Gesch D.B.: Global multi-resolution terrain elevation data 2010 (GMTED2010): U.S. Geological Survey Open-File Report 2011–1073, 26 p, 2011.

Didi Sacré Regis M , Mouhamed, L., Kouakou, K., Adeline, B., Arona, D., Koffi Claude A, K., ... & Issiaka, S. (2020). Using the CHIRPS Dataset to Investigate Historical Changes in Precipitation Extremes in West Africa. Climate, 8(7), 84.

Dee D. P., Uppala S. M., Simmons A. J., Berrisford P., Poli P., Kobayashi S., Andrae U., Balmaseda, M. A., Balsamo G., Bauer, P., Bechtold P., Beljaars A. C. M., van de Berg L., Bidlot J., Bormann N., Delsol C., Dragani R., Fuentes M., Geer A. J., Haimberger L., Healy S. B., Hersbach H., Hólm E. V., Isaksen L., Kållberg P., Köhler M., Matricardi M., McNally A. P., Monge-Sanz B. M., Morcrette J.-J., Park, B.-K., Peubey C., de Rosnay P., Tavolat C., Thépaut J.-N. and Vitart F.: The ERA-Interim reanalysis: configuration and performance of the data assimilation system, Q. J. Roy. Meteorol. Soc., 137, 553-597, https://doi.org/10.1002/qj.828, 2011.

Diaconescu E. P., Gachon P. , Scinocca J., and LapriseR.: Evaluation of daily precipitation statistics and monsoon onset/retreat over western Sahel in multiple data sets. Climate Dyn., 45, 1325–1354, doi:10.1007/s00382-014-2383-2, 2015 .

Easterling, D.R., Meehl, G.A., Parmesan, C., Changnon, S.A., Karl, T.R. and Mearns, L.O.: Climate Extremes: Observations, Modeling and Impacts. Science , 289, 2068-2074. https://doi.org/10.1126/science.289.5487.2068, 2000.

Emanuel K. A.: A scheme for representing cumulus convection in large-scale models. Journal of the Atmospheric Science 48: 2313–2335, 1991.

Fan Y., and van den Dool H. : A global monthly land surface air temperature analysis for 1948 -present, J. Geophys. Res. 113, D01103, doi: 10.1029/2007JD008470, 2008.

Folland C. K., Palmer T. N. , and Parker D. E.: Sahel rainfall and worldwide sea temperatures, Nature, 320, 602 – 607, 1986.

Fontaine B., Janicot S. , and Moron V. : Rainfall anomaly patterns and wind field signals over West Africa in August (1958 – 1989), J. Clim., 8, 1503 –1510, 1995.

Giorgi F., Coppola E., Solmon F., Mariotti L., Sylla M. B., Bi X., Elguindi N., Diro G. T., Nair V., Giuliani G., Cozzini S., Guettler I., O'Brien T., Tawfik A., Shalaby A., Zakey A. S., Steiner A., Stordal F., Sloan L., and Brankovic C. : RegCM4: model description and preliminary tests over multiple CORDEX domains, Clim. Res., 52, 7–29, doi.org/10.3354/cr01018, 2012.

Grell G., Dudhia J. and Stauffer D. R.: A description of the fifth generation Penn State/NCAR Mesoscale Model (MM5), National Center for Atmospheric Research Tech Note NCAR/TN-398+STR, NCAR, Boulder, CO, 1994.

Holtslag A., De Bruijn E., and Pan H. L. : A high resolution air mass transformation model for short-range weather forecasting, Mon. Weather Rev., 118, 1561–1575, 1990.

Hong S. Y. and Pan H. L.: Impact of soil moisture anomalies on seasonal, summertime circulation over North America in a regional climate model. J. Geophys. Res., 105 (D24), 29 625–29 634, 2000.

Huffman, G. J., Adler, R. F., Bolvin, D. T., Gu, G., Nelkin, E. J., Bowman, K. P., Hong, Y, Stocker, E. F., and Wolff, D. B.: The TRMM multisatellite precipitation analysis: quasi-global, multiyear, combined-sensor precipitation estimates at fine scale, J. Hydrometeorol., 8, 38–55, 2007.

Jaeger E. B., and Seneviratne S. I. : Impact of soil moisture-atmosphere coupling on European climate extremes and trends in a regional climate model, Clim. Dyn., 36(9-10), 1919-1939, doi:10.1007/s00382-010-0780-8, 2011.

Kang S, Im E.-S. and Ahn J.-B.: The impact of two land-surface schemes on the characteristics of summer precipitation over East Asia from the RegCM4 simulations Int. J. Climatol. 34: 3986–3997, 2014.

Kim J-E., and Hong S-Y.: Impact of Soil Moisture Anomalies on Summer Rainfall over East Asia: A Regional Climate Model Study, Journal of Climate. Vol. 20, 5732–5743, DOI: 10.1175/2006JCLI1358.1, 2006.

Kiehl J. T., Hack J. J., Bonan G. B., Boville, B. A., Briegleb B. P., Williamson D. L., and Rasch P. J.: Description of the NCAR Community Climate Model (CCM3), Technical Note NCAR/TN−420+STR, 152, 1996.

Koné B., Diedhiou A., N'datchoh E. T., Sylla M. B. , Giorgi F., Anquetin S., Bamba A., Diawara A., and Kobea A. T.: Sensitivity study of the regional climate model RegCM4 to different convective schemes over West Africa. Earth Syst. Dynam., 9, 1261–1278. https://doi.org/10.5194/esd-9-1261-2018, 2018.

Koster R. D., GUO Z. H., Dirmeyer P. A., Bonan G., Chan E., Cox P., Davies H., Gordon C. T., Gordon C. T.,Lawrence D., Liu P., Lu C. H, Malyshev S., McAvaney B., Mitchell K, Mocko D., Oki K., Oleson K., Pitman A., Sud Y. C. , Taylor C. M., 16 Verseghy D., Vasic R., Xue Y., Yamada T.: The global land–atmosphere coupling experiment. Part I: Overview, J. Hydrometeorol., 7(4), 590–610, doi:10.1175/JHM510.1, 2006.

Larsen J.: Record heat wave in Europe takes 35,000 lives. Earth Policy Institute, 2003.

Le Barbé L., Lebel L., and Tapsoba D.: Rainfall variability in west africa during the years 1950-1990. J. Climate, 15 :187–202., 2002.

Loveland TR, Reed BC, Brown JF, Ohlen DO, Zhu Z, Yang L, J. W. Merchant J. W.: Development of a global land cover characteristics database and IGBP DISCover from 1km AVHRR data. International Journal of Remote Sensing 21: 1303–1330, 2000.

Liu D., G. Wang R. Mei Z. Yu, and Yu M. : Impact of initial soil moisture anomalies on climate mean and extremes over Asia, J. Geophys. Res. Atmos., 119, 529–545, doi:10.1002/2013JD020890, 2014.

Klutse B. A. N., Sylla B. M., Diallo I., Sarr A., Dosio A.,Diedhiou A., Kamga A., Lamptey B., Ali A., Gbobaniyi E. O., Owusu K., Lennard C., Hewitson B., Nikulin G.,& Panitz H.-J., Büchner M.: Daily characteristics of West African summer monsoon precipitation in CORDEX simulations. Theor Appl Climatol. 123:369–386 DOI 10.1007/s00704-014-1352-3, 2016.

Nicholson, SE.: The nature of rainfall fluctuations in subtropical West-Africa. Mon. Wea. Rev. 22109, 2191-2208, 1980.

Nicholson SE.: Land Surface processes and Sahel climate. Reviews of Geophysics. 38(1), 117-24139, 2000.

Nikulin G., Jones C., Samuelsson P., Giorgi F., Asrar G., Büchner M., Cerezo-Mota R., Christensen O. B., Déque M., Fernandez J., Hansler A., van Meijgaard E., Sylla M. B. and Sushama L.: Precipitation climatology in an ensemble of CORDEX-Africa regional climate simulations, J. Climate, 6057–6078, https://doi.org/10.1175/JCLI-D-11-00375.1, 2012.

Oleson K., Lawrence D. M., Bonan G. B., Drewniak B., Huang M., Koven C. D., Yang Z.-L.: Technical description of version 4.5 of the Community Land Model (CLM) (No. NCAR/TN-503+STR). doi:10.5065/D6RR1W7M, 2013.

Pal J. S., Small E. E. and Elthair E. A.: Simulation of regional scale water and energy budgets: representation of subgrid cloud and precipitation processes within RegCM, J. Geophys. Res., 105, 29579–29594, 2000.

Peterson T. C., Folland C., Gruza G., Hogg W. Mokssit A., Plummer N. : Report on the activities of the working group on climate change detection and related rapporteurs 1998-2001. Geneva (Switzerland): WMO Rep. WCDMP 47, WMO-TD 1071, 2001.

Philippon N., Mougin E. , Jarlan L. , and Frison P.-L.: Analysis of the linkages between rainfall and land surface conditions in the West African monsoon through CMAP, ERS-WSC,and NOAA-AVHR R data. J. Geophys. Res., 110, D24115, doi:10.1029/2005JD006394, 2005.

Reynolds, R. W. and Smith, T. M.: Improved global sea surface temperature analysis using optimum interpolation, J. Climate, 7, 929–948, 1994.

Simmons A. S., Uppala D. D. and Kobayashi S.: ERA-interim: new ECMWF reanalysis products from 1989 onwards, ECMWF Newsl., 110, 29–35, 2007.

Solmon F., Giorgi F., and Liousse C.: Aerosol modeling for regional climate studies: application to anthropogenic particles and evaluation over a European/African domain, Tellus B, 58, 51–72, 2006.

Sundqvist H. E., Berge E., and Kristjansson J. E.: The effects of domain choice on summer precipitation simulation and sensitivity in a regional climate model, J. Climate, 11, 2698–2712, 1989.

Sylla MB, Giorgi F, Stordal F.: Large-scale origins of rainfall and temperature bias in high resolution simulations over Southern Africa. Climate Res. 52: 193–211, DOI: 10.3354/cr01044, 2012.

Tadross MA, Gutowski WJ Jr, Hewitson BC, Jack C, New M.: MM5 simulations of interannual change and the diurnal cycle of southern African regional climate. Theor. Appl. Climatol. 86(1–4):63–80, 2006.

Thanh N.-D., Fredolin T. T., Jerasorn S., Faye C., Long T.-T., Thanh N.-X., Tan P.-V., Liew J., Gemma N., Patama S., Dodo G. and Edvin A.: Performance evaluation of RegCM4 in simulating extreme rainfall and temperature indices over the CORDEX-Southeast Asia region. Int. J. Climatol. 37: 1634–1647. Published online 28 June 2016 in Wiley Online Library (wileyonlinelibrary.com) DOI: 10.1002/joc.4803, 2017.

Uppala S., Dee D., Kobayashi S., Berrisford P. and Simmons A.: Towards a climate data assimilation system: status update of ERA-interim, ECMWF Newsl., 15, 12–18, 2008.

Wang, G., Yu, M., Pal, J. S., Mei, R., Bonan, G. B., Levis, S., and Thornton, P. E.: On the development of a coupled regional climate vegetation model RCM-CLM-CN-DV and its validation its tropical Africa, Clim. Dynam, 46, 515–539, 2016.

You Q., Kang S., Aguilar E., Pepin N., Flügel W.-A., Yan Y. , Xu Y., Zhang Y. , and Huang J. : Changes in daily climate extremes in China and their connection to the large scale atmospheric circulation during 1961–2003, Clim. Dyn., 36(11-12), 2399–2417, doi:10.1007/s00382-009-0735-0, 2010.

Zakey A. S., Solmon F., and Giorgi F.: Implementation and testing of a desert dust module in a regional climate model, Atmos. Chem. Phys., 6, 4687–4704, https://doi.org/10.5194/acp-6-4687-2006, 2006.

Zeng X., Zhao M. and Dickinson R .E.: Intercomparison of bulk aerodynamic algorithms for the computation of sea surface fluxes using TOGA COARE and TAO DATA, J. Climate, 11, 2628-2644, 1998.

Zhang J, Wang W.C., and Wu L.: Land–atmosphere coupling and diurnal temperature range over the contiguous United States. Geophys Res Lett 36:L06706. doi:10.1029/2009GL037505, 2009.

Zhang J. Y., Wu L. Y. and Dong W. : Land-atmosphere coupling and summer climate variability over East Asia, J. Geophys. Res., 116,D05117, doi 10.1029/2010JD014714, 2011.

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		West Africa	
		MB	PCC	MB	PCC	MB	PCC	MB	PCC
R1mm	TRMM_2003	-6.76	0.98	-3.15	0.99	8.89	0.99	-1.12	0.98
	CTRL_2003	33.17	0.98	-5.25	0.96	53.16	0.96	22.18	0.96
	TRMM_2004	-7.51	0.98	-3.42	0.99	10.44	0.98	-1.34	0.98
	CTRL_2004	29.50	0.98	1.34	0.96	55.46	0.96	23.85	0.95
SDII	TRMM_2003	2.67	0.96	0.22	0.94	-5.24	0.95	1.20	0.86
	CTRL_2003	-7.52	0.97	-9.95	0.94	-13.62	0.77	-7.67	0.73
	TRMM_2004	2.07	0.96	0.45	0.96	-6.44	0.94	1.16	0.86
	CTRL_2004	-7.01	0.97	-9.37	0.94	-14.65	0.81	-7.59	0.77
CDD	TRMM_2003	1.21	0.95	0.89	0.93	-0.93	0.94	-2.29	0.92
	CTRL_2003	0.93	0.90	14.49	0.91	-7.84	0.66	2.63	0.85
	TRMM_2004	2	0.95	1.58	096	-3.17	0.92	-1.75	0.94
	CTRL_2004	4.75	0.91	17.51	0.95	-9.43	0.68	6.99	0.89
CWD	TRMM_2003	-0.48	0.92	0.80	0.94	2.47	0.92	0.37	0.90
	CTRL_2003	45.56	0.83	18.44	0.75	59.21	0.88	31.20	0.81
	TRMM_2004	-0.68	0.92	0.97	0.92	2.38	0.89	0.26	0.87
	CTRL_2004	36.78	0.79	20.48	0.78	60.51	0.82	29.74	0.79
RX1day	TRMM_2003	35.78	0.92	25.31	0.89	14.31	0.86	26.02	0.84
	CTRL_2003	-26.46	0.78	-38.07	0.91	-30.28	0.54	-20.08	0.50
	TRMM_2004	31.66	0.91	20.19	0.91	10	0.88	22.19	0.85
	CTRL_2004	-22.89	0.46	-36.67	0.88	-42.44	0.42	-20.23	0.40
R95pTOT	TRMM_2003	23.19	0.92	13.31	0.94	-0.23	0.96	16.54	0.91
	CTRL_2003	-27.67	0.67	-33.39	0.77	-43.22	0.65	-29.12	0.59
	TRMM_2004	23.26	0.91	12.32	0.94	-0.93	0.95	18.54	0.91
	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 TRMM observation and their corresponding 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.

		Central Sahel		West Sahel		guinea		West Africa	
		MB	PCC	MB	PCC	MB	PCC	MB	PCC
TXx	TRMM_2003	-2.17	0.99	-3.05	0.99	-4	0.99	-2.77	0.99
	CTRL_2003	2.10	0.99	3.02	0.99	-1.34	0.99	0.32	0.99
	TRMM_2004	-2.44	0.99	-3.86	0.99	-3.84	0.99	-2.94	0.99
	CTRL_2004	1.14	0.99	2.02	0.99	-1.41	0.99	-0.16	0.99
TXn	TRMM_2003	0.31	0.99	-1.48	0.99	-0.70	0.99	0.50	0.99
	CTRL_2003	5.12	0.99	6.56	0.99	3.76	0.99	5.65	0.99
	TRMM_2004	-0.76	0.99	-1.73	0.99	-1.38	0.99	-0.32	0.99
	CTRL_2004	3.43	0.99	5.44	0.99	2.75	0.99	4.14	0.99
TNn	TRMM_2003	3.08	0.99	3.43	0.99	1.28	0.99	3.15	0.99
	CTRL_2003	2.37	0.99	3.30	0.99	1.53	0.99	1.45	0.99
	TRMM_2004	3.28	0.99	2.98	0.99	1.20	0.99	3.11	0.99
	CTRL_2004	2.09	0.99	2.55	0.99	1.28	0.99	0.71	0.99
TNx	TRMM_2003	-0.69	0.99	-1.79	0.99	-3.11	0.99	-1.62	0.99
	CTRL_2003	-1.91	0.99	-2.86	0.99	-3.35	0.99	-3.85	0.99
	TRMM_2004	-0.82	0.99	-1.43	0.99	-3.14	0.99	-1.71	0.99
	CTRL_2004	-1.90	0.99	-2.54	0.99	-3.32	0.99	-3.99	0.99

Table 3: The pattern correlation coefficient (PCC) and the mean bias (MB in°C) of TXx, TXn, TNn and TNx indices from the EIN reanalysis and their corresponding control experiments (initialized with initial soil moisture of ERA20C reanalysis) with respect to GTS, calculated for Guinea coast, central Sahel, west Sahel and the entire West African domain for JJAS 2003 and JJAS 2004.

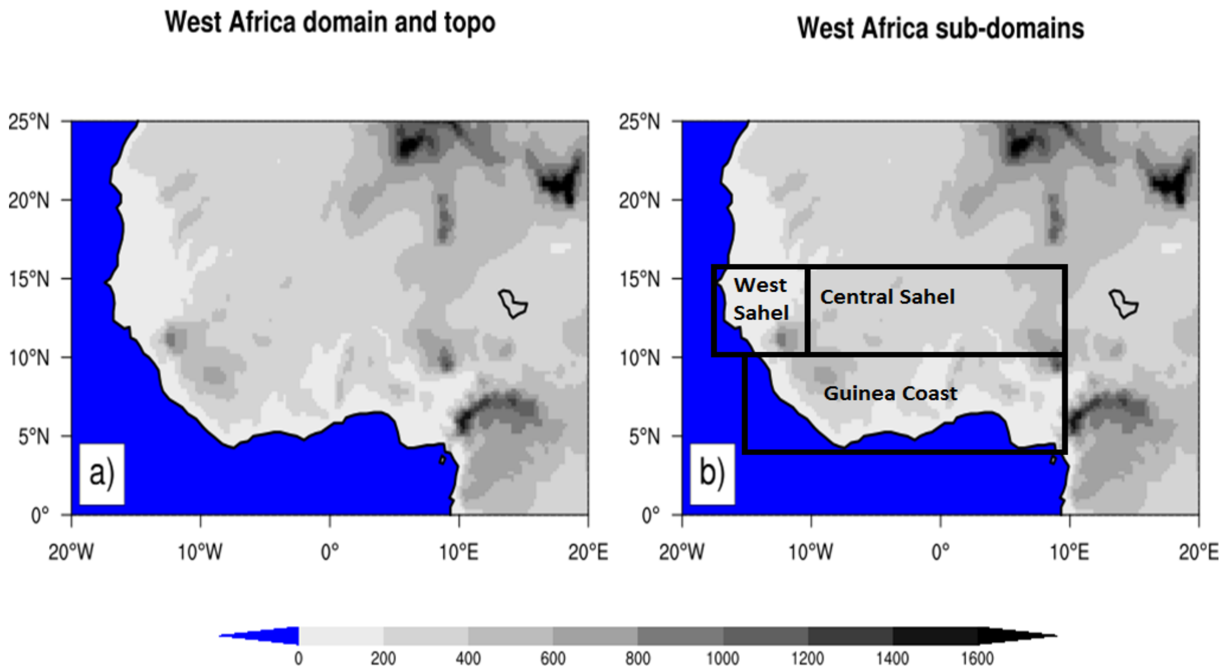

Figure 1: Topography of the West African domain. The analysis of the model result has an emphasis on the whole West African domain and the three subregions Guinea coast, central Sahel and west Sahel, which are marked with black boxes.

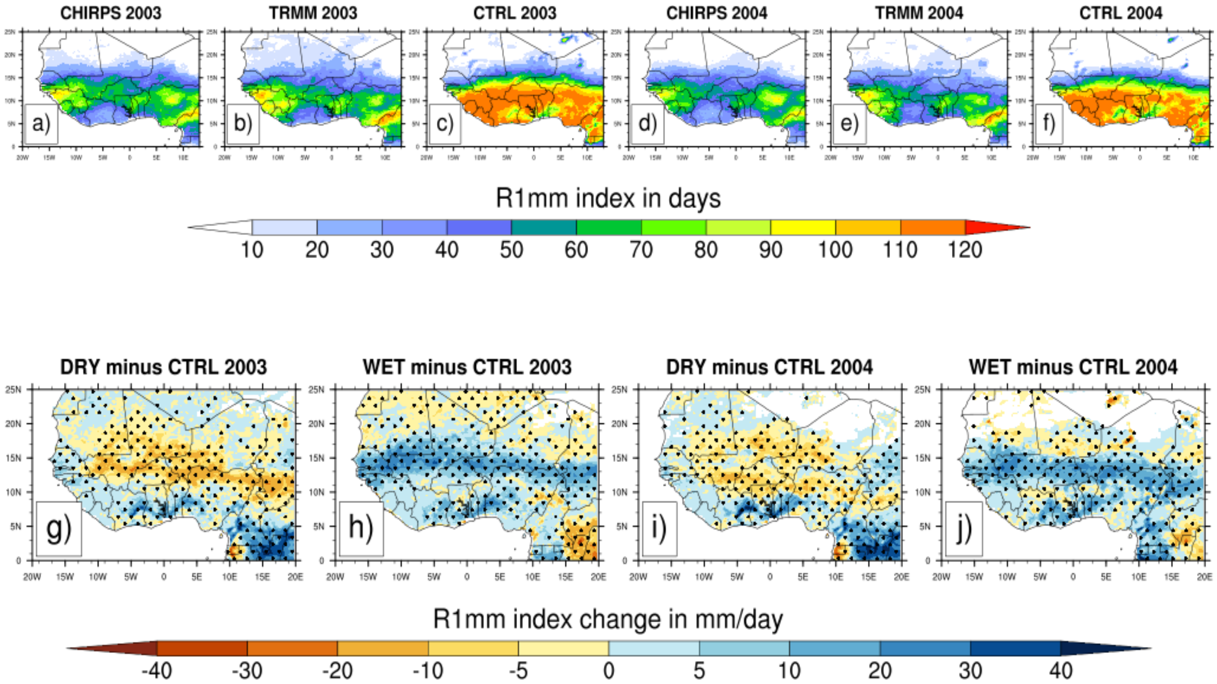

Figure2: Observed 4-month averaged (JJAS) mean values of the number of the wet days (R1mm index in days) from CHIRPS (a and d) and TRMM(b and e) observations for JJAS 2003 and JJAS 2004 and their corresponding simulated control (CTRL) experiments (c and f) initialized with initial soil moisture of the reanalysis of ERA20C (first panel) and changes in R1mm index in days (second panel) for JJAS 2003 and JJAS 2004, from dry (g and i) and wet (h and j) experiments with respect to the corresponding control experiments. Areas with values passing the 10% significance test are dotted.

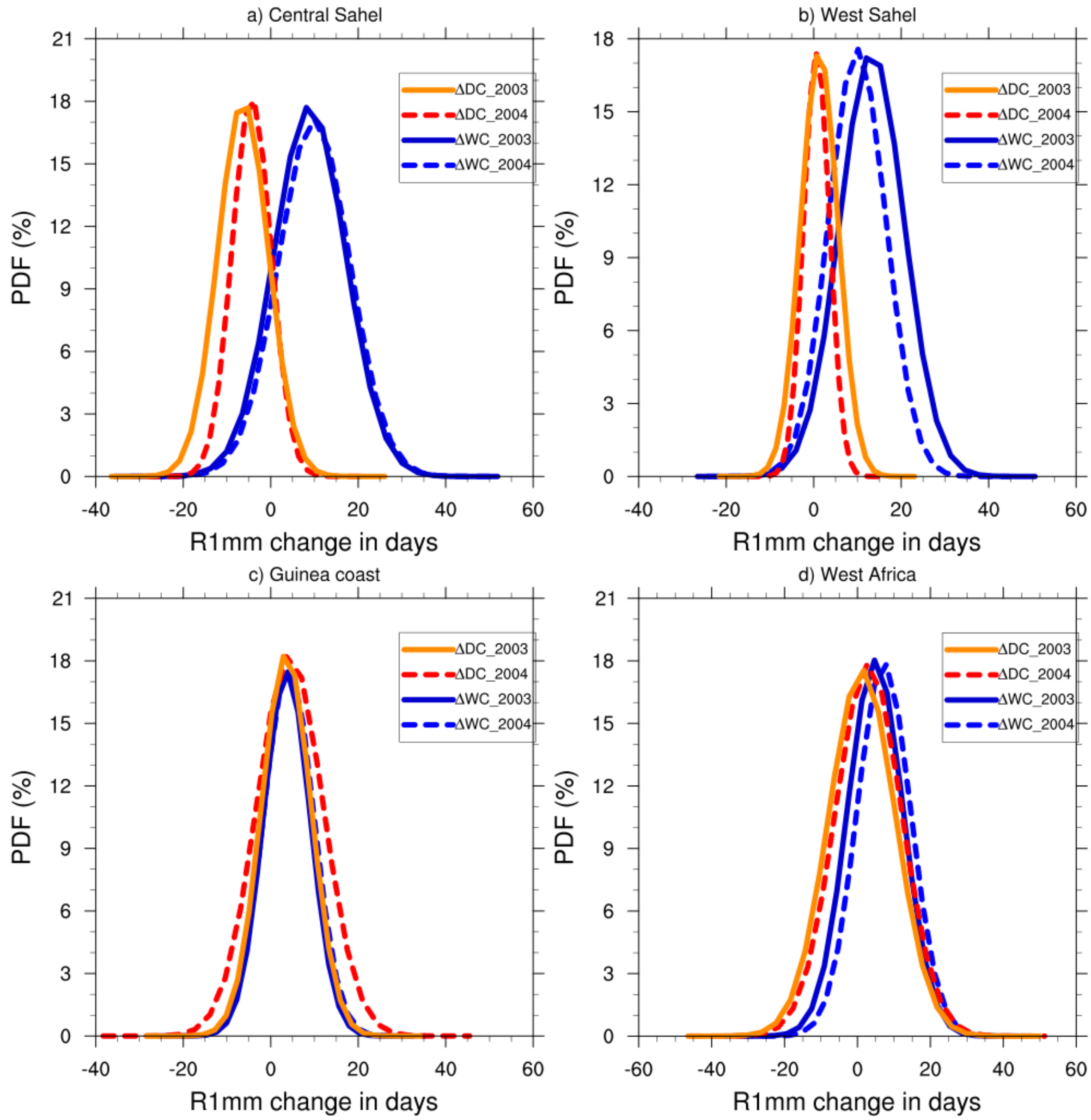

Figure3: PDF distributions (%) of mean values of the number of the wet days change in JJAS 2003 and JJAS 2004, over (a) central Sahel , (b) West Sahel, (c) Guinea and (d) West Africa derived from dry (ΔDC) and wet (ΔWC) experiments with respect to their corresponding control experiment.

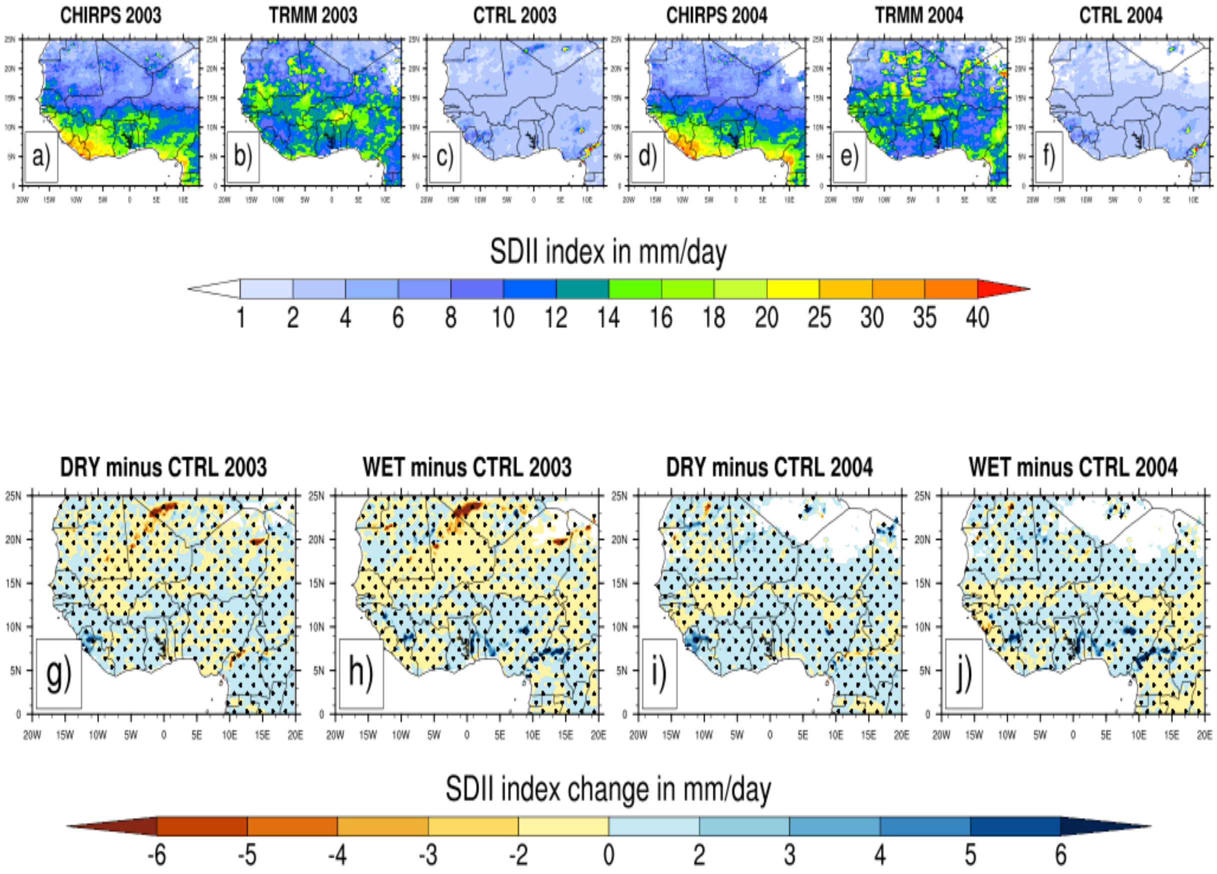

Figure4: Same as Fig. 2 but for the SDII index (in mm.day^{-1}).

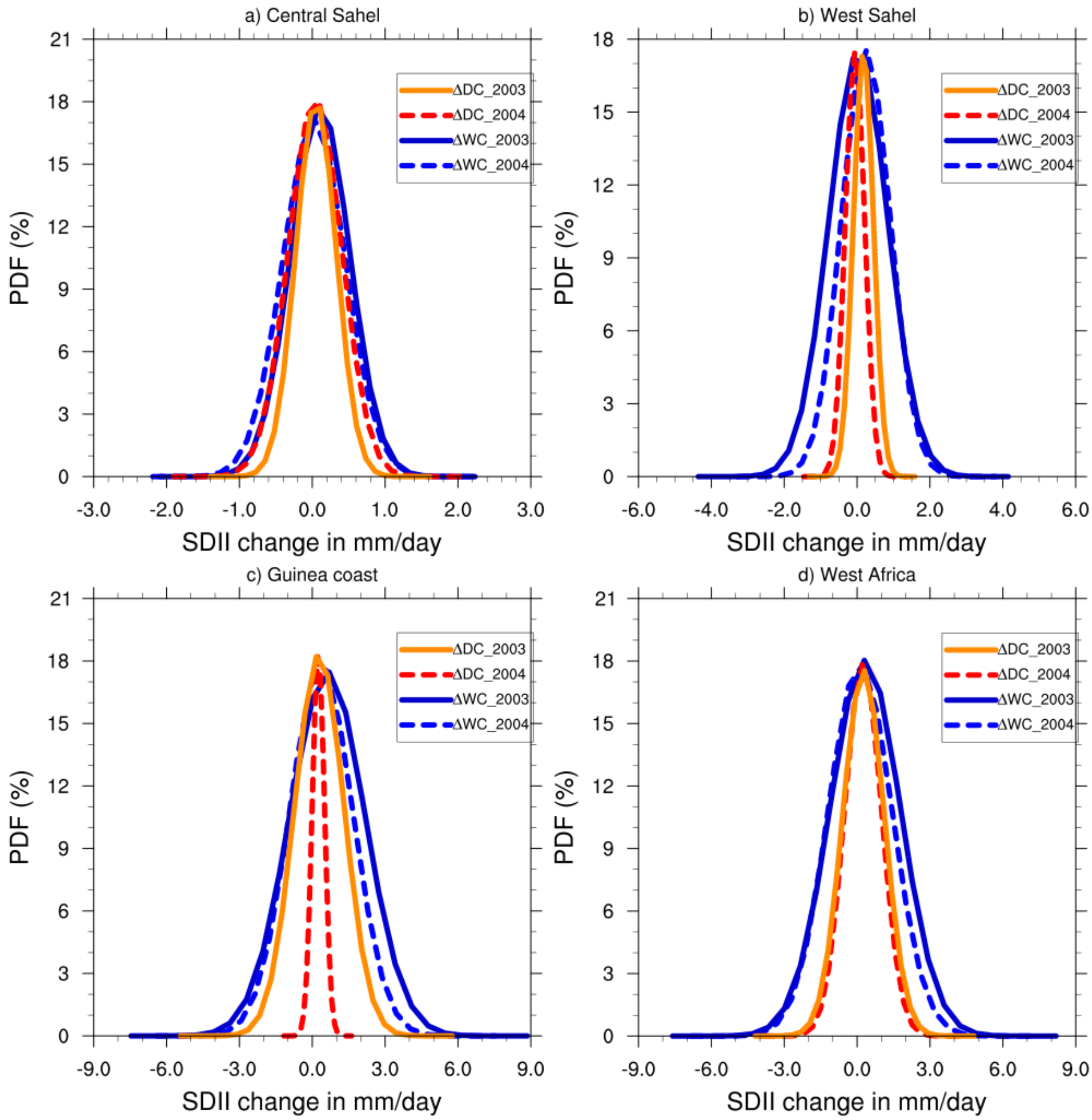

Figure 5: Same as Fig. 3 but for the SDII index (in mm.day^{-1}).

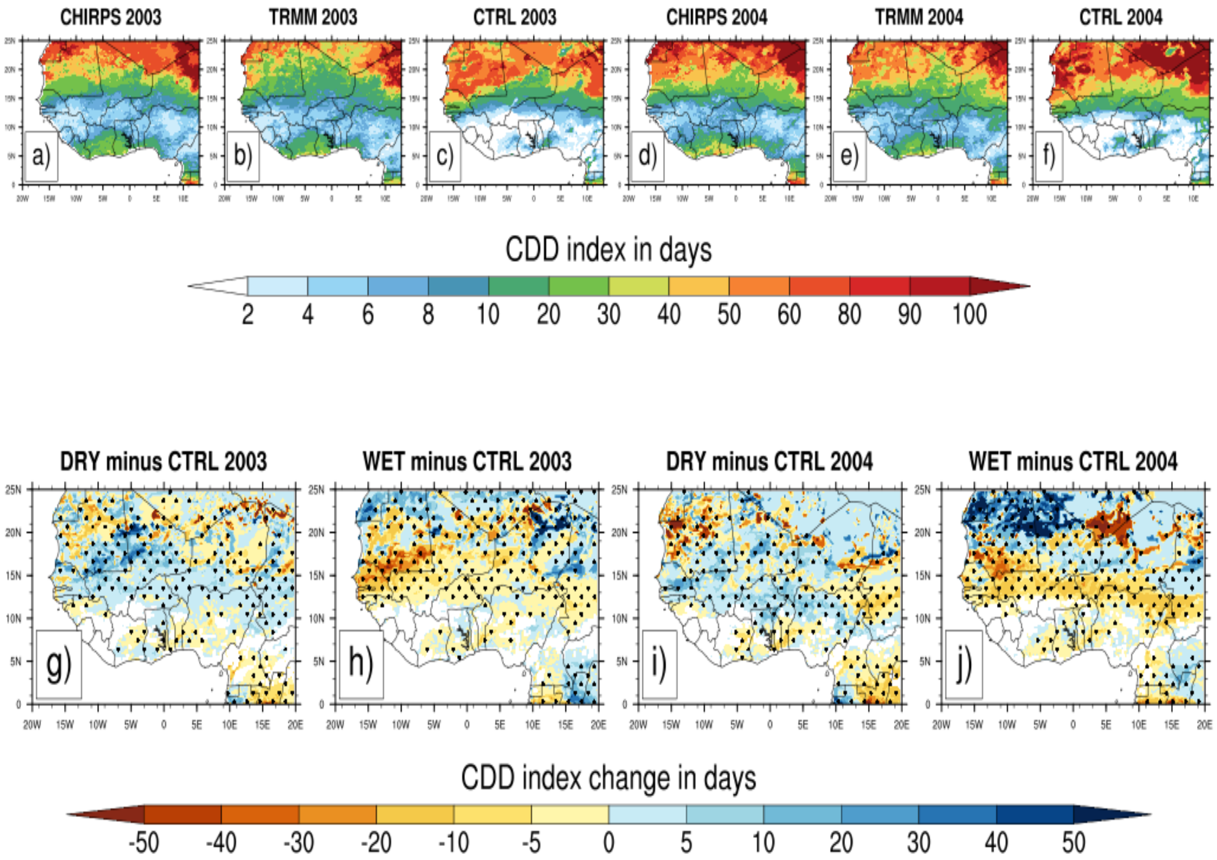

Figure 6: Same as Fig. 2 but for the CDD index (in day).

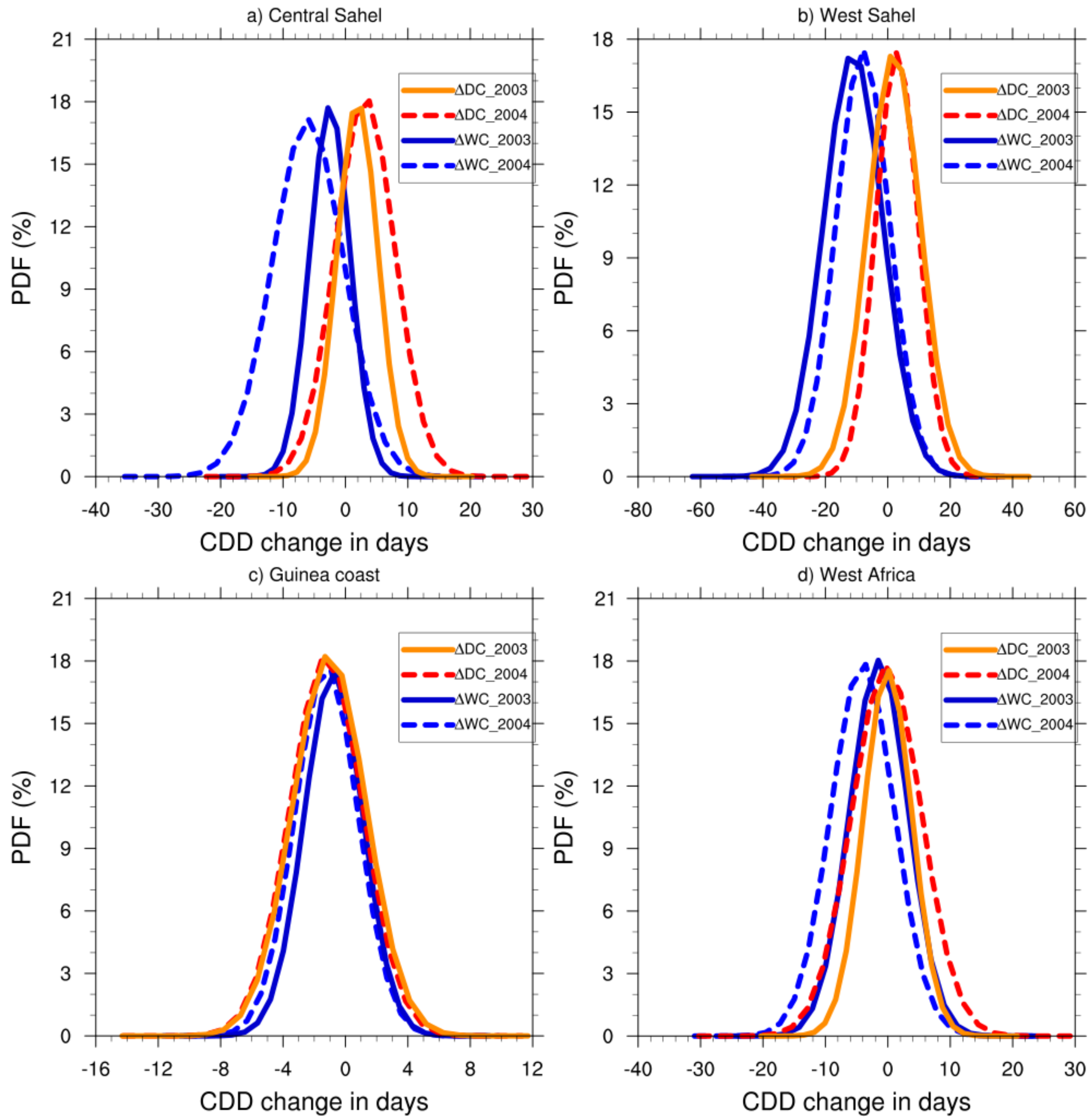

Figure 7: Same as Fig. 3 but for the CDD index (in day).

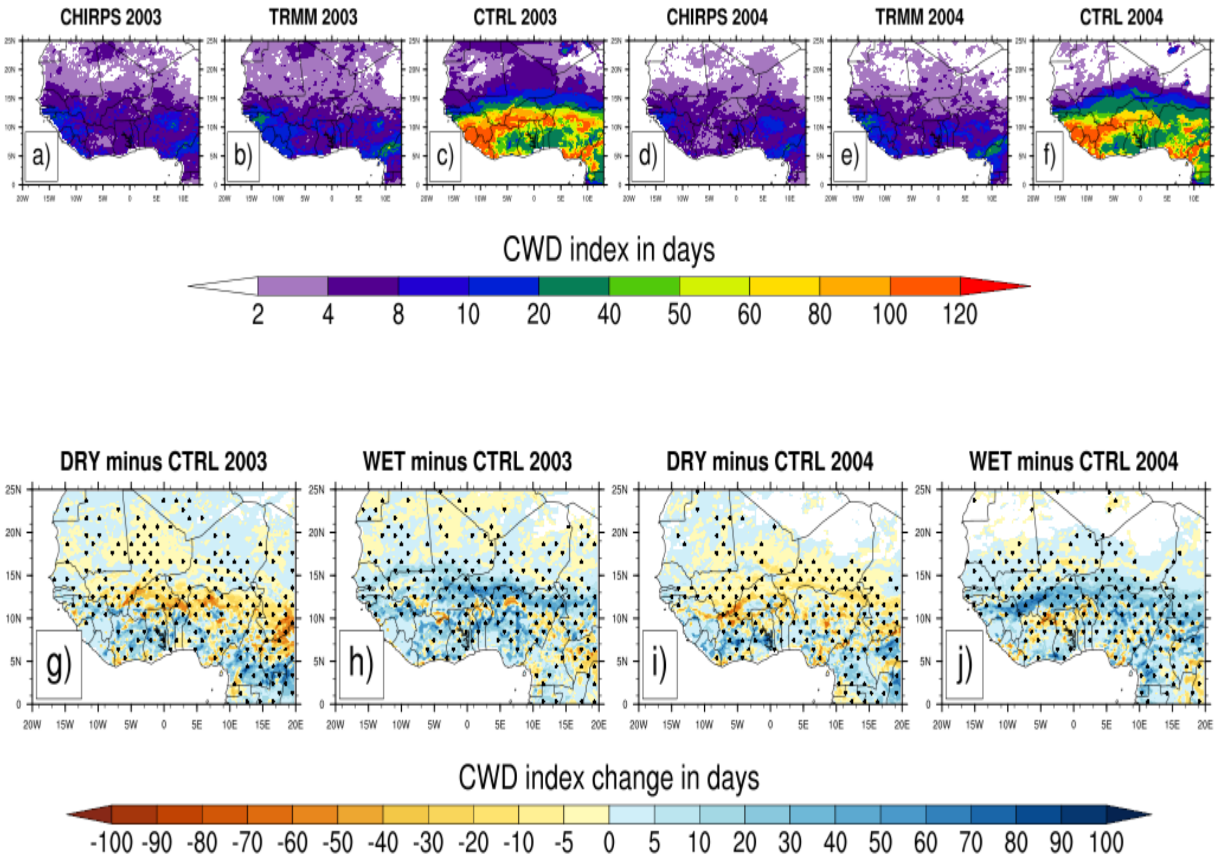

Figure 8: Same as Fig. 2 but for the CWD index (in day).

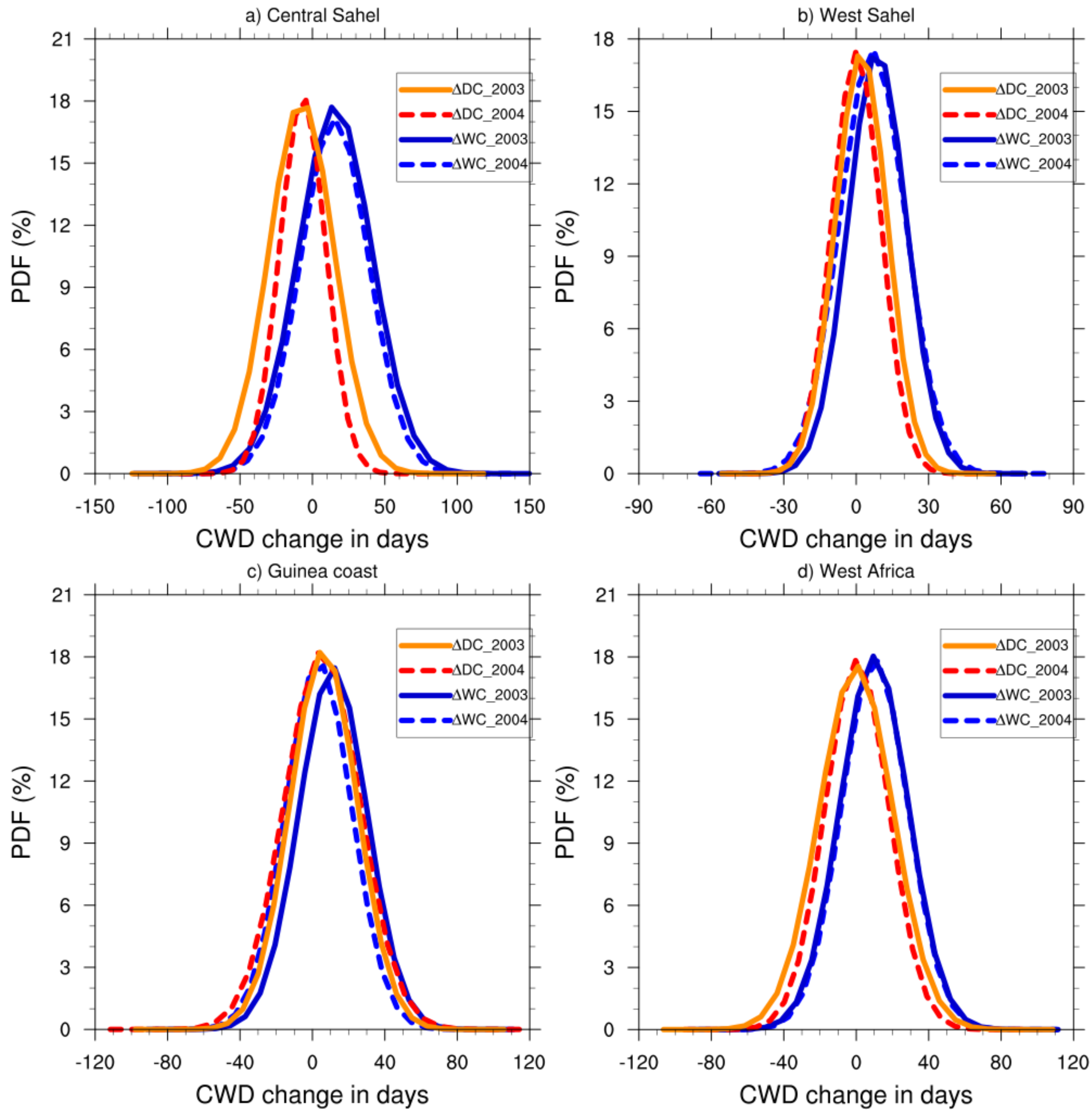

Figure 9: Same as Fig. 3 but for the CWD index (in day).

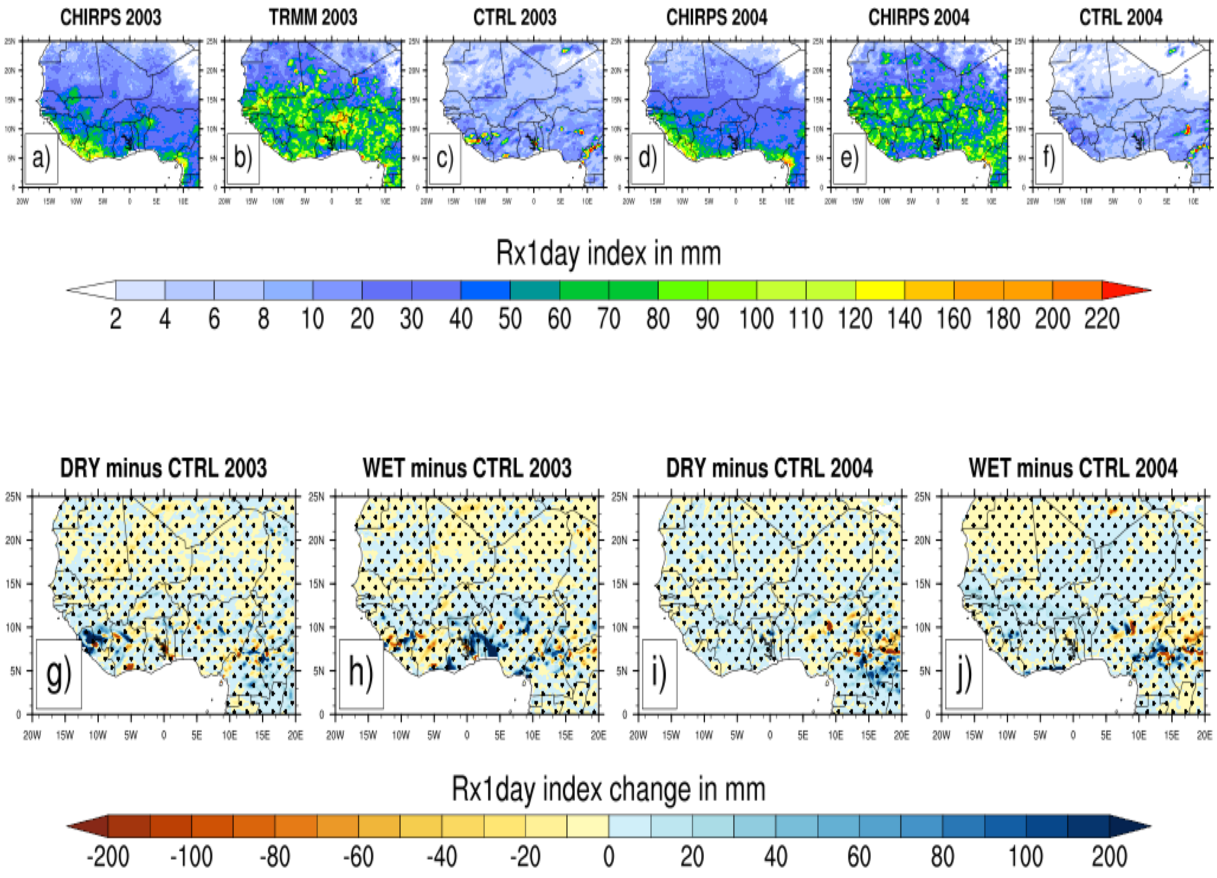

Figure 10: Same as Fig. 2 but for the RX1day index (in mm).

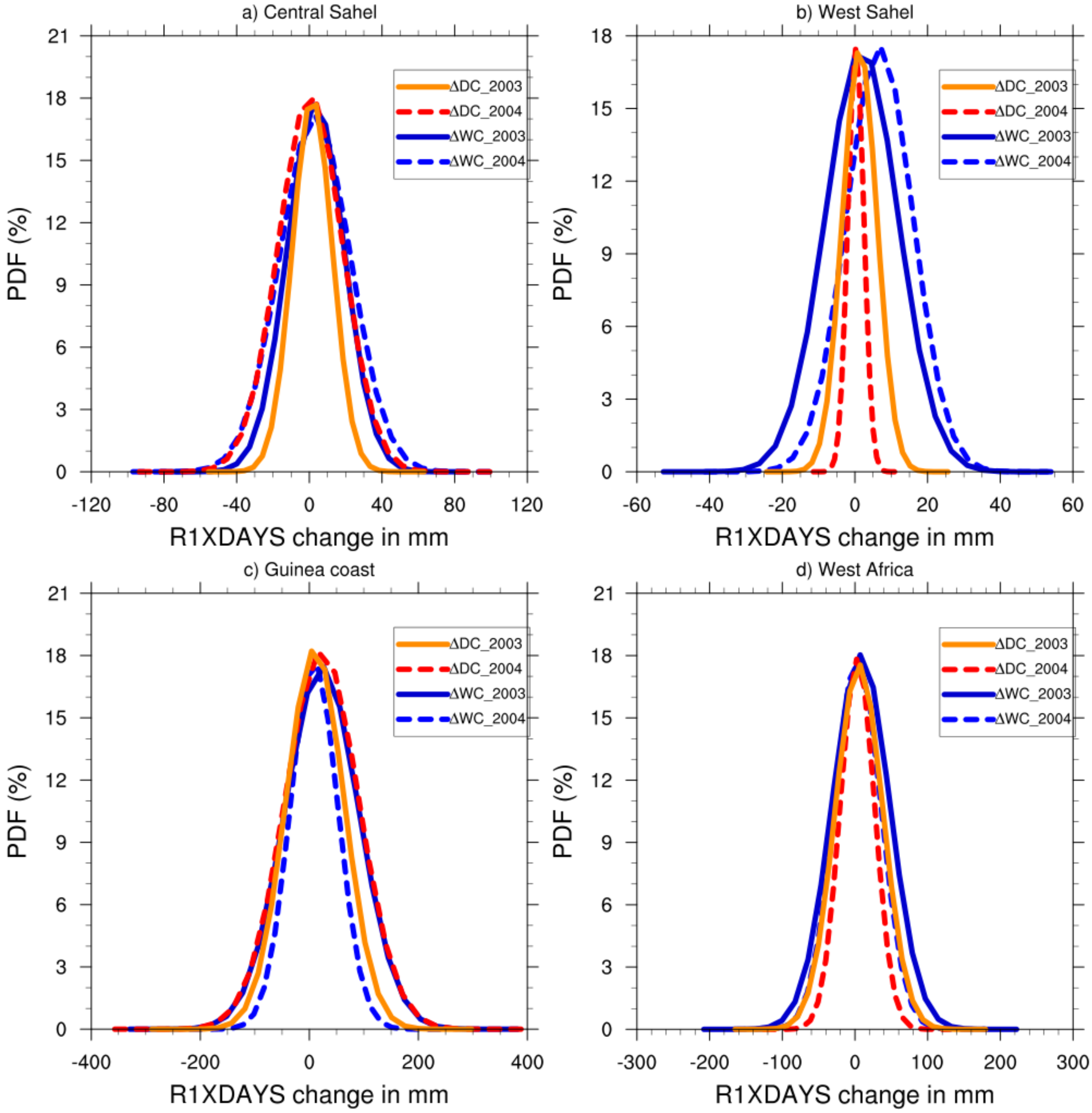

Figure 11: Same as Fig. 3 but for the RX1DAY index (in mm).

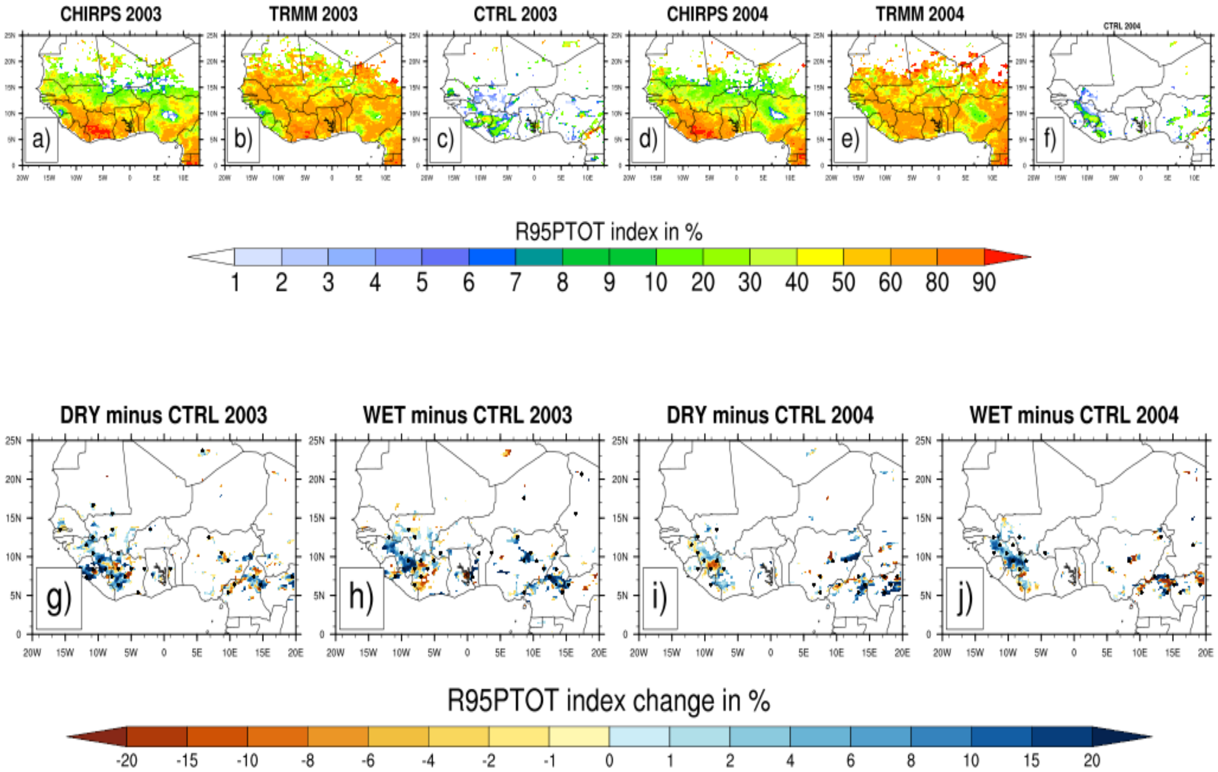

Figure 12: Same as Fig. 2 but for the R95pTOT index (in %).

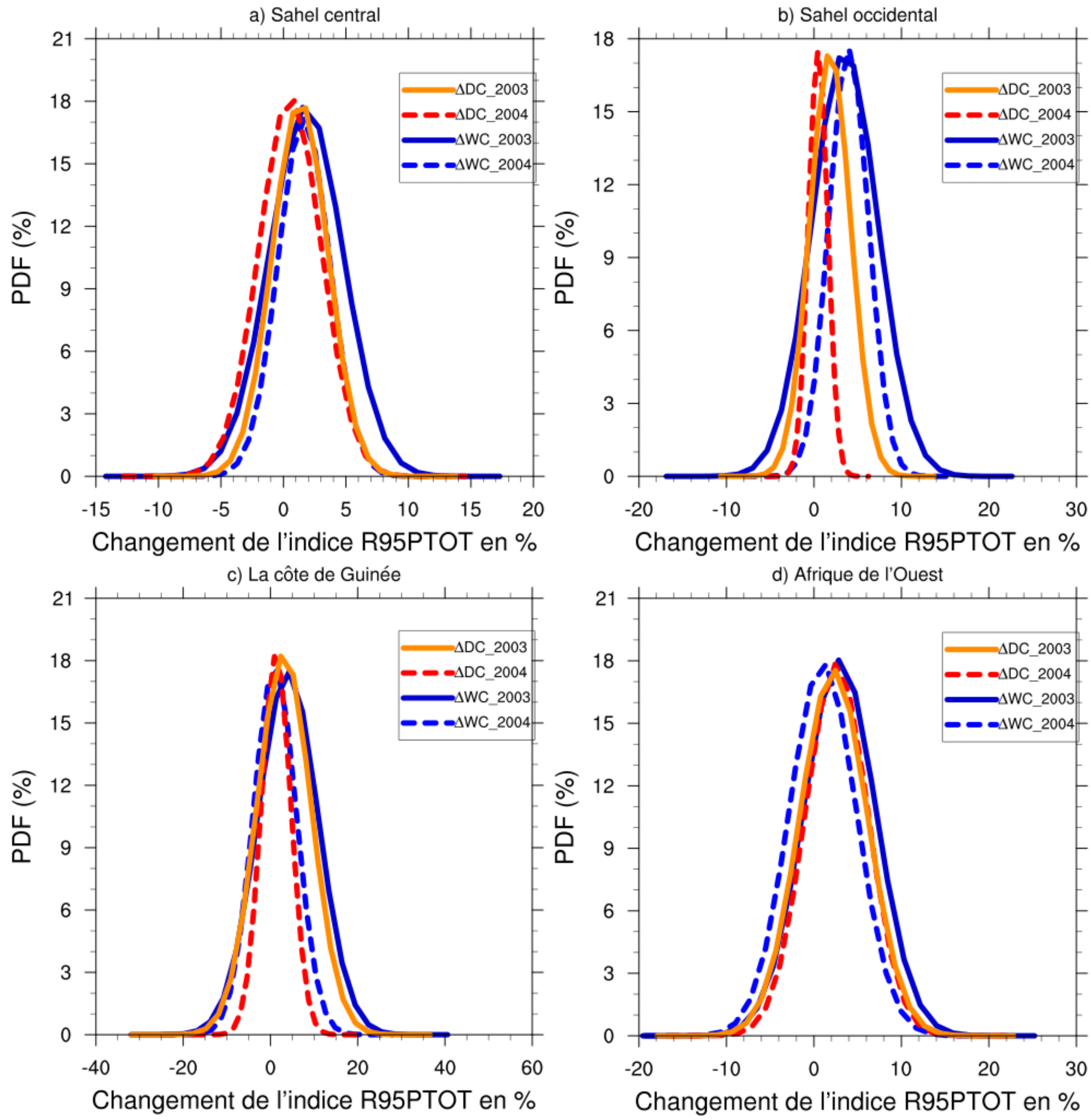

Figure 13: Same as Fig. 3 but for theR95pTOT index (in %).

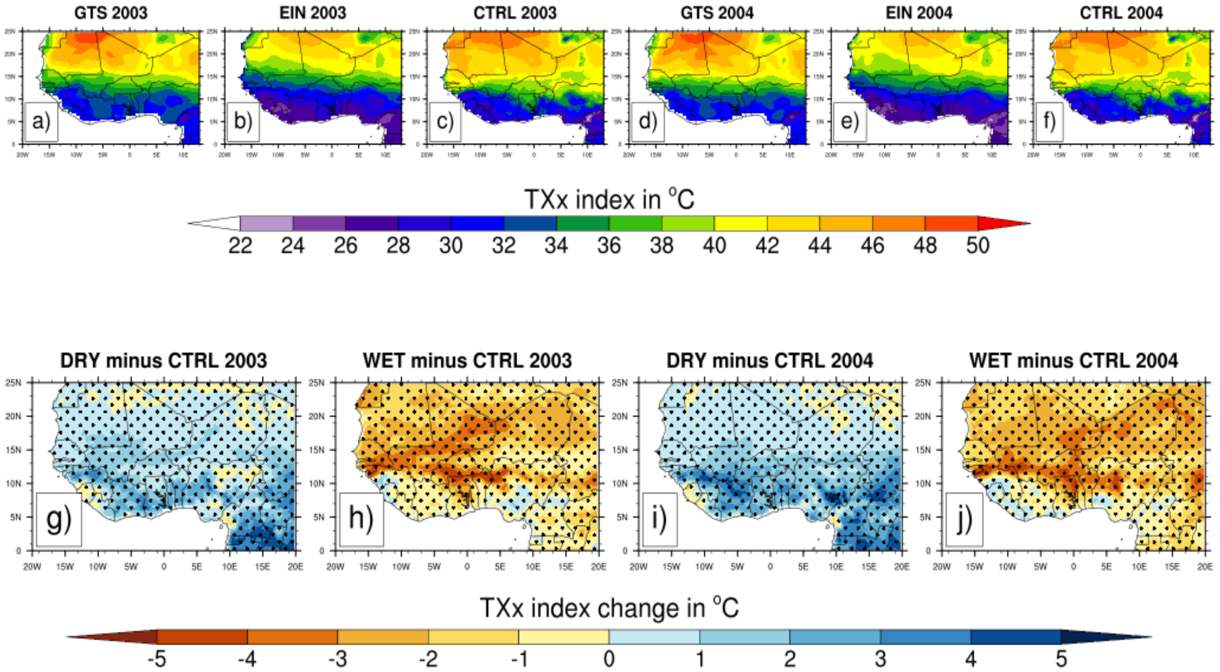

Figure 14: Observed 4-month averaged (JJAS) maximum value of daily maximum temperature (TXx index in°C) from GTS observation (a and d) and The EIN reanalysis (b and e) for JJAS 2003 and JJAS 2004 and their corresponding simulated control (CTRL) experiments (c and f) initialized with the initial soil moisture of the ERA20C reanalysis (first panel) and changes in TXx index in°C (second panel) for JJAS 2003 and JJAS 2004, from dry (g and i) and wet (h and j) experiments with respect to the corresponding control experiments. Areas with values passing the 10% significance test are dotted.

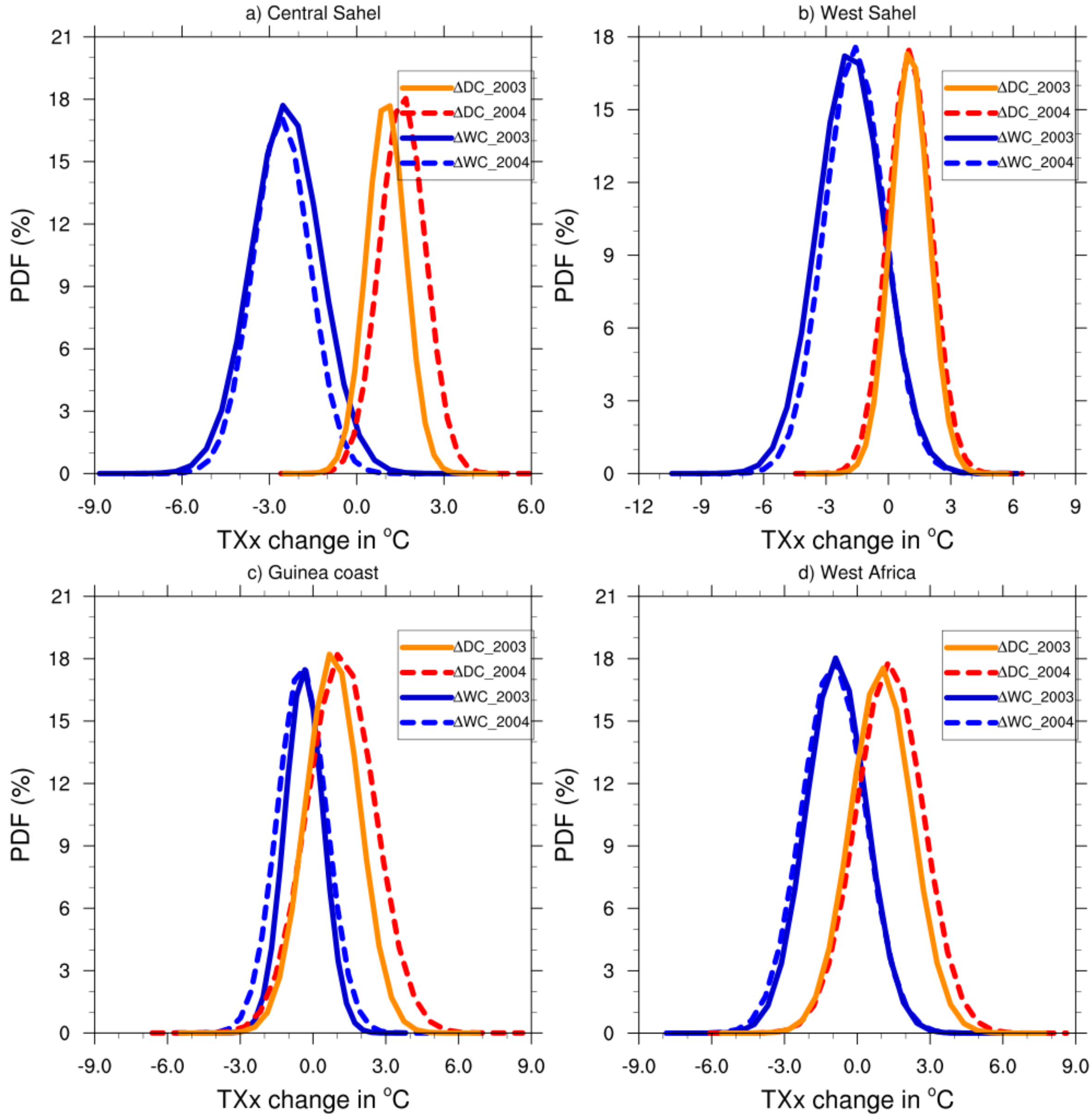

Figure 15: PDF distributions (%) of change in maximum value of daily maximum temperature (TXx index, in°C) for JJAS 2003 and JJAS 2004, over (a) central Sahel , (b) West Sahel, (c) Guinea and (d) West Africa derived from dry (ΔDC) and wet (ΔWC) experiments compared to their corresponding control experiment.

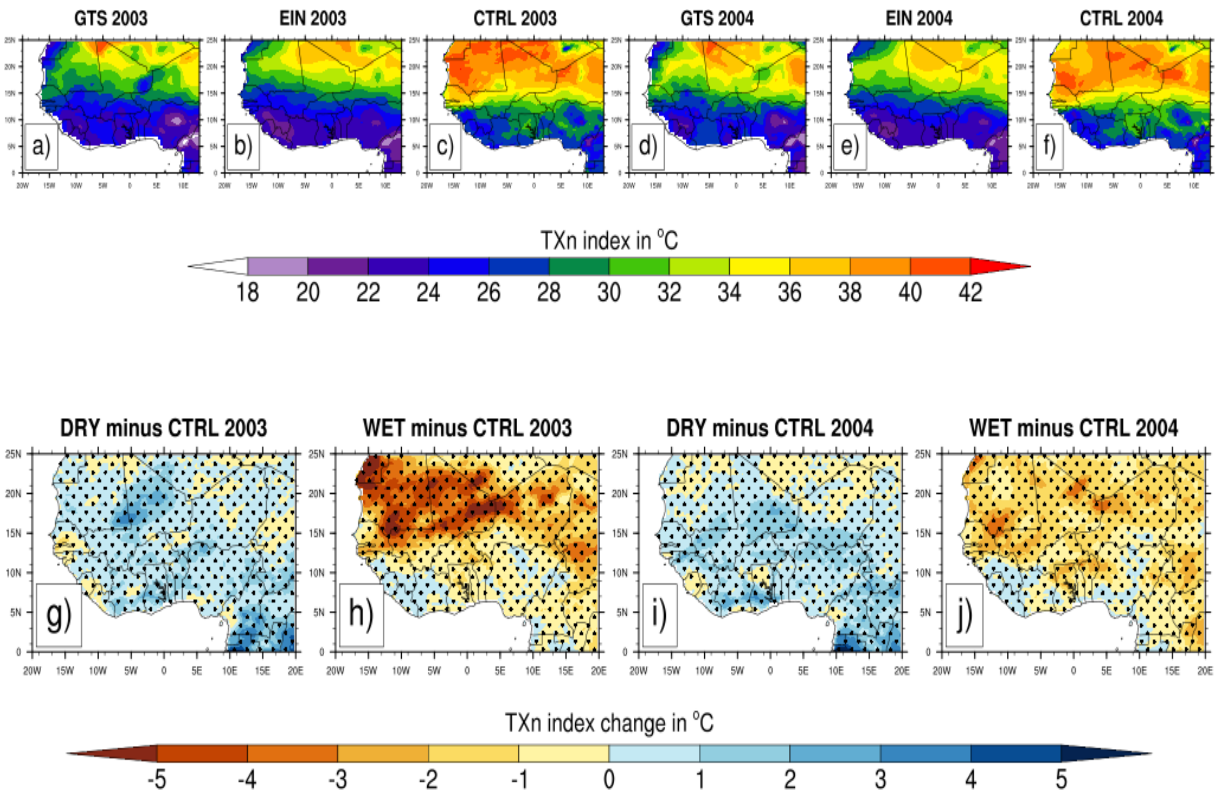

Figure 16: Same as Fig. 14 but for the TXn index

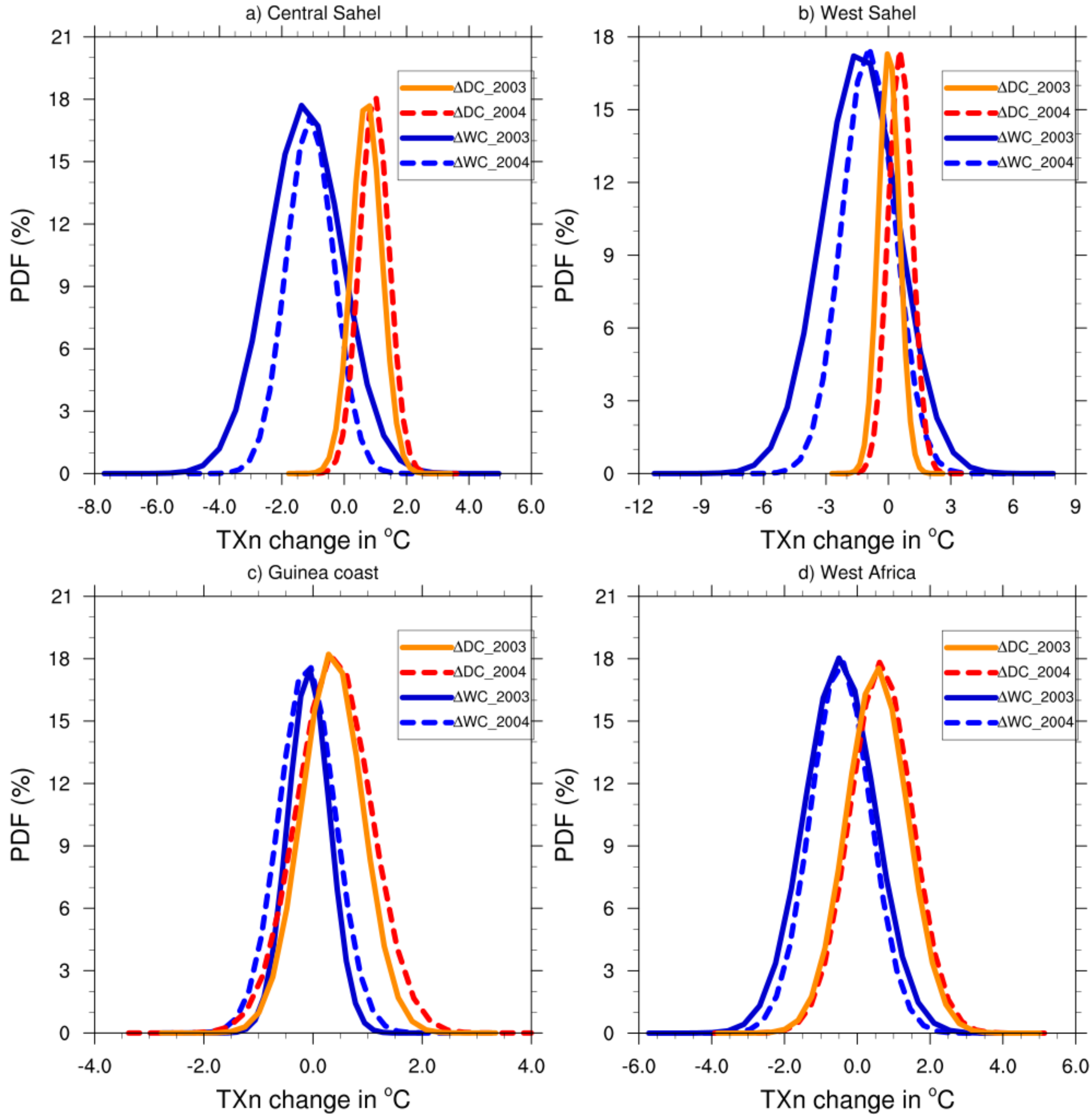

Figure 17: Same as Fig. 15 but for the TXn index.

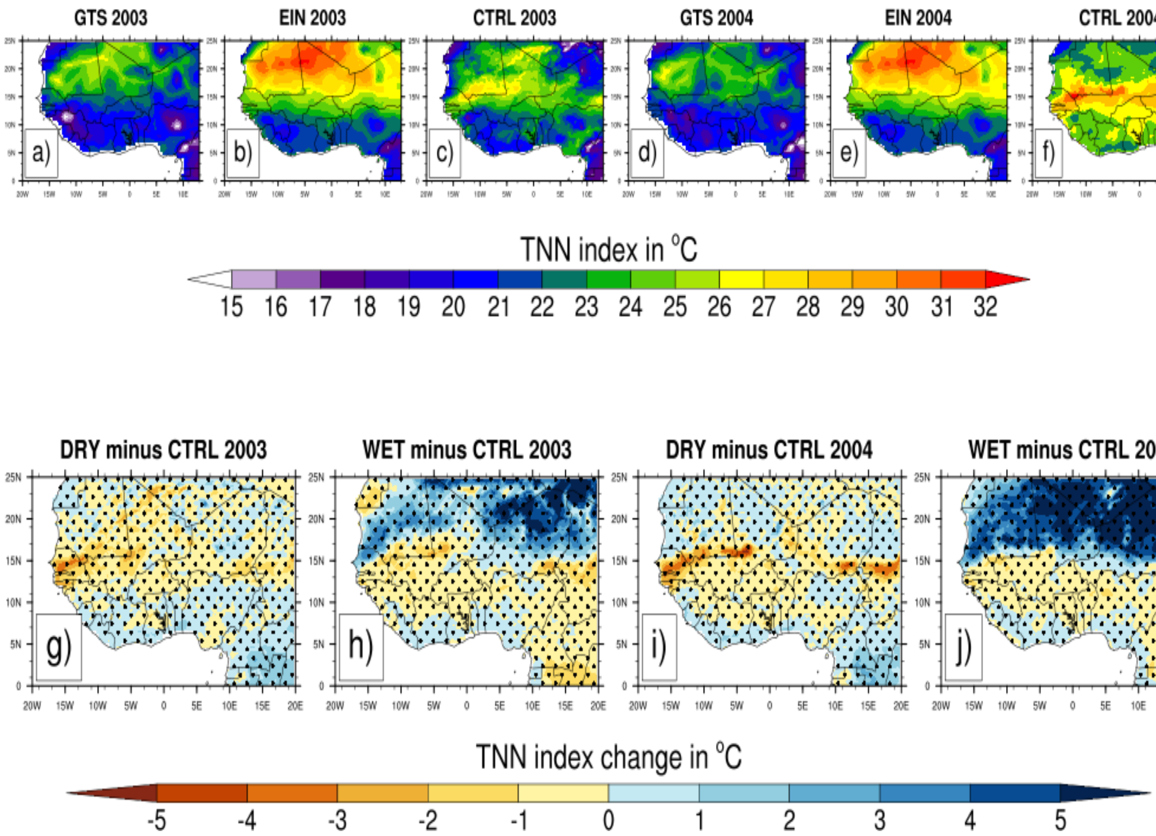

Figure 18: Same as Fig. 14 but for the TNn index.

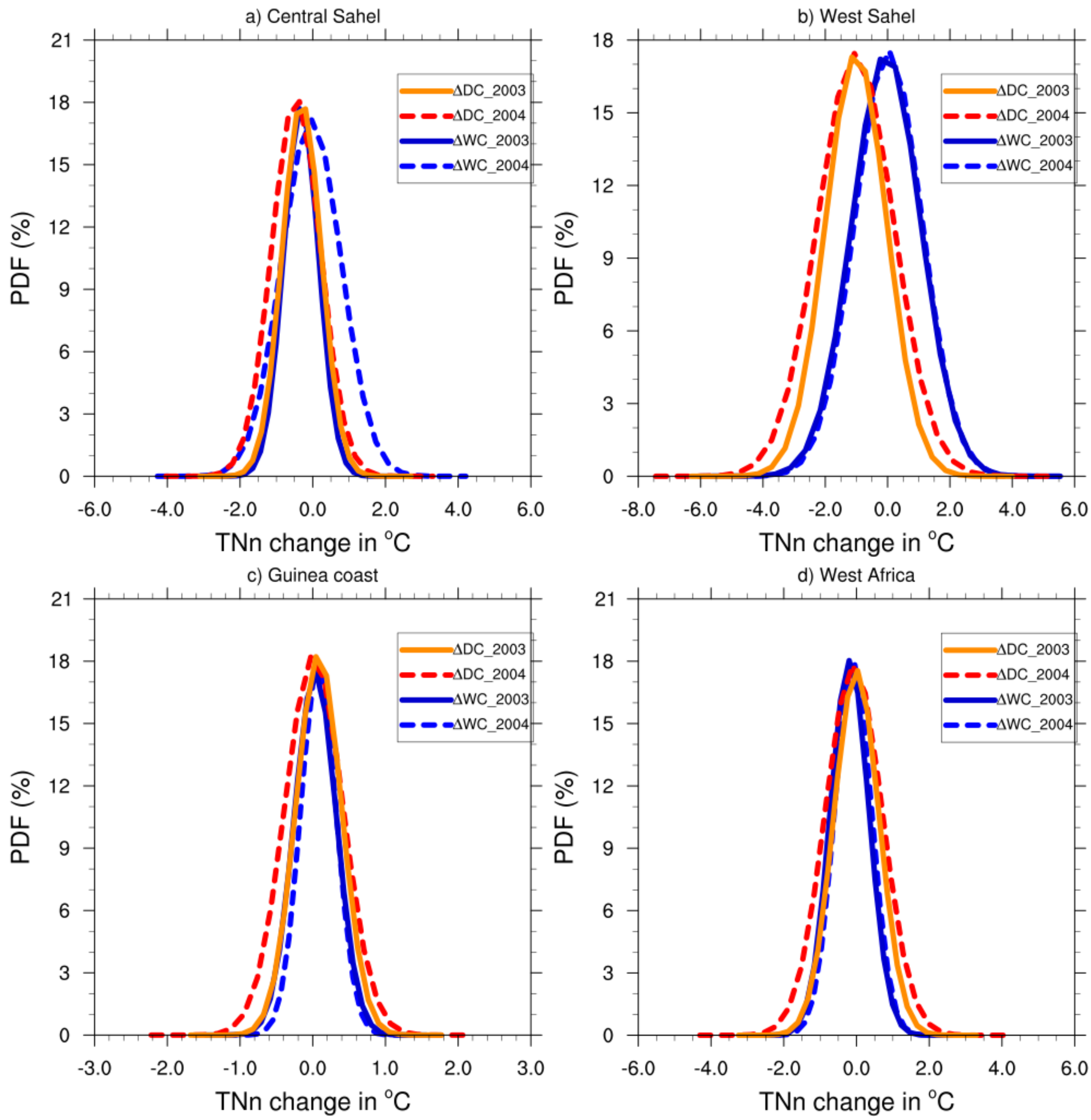

Figure 19: Same as Fig. 14 but for the TNn index.

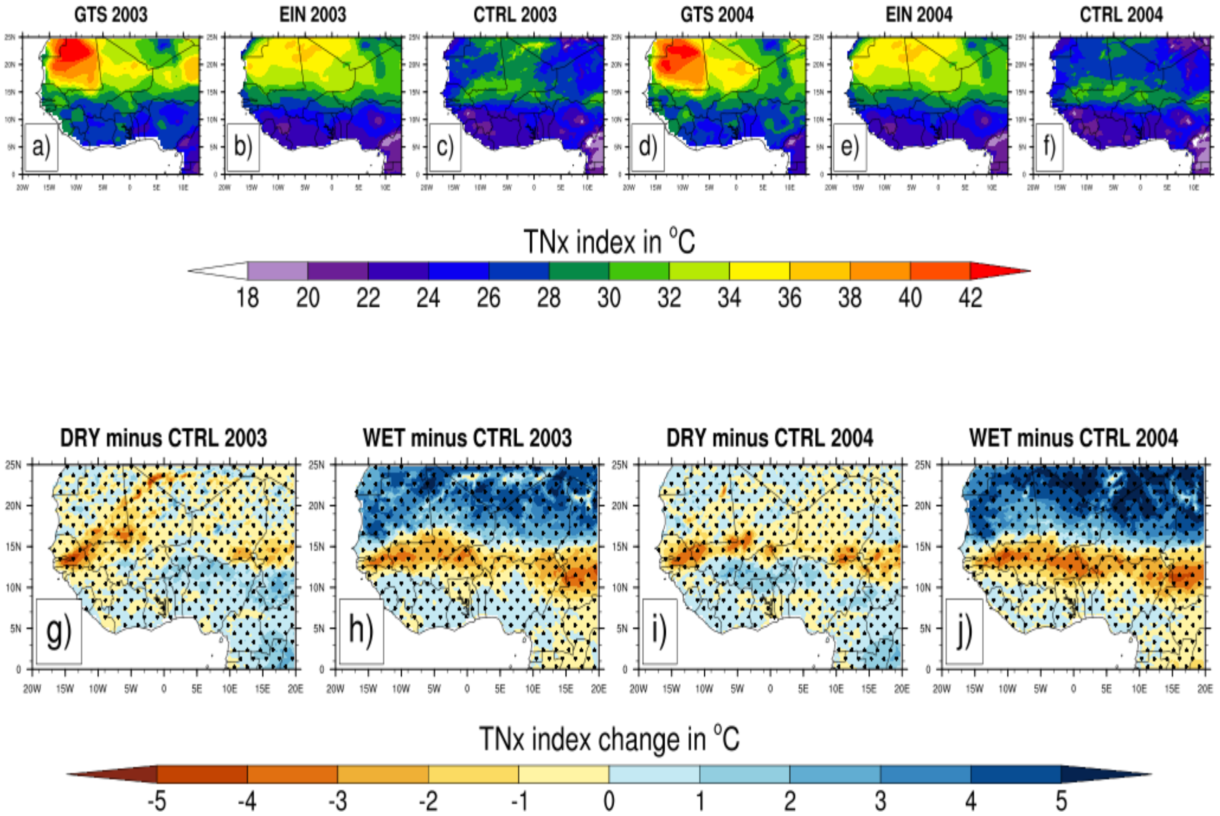

Figure 20: Same as Fig. 14 but for the TNx index

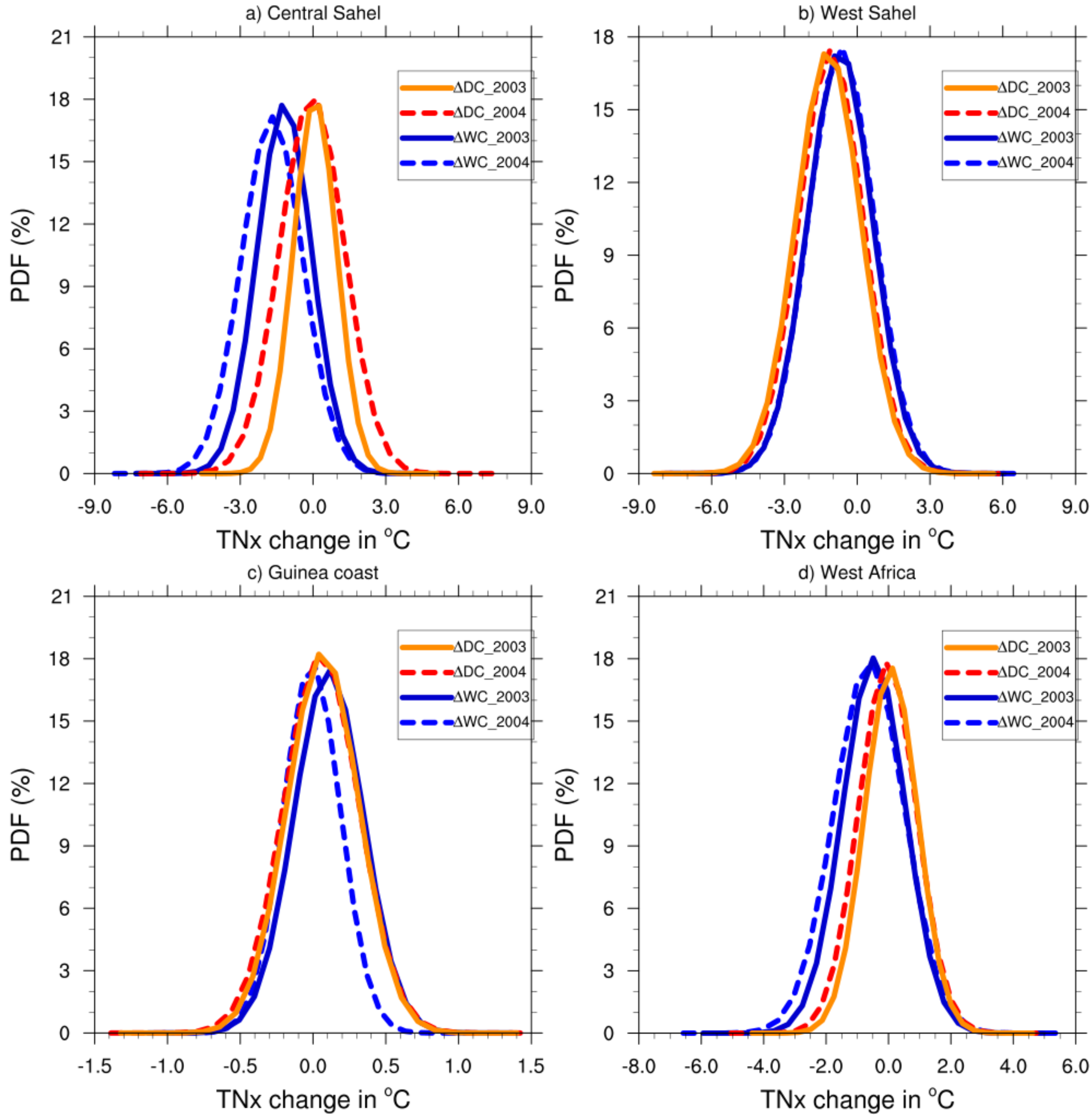

Figure 21: Same as Fig. 15 but for the TNx index.