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Effect of the African greenbelt position on West African summer climate: a regional climate modeling study

Adama Bamba[1] · Ismaila Diallo[2] · N'Datchoh E. Touré[1] · Kouakou Kouadio[1] · Abdourahamane Konaré[1] ·
Mamadou S. Dramé[3,4] · Arona Diedhiou[1,5] · Siélé Silué[6] · Madina Doumbia[1] · Moustapha Tall[4]

Abstract

This modeling study is conducted to examine the potential impact of the reforestation (greenbelt) location (either in Sahel or in Guinean region) on West African summer climate system. To this end, three simulations using the regional climate model RegCM4 driven by ERA-Interim reanalysis were performed at 50 km horizontal resolution over a West African domain for the period 2000–2011. The first experiment, namely the control (CTRL), uses the standard vegetation cover, while the two others incorporate throughout the model integration, a zonal reforestation band of evergreen broadleaf over different locations: (i) over a 13° N–17° N band latitudes in a Sahel-Sahara region (experiment hereafter referred to as GB15N) and (ii) between 8.5° N–11.5° N in the Guinea Coast region (experiment hereafter referred to as GB10N). A comparison of the CTRL experiment with observation reveals a faithful reproduction of the mean boreal and summer seasonal precipitation pattern, though substantial dry/wet biases remain, especially in the Atlantic Ocean. In addition, the seasonal cycle over sub-regions matches satisfactory the observed pattern. The GB15N reforestation leads to a precipitation increase in the range of 2–4 mm/day over the forested areas, whereas in the GB10N reforestation, precipitation increase is weaker and not necessarily located in the forested areas. Temperature cooling is observed over the reforested area and may be explained by a decrease of ground heat flux related to a reduction of the surface albedo.

Adama Bamba and Ismaila Diallo contributed equally to this work.

✉ Adama Bamba
adambamba_2000@yahoo.com

✉ Ismaila Diallo
idiallo@ucla.edu

[1] Laboratoire de Physique de l'Atmosphère et de Mécanique des Fluides (LAPA-MF), Université Félix Houphouët Boigny (UFHB), Abidjan, Côte d'Ivoire

[2] Department of Geography, University of California, Los Angeles (UCLA), Los Angeles, CA 90095, USA

[3] Département de Physique, Faculté des Sciences et Techniques, Université Cheikh Anta Diop de Dakar (UCAD), BP 5085 Dakar, Sénégal

[4] Laboratoire de Physique de l'Atmosphère et de l'Océan Siméon Fongang (LPAO-SF), Ecole Supérieure Polytechnique, Université Cheikh Anta Diop (UCAD-ESP), Dakar, Sénégal

[5] Université Grenoble Alpes, IRD, CNRS, Grenoble INP, IGE, F-38000 Grenoble, France

[6] Université Peleforo Gon Coulibaly, Korhogo, Côte d'Ivoire

1 Introduction

The Sahel region of West Africa has witnessed dramatic precipitation changes from wet conditions in the 1950s to drier conditions in the 1970s and 1980s followed by a partial recovery since the early 1990s (Nicholson 2013, Sanogo et al. 2015, Xue et al. 2016 and cited references therein). These changes are the results of a combination of both natural and anthropogenic forcings. Several studies have attempted to explain the Sahelian severe droughts using variety of approaches: (i) variability of sea surface temperature (SST; Folland et al. 1986; Giannini et al. 2003; Paeth and Hense 2004; Pomposi et al. 2016; Adeniyi 2017); (ii) land surface-atmosphere interactions (Charney et al. 1977; Wang and Eltahir 2000; Koster et al. 2004; Xue et al. 2016; Wang et al. 2016); and (iii) large-scale atmospheric teleconnections related to the El Niño or North Atlantic Oscillation (NAO) (Bader and Latif 2003; Joly and Voldoire 2009). The West African climate is dominated by the West African monsoon (WAM) system, and monsoon variability explains most of the total annual precipitation fluctuations. Atmospheric circulations linked to the African Easterly Jet (AEJ), the Tropical

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Easterly Jet (TEJ), the African Westerly Jet (AWJ), the West African Westerly Jet (WAWJ), and their interactions with the inter-tropical convergence zone (ITCZ) play key roles in the WAM variability (Nicholson 2013) and modulate the Sahel summer rainfall fluctuations (Jenkins et al. 2005; Diallo et al. 2013; Sylla et al. 2013; Diallo et al. 2014).

The WAM is the resultant of several forcings which can be summarized as local, regional, and remote forcing depending on their origin. The remote forcings are mainly from different ocean basins as global SST anomalies have been shown to influence West African climate variability (Giannini et al. 2003; Pomposi et al. 2016). The impacts of aerosols especially dusts from the Saharan and Sahelian regions impact on West African climate variability have been highlighted (Prospero and Lamb 2003; Konaré et al. 2008; N'Datchoh et al. 2012, 2018; Marcella and Eltahir 2014). Continental and land surface forcing are considered as local forcing impacting the West African climate through rapid biophysical processes of energy budget, water cycle, carbon, and momentum exchange and the long-term interactions which arise from fundamental changes in vegetation cover (Zeng et al. 1999; Hagos et al. 2014; Boone et al. 2016).

Since Charney et al. (1977) discussed the role of vegetation in Sahelian 1970s droughts, there have been numerous studies on Sahel climate variability and external forcing (Wang and Eltahir 2000; Koster et al. 2004; Xue et al. 2016, among others). Recently, modeling and observational studies indicate that the climate and the ecosystems across the world are significantly affected by land surface changes (Koster et al. 2004; Alo and Wang 2010; Pitman et al. 2009; De Noblet-Ducoudré et al. 2012), and in particular the West African climate is very sensitive to such changes in surface conditions (Abiodun et al. 2012; Hagos et al. 2014; Nicholson 2015; Boone et al. 2016; Xue et al. 2016; Sylla et al. 2016). For instance, observation based studies by Nicholson (2015) pointed out that land surface characteristics and processes have a significant impact on rainfall variability in Sahel region. Boone et al. (2016) have shown that land degradation could produce the observed Sahel summer drought pattern. In the framework of the West African Monsoon Modelling and Evaluation phase 2 project (WAMME2; Xue et al. 2016), Wang et al. (2016) argued that land cover degradation of a reasonable magnitude and spatial extent could trigger a drought comparable to the observed one. Nogherotto et al. (2013) found that deforestation over the Congo basin strengthens the WAM, thereby causing increased (decreased) precipitation over the Sahel (Gulf of Guinea), while Abiodun et al. (2012) showed that the deforestation weakens the inland transport of moisture needed for West African precipitation. Furthermore, Diasso and Abiodun (2017) showed that reforestation decreases the magnitude of the warming trend over Savanna and reverses the predicted precipitation trend, resulting to an increase in precipitation by 0.8–1.2 mm/day. The aforementioned studies highlight the

key roles of land cover changes in the interaction between land surface processes and the West African climate.

The reforestation has been suggested as solution for climate change mitigation as well as drought mitigation over West Africa (Xue and Shukla 1996; Alo and Wang 2010; Abiodun et al. 2012; Diasso and Abiodun 2017). Although, reforestation seems to be a consensus action between scientists, decision-makers, and policies makers in the region, to the point that the African Union (AU) is approving a greenbelt or great green wall for the Sahara and Sahel initiative project (GGW, Conference of Heads of State and Governments held on January 29 and 30, 2007 in Addis-Ababa). This aims to reforest the Sahelian band from east (Djibouti) to the west (Senegal) in the purpose of tackling the detrimental social, economic, and environmental impacts of land degradation and desertification in the region. Despite all the expected benefit of such project for the regional climate and socioeconomics, there is still a lack of information on its full implication in Africa, especially West Africa. Nevertheless, limited efforts have been devoted to the potential impact of reforestation on the West African climate (Xue and Shukla 1996; Abiodun et al. 2012; Diasso and Abiodun 2017; Odoulami et al. 2017). Works from these studies investigated the impact of reforestation on extreme events (Diba et al. 2016), mechanisms underlying precipitation changes (Xue and Shukla 1996), as well as projected changes in near future mean climate and higher order statistics (Abiodun et al. 2012, 2013; Odoulami et al. 2017; Diasso and Abiodun 2017).

None of the early reforestation studies attempted to assess the impact of the greenbelt location and the associated changes on the WAM summer climate. This work aims to assess the potential impact of the greenbelt location (in Sahel or Guinean regions) and the associated changes induced in West Africa using the Abdus Salam International Centre for Theoretical Physics (ICTP) Regional Climate Model version 4.4 (RegCM4.4; Giorgi et al. 2012). The paper is organized as follows: Section 2 describes the model and experimental design. Section 3 presents results and discussions of the models performances in reproducing the spatial and temporal variability of precipitation in West Africa as well as Green belt position effects on temperature, precipitation, and on large-scale circulation. Summary and main conclusions of the present work are given in Section 4.

2 Methodology and data

2.1 Model description

The recent version of the regional climate model version 4.4 (RegCM4.4; hereafter referred to as RegCM4) (Giorgi et al. 2012; N'Datchoh et al. 2012, 2018; Diallo et al. 2016, 2018; Diasso and Abiodun 2017) developed at the Abdus Salam

International Centre for Theoretical Physics (ICTP) is used in this study. RegCM4 is a compressible primitive equation, sigma-p vertical coordinate model and uses a dynamical core of the Mesoscale Meteorological model version 5 (MM5) from the National Centre for Atmospheric Research/ Pennsylvania State University (NCAR/PSU's MM5; Grell et al. 1994). RegCM4 is an improved version of RegCM3 (Pal et al. 2007) with multiples upgrades in the model physics parameterizations. A list of the physical options available in RegCM4 is provided in Giorgi et al. (2012). Based on previous studies over different African sub-regions (e.g., Mariotti et al. 2014; Bamba et al. 2015; Li et al. 2015; Diallo et al. 2015, 2016, 2018; N'Datchoh et al. 2018; Tall et al. 2017) as well as a series of preliminary experiments, the following options were selected in this study: the radiation scheme from the NCAR Community Climate Model version 3 (CCM3; Kiehl et al. 1996), the nonlocal vertical diffusion scheme of Holstag et al. (1990) to represent the boundary layer processes, the sub-grid explicit moisture (SUBEX) resolvable scale precipitation scheme of Pal et al. (2000), the ocean flux scheme of Zeng et al. (1998), and the cumulus convection scheme of Grell et al. (1994) with the Fritch-Chappell closure assumption (FC; Fritsch and Chappell 1980) to represent the convective precipitation.

In order to describe the role of vegetation and interactive soil moisture in land-atmosphere interactions, the RegCM4 was coupled to two land surface models (LSMs). One is the Biosphere-Atmosphere Transfer Scheme (BATS; Dickinson et al. 1993), while the other is the Community Land Model version 3.5 (CLM3.5, Oleson et al. 2008). In this study, the BATS scheme which has been the default LSM in the RegCM4 for many years has been selected. The BATS scheme contains one vegetation canopy layer, a force-restore model to calculate soil temperature, a single snow layer, one simple surface runoff model, and three soil layers with different depths and calculates land surface variables within these layers (Dickinson et al. 1993). Furthermore, the current BATS considers 22 land use categories including urban and suburban environments and 12 soil color and texture types which were derived from the Global Land Cover Characterization (GLCC) dataset (Loveland et al. 2000). The GLCC is available on a horizontal grid spacing of 50 km (~0.45°) and is based on 1 year (from April 1992 to March 1993) of Advanced Very High Resolution Radiometer (AVHRR) land cover data. The land cover types used in the BATS are listed in Table 1, while Table 2 summarized the main BATS characteristics which are discussed in details in Elguindi et al. (2014).

2.2 Experimental design

Of particular interest in this paper is to assess the possible impact of the reforestation location on West African summer monsoon climate. In order to examine the effects of vegetation

Table 1 Land cover types adapted from Dickinson et al. (1993) and Elguindi et al. (2014)

1.	Crop/mixed farming
2.	Short grass
3.	Evergreen needle leaf tree
4.	Deciduous needle leaf tree
5.	Deciduous broadleaf tree
6.	Evergreen broadleaf tree
7.	Tall grass
8.	Desert
9.	Tundra
10.	Irrigated crop
11.	Semi-desert
12	Ice cap/glacier
13.	Bog or marsh
14.	Inland water
15.	Ocean
16.	Evergreen shrub
17.	Deciduous shrub
18.	Mixed woodland
19.	Forest/field mosaic
20.	Water and land mixture
21.	Urban
22.	Suburban

cover changes (reforestation) on the West African summer climate, three sets of experiments were done. Simulations covering 12 continuous years each, spanning from 01st January 2000 through 31st December 2011 were performed with a horizontal resolution of 50 km and 18 vertical layers (from surface to 50 hPa) over the West African domain, which extends from 35° E to 35° W and 20° S to 35° N (Fig. 1a). From 2005, a growing idea of building a great green wall belt from Senegal to Djibouti had emerged within the African political class, decision-makers and associated partners such as New Partnership of Africa Development (NEPAD), to tackle the ongoing desertification process over the Sahel-Sahara region, in West Africa. In the purpose to better understand how such kind of project could impact climatic parameters such as rainfall and 2m-temperature, we performed an idealistic numerical simulation over the given period of 2000–2011. The first year (2000) was considered as a spin-up of the land surface fields and excluded from the analysis. The chosen domain is large enough to represent the main WAM features and allow for interactions between the WAM and extra-tropical systems as well as to reduce initial and lateral boundary conditions (LBCs) problems (Diasso and Abiodun 2017; N'Datchoh et al. 2018). Note that the meteorological initial and 6-hourly LBCs necessary to force RegCM4 were taken for all experiments from the 1.5° × 1.5° longitude/ latitude ERA-Interim gridded reanalysis (Dee et al. 2011), corresponding to the third generation of European Centre for

Table 2 Summary of the major BATS characteristics

Grid	2 grid including sub-grid, but sub-grid is not used in this study
Model layers	Single snow layer
	Soil layers: 3 groups of soil and snow layers used for temperature and soil moisture calculations
	Single vegetation layers
	Single runoff layer
Surface type	22 surface categories based on GLCC[a]
	8 soil colors and 12 soil textures types
Canopy	All vegetation receives the same amount of radiation
Soil	Two-layer force-restore model
Roughness	Heat and water vapor roughness lengths are constant

[a] The Global Land Cover Characterization (GLCC) dataset (Loveland et al. 2000)

Medium Range Weather Forecasts (ECMWF) reanalysis product. The prescribed SST was derived from the National Oceanic and Atmospheric Administration Optimum Interpolation weekly $1° \times 1°$ longitude/latitude grid datasets described by Reynolds et al. (2002).

In the first experiment (hereafter referred to as CTRL), the land surface conditions were set to the standard vegetation parameter provided by BATS (Fig. 1a). Figure 1a shows the standard vegetation cover over the study domain, characterized by diverse vegetation types (e.g., forest, fields, tall grass, desert). The two remaining experiments are sensitivity experiments in which the CTRL vegetation cover was modified from west to east of the study domain. In this case, reforestation is based on restoring areas of forest or woodlands. In the first sensitivity experiment, denominated as experiment GB15N, the vegetation between 13° N and 17° N which is a combination of grassland, semi-desert, and desert to evergreen broadleaf trees was modified and replaced by forest (Fig. 1b).

In the second sensitivity experiment (hereafter referred to as GB10N), the vegetation covering between 8.5° N and 11.5°N was replaced by evergreen broadleaf (Fig. 1c) with everything else remaining the same.

The reliability of climate experiments results is mainly based on the skill of the climate models in reproducing the observed mean climate. To assess the model performance, precipitation from the CTRL experiment is compared against the monthly observation at $2.5° \times 2.5°$ horizontal grid spacing from the Global Precipitation Climatology Project (GPCP Version 2.2; Adler et al. 2003; available from 1979 to present) in which rain gauge observations are merged with several satellite-based observations. For comparison purpose, GPCP data were interpolated onto the RegCM4 grid through a bilinear interpolation method. Our sensitivity analysis focus mainly on the June-July-August-September (JJAS) seasons, which correspond to the main West African summer monsoon season.
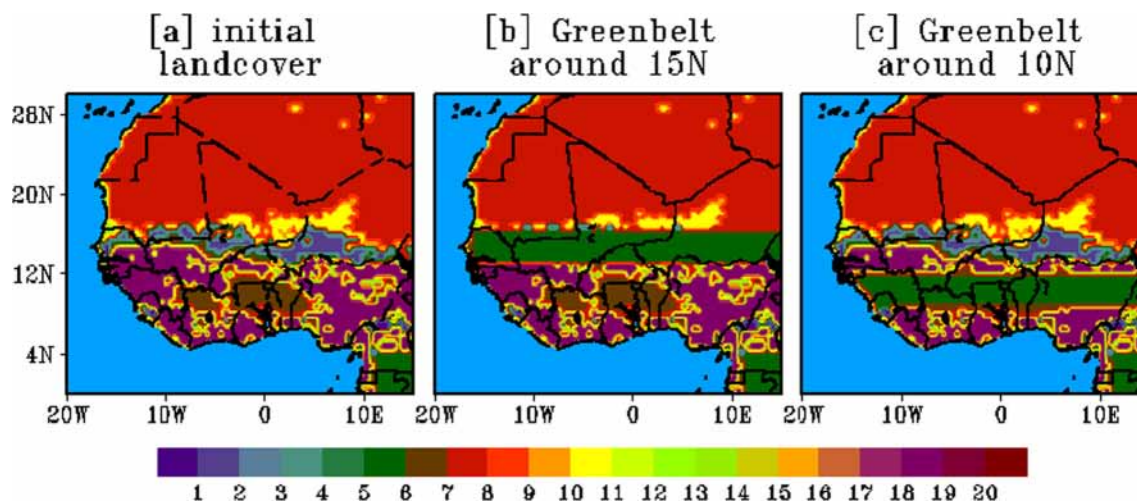

Fig. 1 Distribution of land cover types used in this study for **a** the standard version of the RegCM4 model (hereafter referred to as CTRL), **b** greenbelt reforestation centered around 15° N (hereafter referred to as GB15N), and **c** greenbelt reforestation centered around 10° N (hereafter referred to as GB10N). The green rectangles indicate the reforested zone

3 Results and discussions

3.1 Model evaluation

Figure 2 shows the comparison of simulated rainfall by the RegCM4 with GPCP observations during the boreal winter (December-January-February, DJF; Fig. 2a–c) and summer (June-July-August-September, JJAS; Fig. 2d, e) over West Africa, averaged for the 2001–2011 period. The DJF climatology of GPCP precipitation (Fig. 2a) reveals that during the boreal winter season (DJF) corresponding to the dry season over West Africa, dry conditions are located north of 6° N while the areas of most intense rainfall are confined to the coastal fringes (i.e., the lower latitude, below 5° N). For instance, in regions located south of 5° N rainfall can reach up to 4–6 mm/day over the Atlantic Ocean, while over land it does not exceed 2 mm/day. The RegCM4 CTRL experiment reproduced the major features of the observed DJF rainfall, although there are some wet biases over the Gulf of Guinea (Fig. 2b, c). During the JJAS season, corresponding to the

WAM season, the rainfall intensity decreased southward and northward of the high rainfall band referred as inter-tropical convergence zone (ITCZ) and located between 5° N and 12° N. Furthermore, in Fig. 2d, the rainfall maximum areas are located along the rain belt over complex orographic regions such as the Cameroon Mountain, the Jos Plateau (central of Nigeria), and the Fouta Djallon Highlands (west and central of Guinea). These patterns are well captured by the RegCM4 compared to observations (Fig. 2e). Similarly, the general dryness northwards of 18° N is also faithfully simulated. Nevertheless, the RegCM4 shows dry biases of 1–2 mm/day over Senegal and the Guinean Gulf. There are also wet biases of 2–4 mm/day over central Nigeria (around Jos Plateau) and toward northern parts of Cote d'Ivoire (Fig. 2f). It is worth mentioning that, those biases (dry and wet) are not statistically significant at a significance level of 0.1.

Overall, the RegCM4 CTRL is able to reproduce reasonably the observed boreal and summer precipitation pattern over West Africa, despite some dry and wet biases. It is clear that the performance of the RegCM4 appears in line with

Fig. 2 Mean December-January-February (DJF; **a**, **b**) and June-July-August-September (JJAS; **d**, **e**) precipitation climatology (units: mm/day) from GPCP and RegCM4 CTRL along with the corresponding biases (**c**, **f**) with respect to the observation GPCP for the period 2001–2011
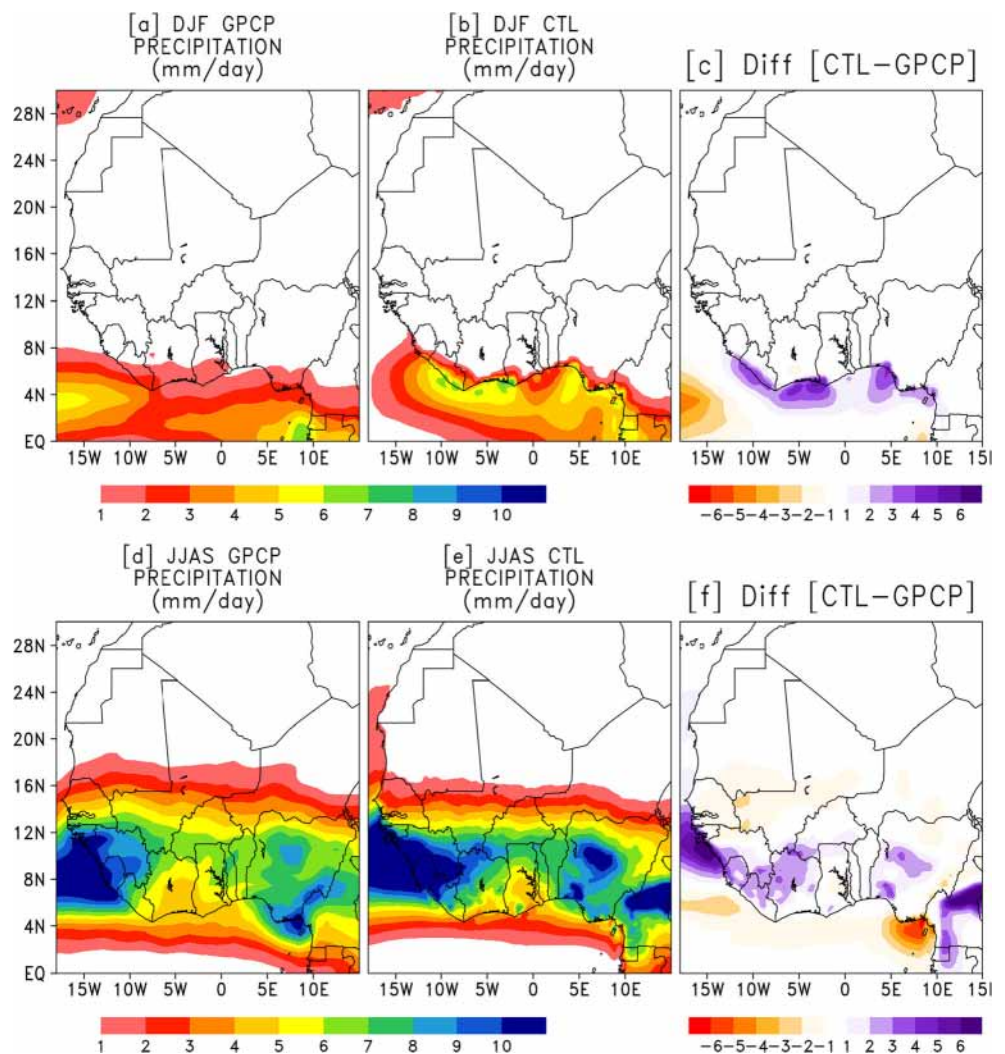
previous work on West Africa using either the RegCM4 with different configurations (Sylla et al. 2015; Saini et al. 2015; Adeniyi 2017; Diallo et al. 2016; Kebe et al. 2016; N'Datchoh et al. 2018) or other regional climate models (Diallo et al. 2012, 2013, 2014; Sylla et al. 2013; Hagos et al. 2014; Gbobaniyi et al. 2014; Druyan and Fulakeza 2016; Klutse et al. 2016). In addition, the RegCM4 simulates accurately the magnitudes/locations of the main WAM circulation features associated with the summer precipitation (not shown). The reasonable performance of the RegCM4 CTRL experiment shows that our settings/configurations are suitable for the investigation of the potential impacts of reforestation location on the regional climate.

3.2 Green belt position effects on 2m-temperature and precipitation

The reforestation effect on the surrounding regional climate is isolated by comparing the difference between GB15N/ GB10N and the CTRL experiments. Since the CTRL and the two sensitivity experiments (GB15N and GB10N) are

identical except for the vegetation cover, then significant differences between the sensitive experiments and CTRL (e.g., GB15N minus CTRL or GB10N minus CTRL) could be attributed to the sensitivity of regional climate responses to a potential reforestation. Figure 3 displays the JJAS difference in mean surface (2m-) temperature between GB15N and CTRL (Fig. 3a) as well as GB10N and CTRL (Fig. 3b). The GB15N induces significant temperature decreases over the Sudan-Sahel region (between 8° N and 18° N; i.e., reforested area). However, there is a slight warming over southward of both Cote d'Ivoire and Ghana (Fig. 3a). In contrast, the GB10N experiment induces a slight cooling over most of Guinean sub-region particularly from Guinea to central Nigeria (Fig. 3b), corresponding to the reforested area. It can be seen that most of these temperature changes are statistically significant; however, the magnitude of cooling is more important in the GB15N compared to the GB10N experiment. This difference highlights the sensitivity of regional temperature responses to the reforestation location. Differences between GB10N and GB15N on local effects may be explained by the fact that the vegetation around 10° N is dominated by humid/wooden savannah including forest, while around 15° N the vegetation is semi-arid grassland. An increase in vegetation cover through the reforestation could cause a decrease
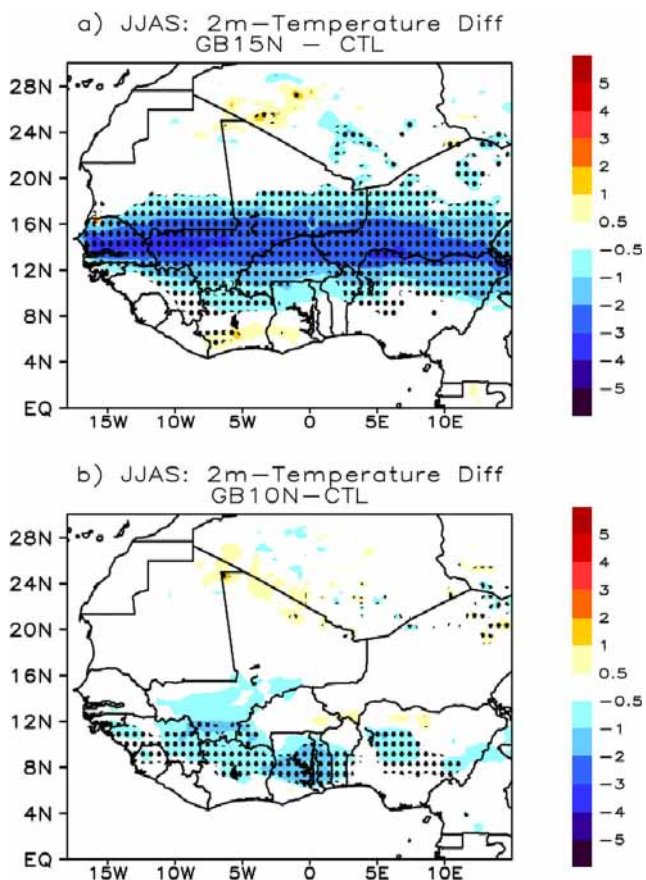

Fig. 3 a, b Mean June-July-August-September (JJAS) 2m-temperature differences (Units: °C) between GB15N and CTRL (GB15N minus CTRL; top panel) and between GB10N and CTRL (GB10N minus CTRL; bottom panel) for the period 2001-2011. The dotted areas denote differences which are statistically significant at a significance level of 0.1
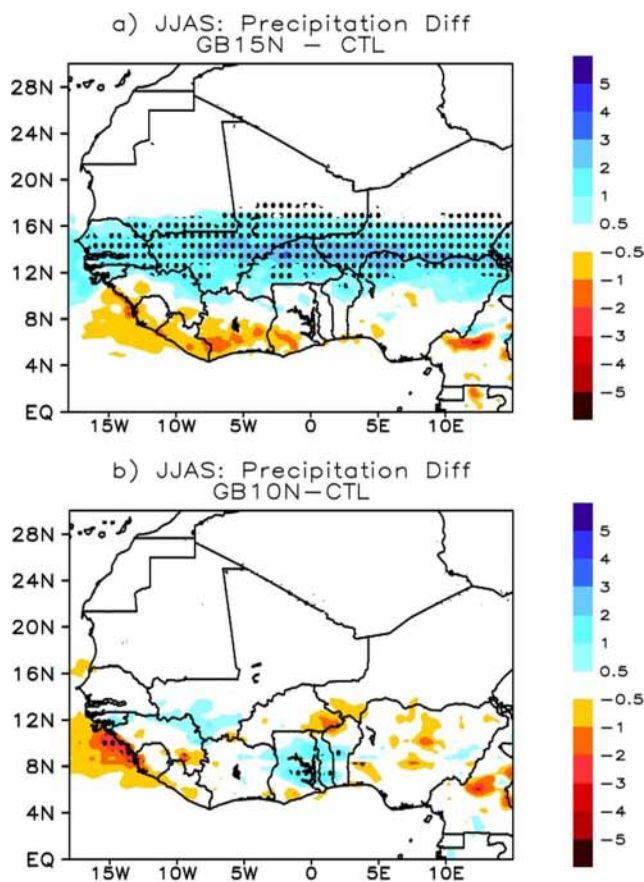

Fig. 4 a, b Same as Fig. 3 but for precipitation. Units: mm/day

of surface albedo in the region especially during the rainy season, leading to decrease in ground heat flux (not shown). This could potentially lead to a cooling effect on the surface and the atmosphere. In fact, the albedo controls the total enthalpy flux exchange with the atmosphere and is therefore linked to moist convection. The leaf area index (LAI) modulates the Bowen ratio (defined as the ratio of sensible to latent heat flux) for regions where the vegetation coverage is significant (Boone et al. 2016). Therefore, changes in albedo will induce changes in surface latent heat flux, which in turn will affect the rainfall pattern. These changes may be largely attributed to land-atmosphere feedbacks.

The precipitation response over West Africa to both the GB15N and GB10N reforestations experiments is shown in Fig. 4. The GB15N reforestation (Fig. 4a) reveals a precipitation increase ranging between 1 to 3 mm/day in the summer rainfall band, where the reforestation was made. On the other hand, rainfall decreases occur south of 8° N (over both the land and the Atlantic Ocean). In the GB10N experiment (Fig. 4b), the rainfall slightly increases over Ghana, Togo, Benin, and the border between Mali and Guinea. It is worth noting that in both experiments the precipitation increases and temperature decreases coincide in space and mostly

correspond to reforested areas. This hence suggests that the reforestation could be used to mitigate against droughts or severe heat waves over West African, particularly the Sahelian countries. The reforestation causes an increase of evaporation and moisture convergence, which in turn potentially leads to the precipitation increases over reforested areas. In summary, our analyses are in agreement with the earlier studies by Abiodun et al. (2012) as well as Diasso and Abiodun (2017). Consistent with these studies, we show here that reforestation may reduce the warming over reforested areas and weaken rainfall over remote areas, particularly toward south (west) for GB15N (GB10N). Our results further emphasize the importance of land vegetation to the characterization of the WAM rainfall.

Figures 5 and 6 illustrate the JJAS inter-annual precipitation difference from 2001 to 2011 of the GB15N and GB10N experiments from the CTRL, respectively. In general for all JJAS, the GB15N reforestation shows a dipole with precipitation increases north of 10°N and decreases to the south. An increase of about 2–8 mm/day is seen along the main WAM rainfall band located between 8.5° N–15° N and 15° W–15° E corresponding partially to the reforested area. While rainfall decreases of 1–4 mm/day is seen over the Guinean Highlands
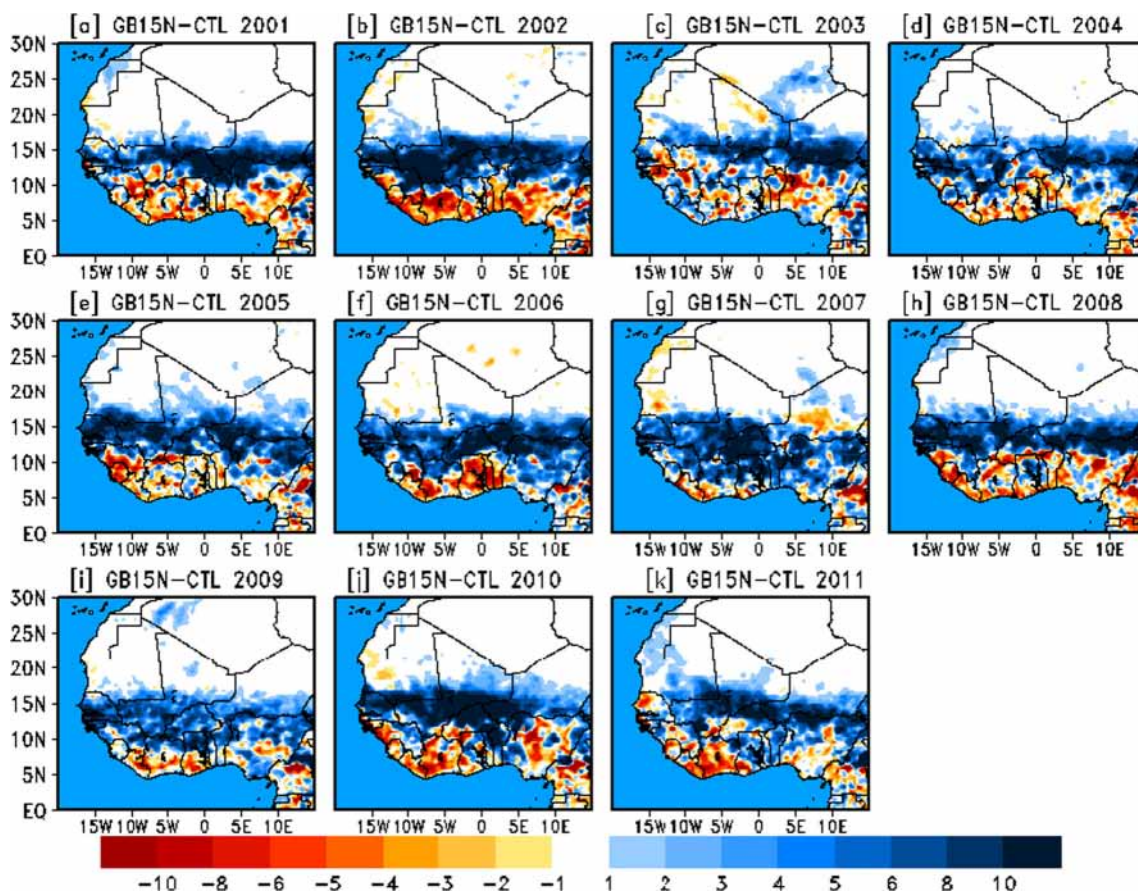

Fig. 5 Mean June-July-August-September (JJAS) precipitation (**a**–**k**; units: mm/day) differences between GB15N and CTRL (GB15N minus CTRL) for each year of the study period (2001–2011).

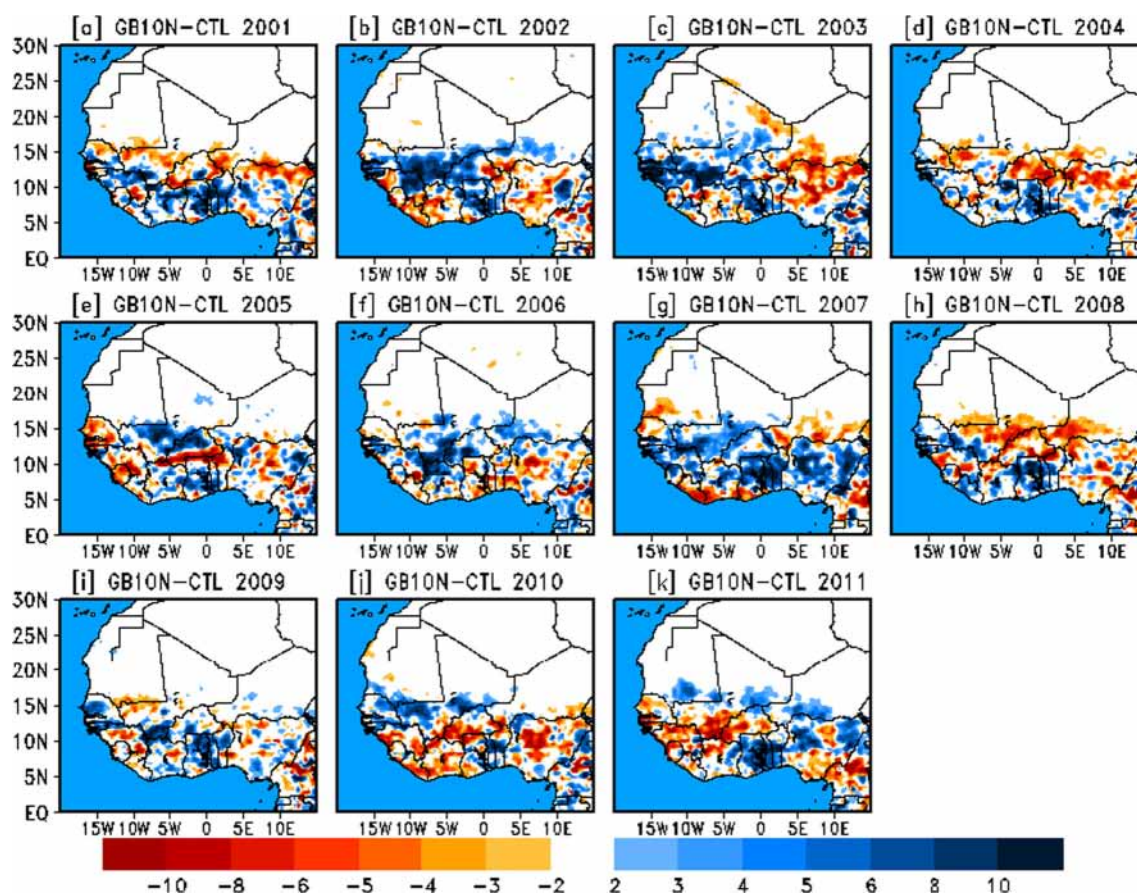**Fig. 6** **a–k** Same as Fig. 5 but for the difference between GB10N and CTRL (GB10N minus CTRL)

and toward south of 6° N. This implies that the rainfall increases over the reforested area could arise from an increase in moisture content associated with a strengthening of low-level convergence. Conversely, the GB10N show more pronounced and widespread precipitation decreases through the ocean and over the complex terrains as well as over the Guinean region. However, wetter conditions of different magnitudes are not found only over the reforested area (e.g., Fig. 6g–i, k) but also over Sahel-Sahara regions (Fig. 6).

Overall, there are strong inter-annual spatial variations of the precipitation caused by both GB15N and GB10N reforestation experiments. The GB15N experiment induces a positive precipitation change over the Sahel and reforested area while GB10N exhibits a mixed (both increases and decreases) over the reforested area. For instance, the GB10N shows wetter conditions over Cote d'Ivoire in 2009, while in 2010 drier conditions emerge over both Cote d'Ivoire and neighboring countries (Ghana, Togo, Benin, among others). Such inter-annual variability suggests a non-specific effect of the reforestation around 10° N (GB10N) on the precipitation in the reforested region. The vegetation around 10° N is dominated by humid/wooded savannah including forest. This could explain why the GB10N reforestation does not have a constant effect on precipitation, as found with GB15N, where the

reforestation has induced persistent wetter conditions over reforested areas throughout the 11 different JJAS season of the study period.

Reforestation effects are also manifested in the annual evolution of temperature and precipitation. Figure 7 displays the intra-seasonal evolution of the zonally averaged (10° W–10° E) monthly differences in 2m-temperature and precipitation between GB15N (GB10N) experiments and the CTRL. It shows that temperature decreases over the Sahel (north of 10° N) from February to October with a maximum decreasing during the monsoon onset period from end of May to July (Fig. 7a). However, a temperature increase occurs from June to August over the Guinean regions. Also, months with strongest cooling are associated with the largest increases of precipitation (Fig. 7c), indicating an enhancement of the Sahel wetter conditions in GB15N reforestation. Overall, the GB15N shows a similar spatio-temporal distribution for precipitation changes with months of wetter (drier) conditions coinciding with months of maximum cooling (warming) surface temperature. The GB10N reforestation induces mainly temperature decreases over the reforested area (Guinean region) from February to November, albeit there are slight temperature decreases over Sahel from May to August (Fig. 7b). Conversely, the intra-seasonal variability of precipitation
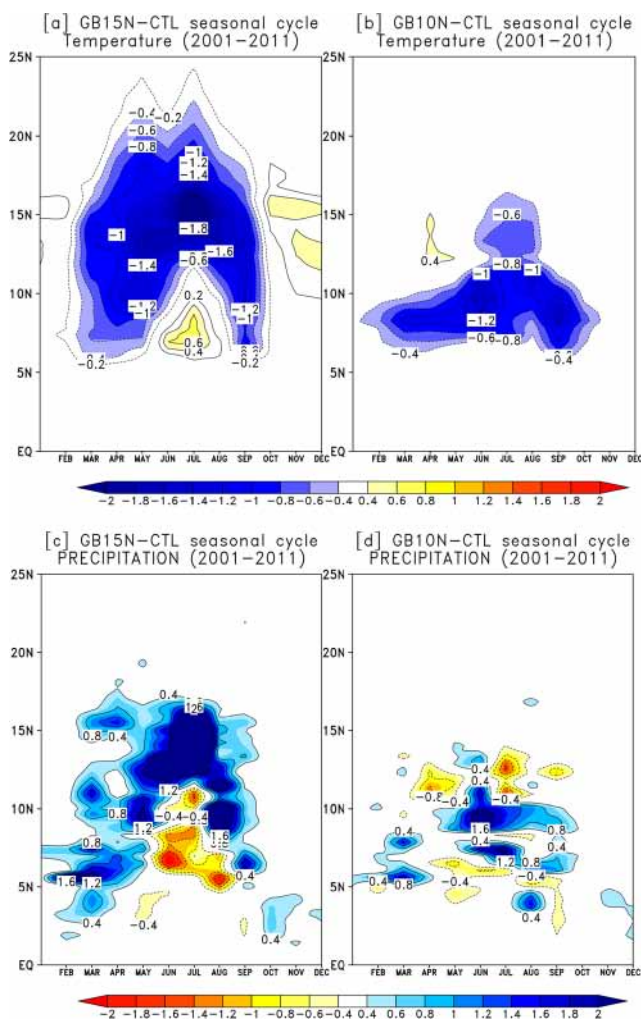
Fig. 7 Temporal evolution of monthly mean difference between GB15N and CTRL (GB15N minus CTRL; **a**, **c**) and also between GB10N and CTRL (GB10N minus CTRL; **b**, **d**) averaged over l0 W–l0 E for the period 2001–2011 from: 2m-temperature (top panels; **a**, **b**; units: °C) and precipitation (bottom panels; **c**, **d**; units: mm/day)

changes resulting from the GB10N reforestation is quite complex. Figure 7d shows a widespread precipitation increases/decreases over the reforested areas and the Sahel. There are increases of 0.6–1.5 mm/day over reforested areas from July to September and decreases of 0.4–0.8 mm/day from April to May.

Figure 8 further illustrates the precipitation annual cycle over the Guinea Coast (10° W–10° E, 4° N–12° N) and the Sahel (10° W–10° E, 12° N–20° N) by showing the area-averaged precipitation for CTRL, GPCP, GB15N, and GB10N (Fig. 8a, b) along with their differences (GB15N minus CTRL, GB10N minus CTRL; Fig. 8c, d). The area averages of the differences over Sahel, Guinea Coast, and the whole West Africa for both precipitation and surface temperature are summarized in Table 3. The mean annual cycle of precipitation over both Sahel and Guinea Coast including the

timing [single (double) peak(s) over Sahel (Guinea Coast)] and magnitudes are quite well reproduced, although some dry/wet biases are evident. Figure 8c, d shows that due to the GB15N reforestation, the average precipitation increases from March to November over the Sahel with a peak occurring in August. Over the Guinea Coast, the GB15N reforestation induces a precipitation increases throughout almost the whole year, except from July to September. Table 3 shows that the GB15N produced during summer (JJAS) about 1.03 and 0.55 mm/day rainfall increases over Sahel and the whole West Africa, respectively. The largest precipitation increases over the Sahel does occurs in May and August indicating an extent of the length of the Sahel rainy season. However, the GB10N reforestation does almost not induce precipitation changes during the whole year over the Sahel, while over Guinea Coast, the GB10N reforestation leads to a precipitation enhancement from October to June, suggesting that the GB10N reforestation could likely enhance wetter conditions over the Guinea Coast.

In summary, the results show that the reforestation impacts on precipitation and temperature are diverse. The GB10N reforestation has opposite effects over the Sahel and Guinea Coast. On the one hand, it enhances drought frequency by reducing precipitation over Sahel. On the other hand, by weakening down the monsoon flow, the GB10N reforestation enhances wet conditions over the Guinea Coast. Since the GB10N and GB15N reforestation have different effects on the Sahel surface climate, our results suggest that decision-makers should be cautious of selected reforested areas for the implementation of the green wall initiative. Future reforestation project requires careful and significant consideration of its practicability and potential regional impacts on the West African countries climate.

3.3 The impact of green belt position on circulation

In order to understand the dynamical processes underlying the precipitation change caused by the green belt position, we analyze the moisture flux distribution along the ITCZ position as well as zonal averaged vertical velocity and temperature. Figure 9a, b shows the changes in 925 hPa wind direction (vectors) superimposed to relative humidity (shaded) and the convection zone (contours). The contour line is showing the low pressure belt where many convergence processes take place. This could correspond to the ITCZ's mean position during JJAS (Sultan and Janicot 2000). However, its northernmost position is reached around 20° N in July–August (Nicholson and Grist 2003). In both experiments, the maximum increase of relative humidity is mainly observed over the reforested areas. The reforestation increases the relative humidity, thus, causes an increase of evaporation rate. In the GB15N experiment, relative humidity maxima exceed 10% over the Sahel band between 12° N and 18° N, while lower

Fig. 8 Domain averaged
precipitation evolution over Sahel
(**a**, **c**) and Guinea Coast (**b**, **d**) for
a, **b** GPCP (Observed), CTRL,
GB15N, and GB10N and **c**, **d**
their differences (GB15N minus
CTRL and GB10N minus CTRL)
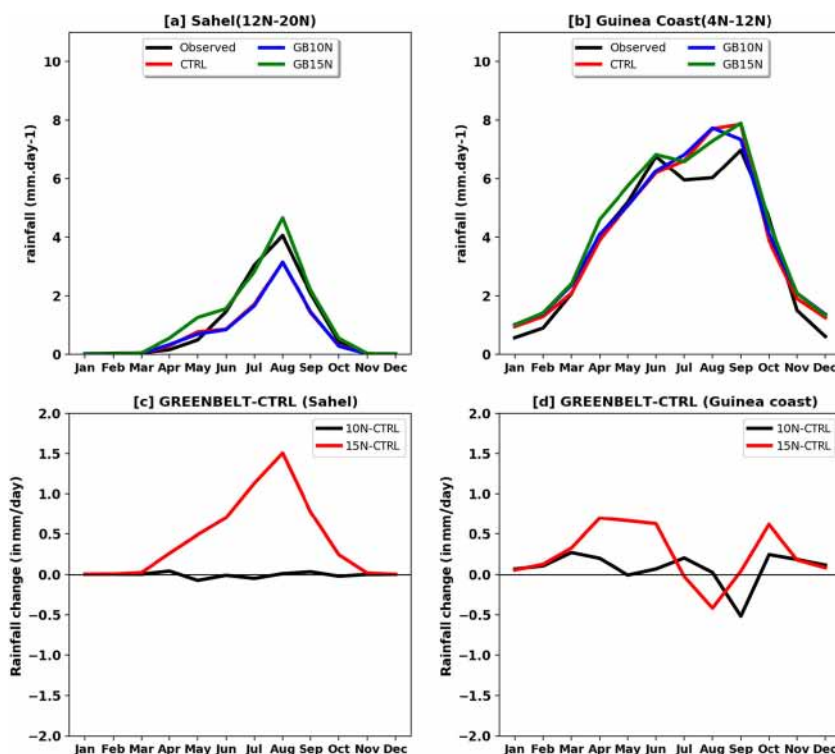
surface pressure leads to stronger low-level southwesterly wind convergence around 15° N (Fig. 9a). In addition, the increase of both evaporation rate and relative humidity weight this impact of convergence change, which combined together, causes the wetter conditions over the whole Sahel band. In opposition to GB15N, for the GB10N, we note an increase of relative humidity over both, the Gulf of Guinea and the reforested area, however the poor/weak low-level wind convergence outweighs this impact of humidity change, which combined causes a precipitation reduction over the Gulf of Guinea countries. Thus, in GB10N, there was not enough/ sufficient moisture convergence over the savannah area to enhance precipitation in this West African sub-region.

To further investigate the circulation changes, which led to changes in rainfall caused by reforestation, Fig. 10a, b shows the latitude-height JJAS wind velocity (shaded) and temperature (contours) changes from GB15N and GB10N, respectively. We recall that, in Fig. 10, negative velocity represents

upward, while positive velocity represents downward. The changes of vegetation will impact the upward and downward of air column in the troposphere. In GB15N, shallow cooling and deep warming between 750 and 550 hPa, both centered about 15° N lead to a large scale of upward motion from 925 to 550 hPa and enhancing of uplifting over Sahel (Fig. 10a). According to Diedhiou et al. (1999), such conditions are favorable to the development of squall lines, which in turn could cause the mid-troposphere convection found over Sahel (Fig. 10a). Consequently, the more unstable vertical temperature structure, the enhancement of uplifting, and water supplies result to the enhancement of precipitation over Sahel, in particular the whole reforested area. The GB10N shows a latitude-height structure closer to that of GB15N; however, the lack of moisture and water supply, discussed earlier (see Fig. 9b), outweighs the upward motion impact, resulting to a lower change (increase and decrease) of precipitation over the reforested area.

Table 3 Mean June-July-August-September (JJAS) simulated precipitation (unit: mm/day) and surface temperature (unit: °C) changes induced by different reforestation scenarios over Sahel, Guinea Coast, and whole West Africa

	Precipitation (unit: mm/day)		Surface temperature (unit: °C)	
	GB15N - CTRL	GB10N - CTRL	GB15N - CTRL	GB10N - CTRL
Sahel	1.03	− 0.01	− 1.36	− 0.19
Guinea Coast	0.06	− 0.05	− 0.27	− 047
West Africa	0.55	− 0.02	− 0.82	− 0.33

Fig. 9 Mean June-July-August-September (JJAS) differences in relative humidity (shaded; units: %) at 925 hPa and wind direction (vectors, units: m/s) between **a** GB15N and CTRL (GB15N minus CTRL) and **b** GB10N and CTRL (GB10N minus CTRL); zero isoline of the meridional wind at 925 hPa (red contour line)
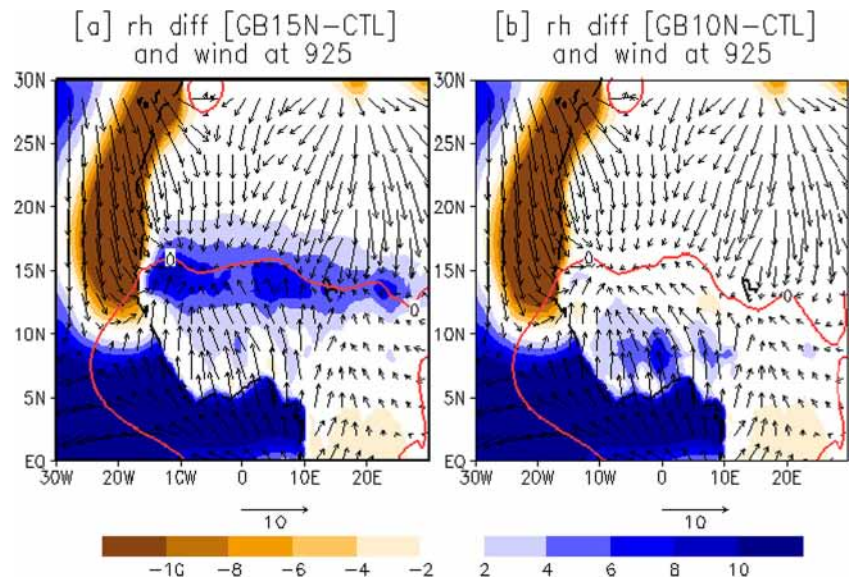
4 Summary and conclusion

The land surface is known as an important part of the climate system. Changes in surface energy budgets resulting from land cover change can have a profound influence on regional and local climates. In this study, we present a validation of mean climatology and annual cycle of rainfall from the latest version of the Abdus Salam International Centre Theoretical Physics regional climate model, namely RegCM4. Particularly, in order to investigate the potential impact of the greenbelt (reforestation) location on West

African summer monsoon climate, we performed three experiments (CTRL, GB15N, and GB10N) without and with reforestation at 50 km horizontal grid spacing and spanning over the period 2000–2011. In the first experiment referred to as CTRL, the standard vegetation of the BATS land surface is used; however, for the remaining two experiments (sensitivity experiments), vegetation covers have been modified and replaced by a reforested zonal band from east to west and placed either between 13° N and 17° N (referred to as GB15N) or 8.5° N and 11.5° N (referred to as GB10N), while all other settings remaining the same. The rainfall

Fig. 10 Latitude-height cross section averaged over 10°W-10°E of mean June-July-August-September (JJAS) temperature (contours, units: °C) and omega (shaded; units: Pa/s) from **a** difference between GB15N and CTRL (GB15N minus CTRL) and **b** difference between GB10N and CTRL (GB15N minus CTRL). Blue color indicates upward motion, whereas red color displays downward motion
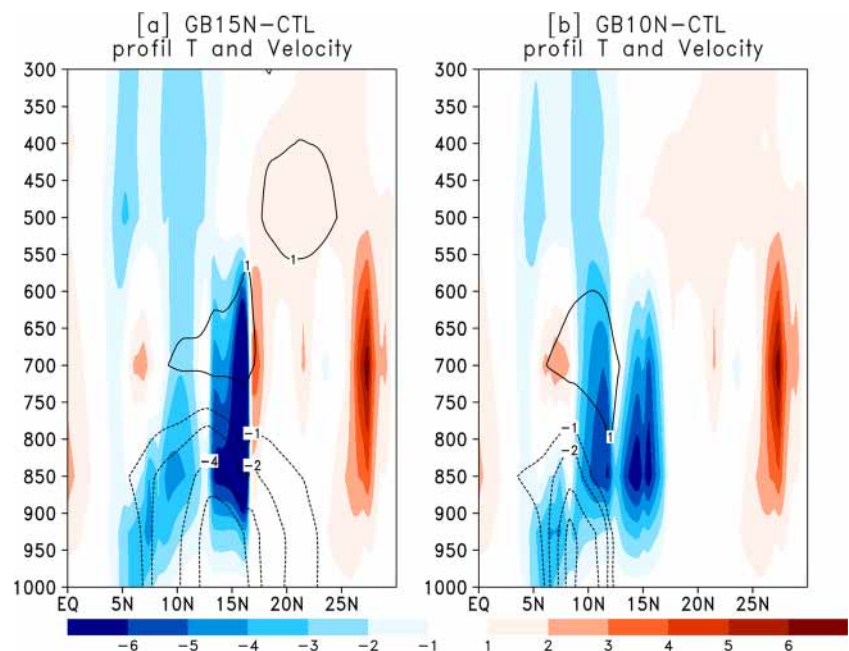
from the CTRL experiment was compared against GPCP. Overall, though some dry/wet biases, the RegCM4 CTRL reproduces faithfully the seasonal climatology as well as the month-to-month evolution over both Sahel and Guinea Coast sub-regions.

The sensitivity experiments results show that the location of the reforestation has a significant impact on the WAM summer climate. Depending on the position of the green belt, the main temperature cooling is observed over the reforested area, which probably results from a decrease of ground heat flux caused by a reduction of albedo. For instance, in the GB15N an extended temperature cooling reaching 4 °C is found over the Sudanese-Sahel region mainly between 8° N and 18° N. Significant difference has been observed in the spatial distribution of the rainfall over the region. Thus, neither GB15N nor GB10N has caused significant change in rainfall over Guinea Coast. The impact of GB15N on rainfall is positive in the Sahel and negative over Guinea Coast. On the dynamical processes of GB15N experiment, the relative humidity has increased about 10% over Sahel band between 12° N and 18° N with a centripetal movement of the wind converging toward latitude 15° N. Further, it has increased the evapotranspiration upward flux, therefore the relative humidity.

Overall this study suggests a careful choice of efficient location of the greenbelt for tackling environmental impacts of land degradation and desertification in West Africa, particularly the Sahel region. However, since the results are based on a single regional climate model, more research with large ensemble members, different regional climate models, and different land surface models are necessary to further explore the potential impact of reforestation location on WAM summer climate.

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