The possible role of the Sahel Greenbelt on the occurrence of climate extremes over the West African Sahel

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Funding information
African Development Bank (AfDB), Grant/Award Number: Institutional Support to African Climate Institute; African Union Research Grants financed through the Financing Agreement between the European Union Commission and the African Union Commission (DCI-PANAF/2015/307-078), Grant/Award Number: AURG II-1-074-2016; German Federal Ministry of Education and Research (BMBF), Grant/Award Number: West African Science Center for Climate Change; Institut de la Recherche pour le Développement (IRD), Grant/Award Number: APTE-21/FSP-AGRICORA

Abstract
The “Great Green Wall” of trees (GGW) is an emblematic Pan-African initiative of re-greening the Sahel through afforestation and assisted natural regeneration of trees in order to tackle desertification, soil degradation and to mitigate greenhouse gases. This study investigates (i.e., The Sahel Greenbelt) the potential impacts of the GGW and other assisted natural regeneration of trees on the frequency and intensity of extreme climate events over the Sahel and West Africa using the regional climate model (RegCM version 4.3). Our investigation shows that the Sahel greenbelt would increase significantly the number of rainy days (+9%) and the intensity of heavy rain events over the Sahel while extreme dry spells decrease (−4%). Important shifts appear in the modes of variability of all precipitation indices. These probability distribution shapes reveal tremendous intra-seasonal variability as the new land use land cover (LULC) changes affect the regional climate. Changes in atmospheric circulation including increase of the moisture convergence and evapotranspiration appeared to be the main drivers of heavy rainfall changes. For temperature extremes, the maximum temperature shows significant decrease around the GGW area during summer and an increase in other seasons while the diurnal temperature range increases significantly without an evident change in temperature trends. Intra-seasonal distributions of temperature extremes show less obvious changes compared to precipitation extremes. This investigation highlights the role of the planned and implemented re-greening policies (i.e., afforestation by the GGW project and policies of assisted natural regeneration of trees) in affecting the frequency and the amplitude of some climatic extreme events (e.g., heavy rain events, maximum temperatures, etc.). These planned LULC policies need to be accounted for in the diagnostics and future projections of climate extremes over the region.

KEYWORDS
climate extremes, Sahel Greenbelt, RegCM4, Sahel, variability
1 INTRODUCTION

In West Africa, hydro-meteorological hazards are mainly associated with shifting patterns in weather and climate with climate variability being a key challenge to agriculture, public health and other socio-economic development sectors. The combination of dryness, heavy rainfall, heat waves and others climate extremes (Ly et al., 2013; Sanogo et al., 2015; Taylor et al., 2017) means that rain-fed agriculture will become more and more a risky venture and droughts or flooding are likely to be a common feature of life in the future (Mariotti et al., 2014; Fotso-Ngumo et al., 2017; Tall et al., 2017). The impacts of these extreme climate events on humans and the local environment slow down partly the local economic development and increase the vulnerability of natural systems in the West African Sahel. Policymakers require evidence-based information on threats related to climate extremes to support policy-making and econometric forecasting. Therefore, the assessment of climate extreme events is crucial for monitoring and planning climate change policies and resources mobilization in areas of potential crisis.

Observations have shown that the climate in many locations of West Africa is changing and arguments of a small rainfall recovery have also emerged (Maidment et al., 2015; Panthou et al., 2018) alongside temperatures increase. The most recent rainfall features include increased frequency and intensity of daily rainfall (Taylor et al., 2017; Salack et al., 2018), false starts and early cessations of rainy seasons, a decreasing diurnal temperature range, an increasing number of hot nights and warm days (Salack et al., 2015). As these mixed wet/dry features found in the regional climate are attributable to and may likely be enhanced by global warming (Salack et al., 2016), the question concerning the factors which better explain these changes is still under debates in the scientific community. Some research results suggested that the overall recovery is more explained by the direct increase in atmospheric greenhouse gases and other aerosols (Dong and Sutton, 2015), others believe that the warming of the oceans, in the form of increasing sea surface temperatures (SSTs; Giannini and Kaplan, 2018), and the internal variability of upper wind patterns of the regional atmosphere (Salack et al., 2016) mediate the effect of atmospheric aerosols.

As the rate of atmospheric greenhouse gases increases, reforestation activities are mostly suggested to by African countries as the best affordable measures to contribute to the global mitigation efforts. The reforestation/afforestation options are very often presented as large-scale implementation activities of planting trees and forest management policies in the form of assisted natural regeneration of trees. These land use land cover (LULC) policies are part of the human induced changes that affect land–atmosphere feedbacks. They tend to alter surface properties relevant for the climate equilibrium, to sequester carbon in trees biomass and are suitable for generating favorable atmospheric circulation patterns for enhanced precipitation and evapotranspiration favorable to the regional climate (Xue and Shukla, 1996).

The recently observed increase in rainfall was also associated with vegetation re-greening over some areas of West Africa and other locations of the continent (Hoscilo et al., 2014). Some finds by Taylor et al. (2017), based on satellite observations, suggest a rapid regional intensification of Meso-scale Convective Systems (MCSs) whose potential drivers may include mineral aerosol concentrations and vegetation cover. Further investigations, using model-based simulations, often indicate that reforestation/afforestation may increase the average rainfall and decrease mean temperature during summer season (Abiodun et al., 2012; Hagos et al., 2014; Bamba et al., 2018), along with increasing (decreasing) the number of heatwave events over the reforested area (Sahel and Guinea coast) or causing a decrease (increase) of droughts occurrence over the Savanna and Guinea coast (Sahel) especially from July to September (Diasso and Abiodun, 2017; Odoulami et al., 2017).

However, many re-greening policies at the regional scale can also affect the occurrence, distribution and variability of the regional weather and climate, depending mostly on the location of the LULC changes. A reforestation hypothesis applied over 15°–20°N subregion showed a substantial increase in rainy days during summer season over the whole of West Africa for the 2003–2009 period, with a maximum increase zone found between 6°N and 17.5°N (Diba et al., 2016). However, observed rainfall data analysis, over 1983–2010, reveals that the majority of locations in the Sahel shows a statistically significant increase in total rainy days and the Guinea Coast exhibits weak and non-significant trends except for heavy rain events (Maidment et al., 2015). This mismatch of observations and model-based simulations can be linked to model physics discrepancy, the location of the hypothetical LULC change areas considered and/or the uncertainties in the forcing data.

In this study, the land cover change is based on practical land management policies in the form of the Great Green Wall (GGW) as it is implemented across the Sahel from the Western coast of Senegal to eastern coast of Ethiopia (Dia and Duponnois, 2010; Pan-African Agency of the Great Green Wall-PAGGW, 2016). The objective of this paper is to assess the dominant features of the regional climate that may be induced by an established Sahel Greenbelt in the form of the GGW afforestation scenario and other assisted natural regeneration of trees with the particular focus on changes in trend, variability and seasonal distribution of some climatic extremes. The assessment is conducted using the Regional Climate Model (RegCM4.3 as RegCM4 here-with) (Giorgi et al., 2012). The regional climate model, data and experimental design are described in section 2. The
main results are provided in section 3 followed by a discussion and recommendations in section 4.

2 | METHODOLOGY

2.1 | The Sahel Greenbelt scenario

Rainfall has returned slightly relative to the 1980s drought conditions (Lebel and Ali, 2009), with some high variability of extreme events (Ly et al., 2013; Salack et al., 2016; Taylor et al., 2017; Salack et al., 2018). There are indications that farmers' management of land and agroforestry through natural regeneration is also achieving success by ingeniously modifying traditional agroforestry, water and soil-management practices (IFPRI, 2009). These practices have helped rehabilitate thousands of hectares of land with renewed vegetation cover (Ouedraogo et al., 2014) even before large-scale initiatives such as the GGW. The GGW is a Pan-African project initiated by the Head of states and Governments of the Community of Sahel-Saharan countries (CEN-SAD) and supported by the African Union (AU), Food and Agricultural Organization (FAO) and the European Union (EU). The project aims at re-greening the Sahel region by planting trees over at least 15-km wide belt (between 400 and 100 mm isohyets) which stretches from Dakar to Djibouti in order to tackle desertification, soil degradation and to mitigate atmospheric greenhouse gases emissions (Dia and Duponnois, 2010; Pan-African Agency of the Great Green Wall-PAGGW, 2016). It draws from the strong commitment of 11 African countries (Figure 1a) and aims at increasing the vegetation cover, to restore and enhance the potentiality of arid and semi-arid zones for sustainable development, and food security. The operationalization of the GGW project integrates all national policies on sustainable land management and rural development based on successful practices and experiences such as reforestation, agroforestry, assisted natural regeneration and soil restoration/conservation. It includes and consolidates all “re-greening” work-in-progress actions conducted by in the CEN-SAD member States, and supports, organizes and facilitates the incoming of future projects (Pan-African Agency of the Great Green Wall-PAGGW, 2016). Therefore, the GGW footprint goes beyond the theoretical 15-km width defined in the initial project documents of Dia and Duponnois (2010).

Our current assessment is based on the hypothesis that this GGW project and other already existing re-greening policies would change LULC over the Sahel (10°–18°N; 15°W–30°E), and influence the frequency and amplitude of climate extremes.

2.2 | Experimental design

RegCM4 is used to simulate the potential impacts of the GGW over the Sahel and West Africa. It is a hydrostatic, sigma vertical coordinate limited area model developed and maintained by the Abdus Salam International Center for Theoretical Physics (ICTP). The radiative parameterization, including the planetary boundary layer and convection

FIGURE 1  (a) Trace of GGW (adopted from Pan-African Agency of the Great Green Wall-PAGGW, 2016; http://books.openedition.org/irdeditions/2110#illustrations). (b) Land use change. 1. Crop/mixed farming, 2. Short grass, 3. Evergreen needle leaf tree, 4. Deciduous needle leaf tree, 5. Deciduous broad leaf tree, 6. Evergreen broad leaf 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
resolving schemes, are best described by Giorgi et al. (2012). In this experiment, we used the biosphere–atmosphere transfer scheme (BATS), surface package designed to describe the role of vegetation and interactive soil moisture in modifying the surface-atmosphere exchanges of momentum, energy and water vapor (Dickinson et al., 1993). BATS has a vegetation layer, a 10 cm (cm) thick surface soil layer, 1–2 m (m) thick root zone layer, 3 m (m) thick deep soil layer and 12 soils color and texture types (including a snow layer option). It has also 22 soil cover and vegetation types that are based on the global land cover characterization data.

Two experiments were performed over CORDEX-Africa domain (Coordinated Regional Climate Downscaling Experiment) namely a control (REF) and a GGW perturbed scenario over 50 km horizontal resolution, 18 pressure levels with the initial and lateral boundary conditions coming from ERA-Interim reanalysis (6-hourly time steps and 0.75 × 0.75° grid resolution; Dee et al., 2011). Both REF and GGW runs used Grell parametrization scheme for convective precipitation (Grell, 1993). The weekly time step SSTs from Optimum Interpolation Sea Surface Temperature (Reynolds et al., 2007) are prescribed to both REF and GGW scenario and run over 1988–2012 period with 1-year spin up. Using CORDEX-Africa (Giorgi et al., 2009) helps (a) depict the influence of other large scale triggers of the regional atmospheric dynamics such as SSTs of different ocean basins, and the interactions of WAM with extratropical systems, and (b) reduce the problems of the lateral and boundary conditions (Diasso and Abiodun, 2017).

The preliminary model evaluation runs have shown good agreements between RegCM4 and observations (Figures S6–S9, Supporting Information). The GGW scenario is different from the REF run due to changes in vegetation cover prescribed by modifying model parameters such as leaf area index (LAI), vegetation albedo, roughness length, etc. (Table S1). Details on model configurations and model evaluation results are provided in Table S1 and Data S2). Through the land surface scheme BATS, short grass has been replaced by the deciduous needle-leaf trees between 14.08°N and 15.84°N stretching over the entire Sahel (Figure 1b). Other land surface schemes can be used to run the RegCM4 model (Koné et al., 2018). However, when it comes to depicting extreme events, BATS scheme has strong response and feedback with the atmospheric forcing as it also uses a multi-layered soil model (Giorgi et al., 2014). By using BATS scheme, our results are easily comparable to those found by previous studies. To analyze the variability and change of climatic extremes, we used 10 precipitation and temperature related indices as defined by the Expert Team on Climate Change Detection and Monitoring (https://www.wcrp-climate.org/data-etccdi) (detailed descriptions of the indices are provided in Data S1 and Table S2, Supporting Information).

3 | RESULTS

3.1 | Trends of rainfall and temperature extremes

The regional trends and their distribution are summarized in Figure 2a,b for both rainfall and temperature extremes. The GGW scenario run shows a significant increase in the total number of rainy days (RR1) over the West African Sahel with a slight decrease over coastal regions mainly over Ivory Coast and Togo (Figure 2a). Observed rainfall data analysis over 1983–2010 period reveals that the majority of stations in the Sahel shows a statistically significant increase in the total rainy days and the Guinea Coast exhibits weak and non-significant trends except for extreme rainfall events (Maidment et al., 2015; Sanogo et al., 2015). The increase in RR1 over the Sahel may likely increase seasonal rainfall amount since this is determined by the number of rainfall events (Mathon et al., 2002). In fact, afforestation increases the evapotranspiration rates (Figure S1a) and moisture convergence, and with the increase in surface roughness length, they both participate to enhance atmospheric humidity transport and favor the development of deep convection. This argument is backed-up by evidently weak of outgoing longwave radiations (OLR) during June–September depicted in Figure 2a.

The structure of the zonal wind profiles shown a decrease in the African easterly jet (AEJ) and increase in the tropical easterly jet (TEJ) which induce more favorable conditions for an increase in rainfall (Figure S1b). A change in the structure of the jets and an increased evapotranspiration rate are the triggers of the increase in rainy days (RR1) and seasonal rainfall amount (Hagos et al., 2014). A reduction of RR1 over the coastal areas can be partly explained by a decrease in evapotranspiration (Figure S1a), a deep and slowing monsoon flow, a decreasing land-sea temperature gradient and an increasing of drag coefficient (Abiodun et al., 2012). However, these RR1 features are somehow different from the results of Diba et al. (2016) who found an increase of RR1 all over West Africa. This difference comes from the convective precipitation scheme used, the location of the afforested/reforested area and the vegetation types and the simulation period considered in this study.

Comparing changes in RR1 under wet and dry seasons exhibits no change patterns but a slight decrease toward northern subregions of the Sahel (e.g., Burkina Faso, Mali) for the cluster of dry years compared to the cluster of wet years (Figure S2). This shows clearly that re-greening activities can add more rainfall events, can increase rainfall
amounts and subsequently reducing drought severity (i.e., drought intensity and length) over the Sahel. Previously, Xue et al. (2016) have identified the role of land surface processes in responding to and amplifying the 1970–1980 drought over Sahel. They found that up to 40% of precipitation deficit (difference between 1980s and 1950s) was explained by LULC changes. Also, the heterogeneity of the signal is consistent with the work of Diasso and Abiodun (2017) who show that future reforestation may decrease drought events over a reforested Savannah and increase it over the Sahel.

Subsequently to RR1 patterns, there is a significant increase in extreme wet spells (CWD) and a decrease in extreme dry spells (CDD) over the GGW areas and Sahel region (Figure 2a). The amount of rainfall, contributed by heavy rain events (R99P), presents almost the same spatial pattern as RR1 (Figure 2a) and an identical +9.76% rate of change (Table 1). The increasing humidity over GGW areas

FIGURE 2 Changes (GGW-REF) for (a) rainy days RR1 (day), maximum consecutive dry days CDD (day), maximum consecutive wet days CWD (day), extremely wet day rainfall R99P (mm), JJAS outgoing longwave radiation (OLR) and (b) seasonal changes of warm days TXx (°C) and warm nights TNx (°C), diurnal temperature range DTR (°C) over West Africa (hatched areas are significant at 95% (t test)). DJF (December–January–February), MAM (March–April–May), JJA/S (June–July–August/September), SON (September–October–November)
and Sahel region reinforces the atmospheric water content and moisture convergence in the boundary layer that sustains intense precipitation once convection is initiated (Sylla et al., 2015). The intra-seasonal timing and intensity of R99P is provided in Figure S3 and exhibit a significant change of both. The impact of the GGW during wet (dry) seasons is not obvious (Figure S2), but slightly dominant increase zones are exhibited alongside increasing frequency and intensity. The increase in R99P intensity for dry (wet) years is at +2.46% (+6.57%). The maximum one-day rainfall amount shows the same spatial distribution as R99P (Figure 2a), that is, an increase over Sahel region and GGW areas and a decreasing trends elsewhere.

Maximum temperature (Tmax) shows a significant increase during December–January–February (DJF), March–April–May (MAM), September–October–November (SON) seasons over GGW areas and a decrease elsewhere (Figure S4). It also decreases in June–July–August (JJA) season. The changes in maximum temperature coincide with an increase in near-surface sensible heat flux and a lower top-of-atmosphere outgoing longwave radiation (respectively Figures S5 and 2a. Further details on the energy

**FIGURE 2** (Continued)
balance are given in Data S2). On another hand, the change in minimum temperature (Tmin) is weaker than the change in Tmax (Figure S4) from March to November and slightly increases in DJF. The spatial distribution of the changes in Tmin and Tmax affect the diurnal temperature range (DTR) defined as the difference between maximum and minimum temperatures (Figure 2b). There is an important increase (>1°C) of DTR over GGW areas and a slight decrease (<1°C) elsewhere in DJF, MAM and SON seasons. For the summer season (JJA), the change is smaller partly due to increasing rainy days. This warming signal, over the afforested/reforested areas favors the outbreak of heatwave events (Odoulami et al., 2017; Diba et al., 2019). The warm days (TXx) increase significantly over GGW areas and decreases elsewhere in all seasons (Figure 2b). However, warm and cool nights (TNx and TNn, respectively) show the same distribution as minimum temperature (Figure S4). Warm nights of DJF have increased in Central-eastern regions of the Sahel and decreased in other seasons of the year (Figure 2b).

### 3.2 Modes of variability of extreme events

The probability distribution of all rainfall extremes exhibited tremendous changes in shape at different timescales (Figure 3a). The mode of variability of the number of rainy days (RR1) shifts toward a higher number of rainy days corresponding to an average increase of ~10 days (Figure 3a). This change triggers a reduction in the length of the maximum consecutive dry spells (CDD) from high probability values around 100 days to 90–95 consecutive days. In a unimodal rainfall regime like that of the Sahel, CDD is a proxy for onset (cessation) of rainy seasons. Therefore, a shift in CDD denotes a possible earlier onset of season due to increase in the number of rainy days under GGW scenario.

The amplitude of extremely intense rainfall or heavy rain events (R99P) exhibits two modes of variability. In the Sahel, the distribution of heavy rain events is known to exhibit a bimodal shape. Indeed, recent investigations by Salack et al. (2018) identified three categories of heavy rain events of different intensities. The three categories of heavy rains exhibit an intra-seasonal timing that follows the phases of the West African monsoon. Category 1 and 2 are observed in the same period, between weeks 27 and 35 of the year with an accumulated daily amount varying in the 37–65 mm range and less than or equal to 85 mm/day respectively. In category 3, rain rates are greater than 85 mm/day, observed between 28th and 38th week-of-the-year. The proportion of rainfall category 3 is only 8% of the overall heavy rain events and constitutes the tail of the distribution. These two modes of variability in the timing of heavy rain events are well captured by the GGW scenario runs (Figure S3).

Figure 3b shows no significant change in the thresholds of temperature amplitudes defining cool (warm) nights and warm (cool) days. In other words, the presence of the GGW and other re-greening activities would not affect the average heat waves index of the Sahel (West Africa) region, the number may increase though.

### 4 DISCUSSION AND RECOMMENDATIONS

The climate of West Africa (Sahel) is changing and extreme events are becoming more frequent and their amplitudes are increasing (Ly et al., 2013; Sanogo et al., 2015; Taylor et al., 2017; Salack et al., 2018). This study reveals changes in the variability and the trends of some climatic extreme events as a result of LULC changes deriving from the complex dynamic feedbacks between the ground cover and the atmosphere using RegCM4 simulations of a GGW scenario. Under a complete GGW scenario, the increase in rainy days can lengthen the duration of the rainy season, increase the total rainfall amount of the season and amplify the daily rain rates of heavy rain events. These results are very similar to recent observations made from in-situ measurement and
remote sensing (Hoscilo et al., 2014; Panthou et al., 2014; Taylor et al., 2017; Salack et al., 2018). An increase of rainy days with a positive trend over the Sahel can trigger a precocity of the rainy season (e.g., decreasing CDD) sprinkled by extreme wet spells (i.e., increasing CWD) while daily rain rates of heavy rain events (R99P) increase as well.

The annual trends of minimum and maximum temperatures are stationary over the Sahel. However, the seasonal analysis of diurnal temperature range (DTR) shows an increase at all seasons except in JJA where fluctuations in moisture fluxes and radiative heating due to rainy events attenuate daily temperature amplitude. This relationship between DTR, rainy days and rainfall amount makes DTR anomalies useful to detect drought flags in the Sahel as discussed by Salack et al. (2016). The results on the increase in the number of warm days and the reduction of cool nights are similar to the observations made by Ly et al. (2013) who found a negative trend in the number of cool nights, and more frequent warm days and warm spells over the 1960–2010 period for locations inside the continent and in coastal areas of West Africa as a result of global climate warming. The re-greening also contributes but a small portion of the increase in the number of warm days and the reduction of cool nights with an increase in cloud cover which is the factor modulating precipitation and intervening in the energy balance of the surface. Hence, the radiative effect of cloud cover and surface albedo play a very important role in the terrestrial radiative budget that determines surface temperature amplitudes. The decrease in temperatures during JJA season shown in this study is also similar to

**FIGURE 3** Probability distributions over Sahel (10°–18°N, 15°W–30°E) of (a) RR1 (day); CDD (day); R99P (mm) and R99P date of occurrence (WOY), (b) TNn (°C); TXx (°C), TXx (°C) and Tsn (°C). Blue line for GGW and red for REF.
the results found by other authors such as Diba et al. (2016). During the summer season (JJA) non-radiative effect can dominate and the cooling effect can be related to the increase of evapotranspiration, number of rainy days and average daily rainfall amount.

The climatic extremes, associated with the regional warming and the return of rainfall regimes toward wetter conditions, can be explained by several atmospheric and LULC feedback processes. Most of the rainfall increase coincides with the re-greening patterns at some locations suggesting a climatic influence of the LULC changes but at other locations non-climatic factors are to be considered (Hosciolo et al., 2014). However, more planned re-greening policies like afforestation by the GGW project and other assisted natural regeneration of trees (i.e., The Sahel greenbelt) would also exacerbate the frequency and the amplitude of some extremes related to rainfall and temperature. This Pan-African project is still ongoing and may affect Sahel climate variability which is already impacted by global warming (Giannini, 2015; Salack et al., 2016; Giannini and Kaplan, 2018). Hence, the “new” LULC changes interact with the internal variability of the regional atmospheric factors of the West African monsoon such as an enhanced Saharan heat low and low-to-upper level wind variations (Evan et al., 2015; Salack et al., 2016), the rapidly increasing air pollution and greenhouse gases (Dong and Sutton, 2015; Knippertz et al., 2015), to increase the size, the intensity, the frequency and the organization of mesoscale convective systems (Bell and Lamb, 2006; Taylor et al., 2017) which are bringing in more intense rainfall events, more rainy days and other changes in temperatures as shown in this study. This assessment corroborates, along with other studies (e.g., Abiodun et al., 2012; Diba et al., 2016), the potential role played by vegetation covers to explaining the frequency and amplitude of some climate extremes. However, its results stand out other contributions (e.g., Diba et al., 2016) by specifically targeting LULC policies actually implemented in the Sahel (West Africa) as part of the human induced changes in land–atmosphere feedbacks. These LULC policies need to be accounted for in the diagnostics and future projections of climatic extreme events over the region.

This paper used the regional climate model to simulate the potential impacts of the Sahel Greenbelt like the GGW and other assisted natural regeneration of trees on the frequency, intensity and timing of climate extremes. Therefore, due to the complexity of the West African monsoon and the interplay of its main features and the weakness of regional climate models, we recommend further investigations on how LULC–atmosphere interactions may affect the trends and variability of climatic extreme events over the region.

ACKNOWLEDGEMENTS

The authors thank the African Development Bank (AfDB) through the Institutional Support to African Climate Institutions Project (ISACIP) and AGRHYMET Regional Center (http://www.agrhymet.ne) which supported the acquisition of high-performance computer used for this study. This work was partly supported by APTE-21/FSP-AGRICORA project funds (MEAIE/IRD, AGRICORA axe 1, convention 2016–2018) provided by the French Ministry for Europe and Foreign Affairs (MEAIE) through Institut de la Recherche pour le Developpement (http://www.ird.fr/). S.S. and A.S. appreciate partial funding from the UPSCALERS project (AURG II-1-074-2016) which is part of the African Union Research Grants financed through the Financing Agreement between the European Commission and the African Union Commission (DCI-PANAF/2015/307-078). The contents of this paper is the sole responsibility of the authors and can under no circumstances be regarded as reflecting the position of the African Union Commission. The West African Science Center for Climate Change and Adapted Land Use (www.wascal.org) is sponsored by the German Federal Ministry of Education and Research (BMBF). We are thankful to the four/anonymous reviewers whose comments helped improve the quality of this paper.

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section at the end of this article.

**How to cite this article:** Saley IA, Salack S, Sanda IS, *et al.* The possible role of the Sahel Greenbelt on the occurrence of climate extremes over the West African Sahel. *Atmos Sci Lett*. 2019;20: e927. https://doi.org/10.1002/asl.927