Climate change and variability: empirical evidence for countries and agroecological zones of the Sahel

Oudah Yobom[1]

Abstract

This article statistically evaluates the extent of climate change and variability in the Sahelian countries since 1901. We perform a statistical analysis based on a linear regression model estimated by ordinary least squares (OLS) and on a structural change model estimated at two different scales (countries and agroecological zones) for temperature and precipitation. CRU is the main source of our data but obtained through two different websites. The first database from the World Bank provides temperature and precipitation data from 1901 to 2012 and are provided at the country level. The analysis of agroecological zones is based on an original database from 1901 to 2016 constructed with data available on the website of the Royal Netherlands Institute of Meteorology. The results suggest that climate change has indeed started in all the countries of the Sahel with 1980 being a turning point of global warming. They also suggest that agroecological zones are experiencing climate change and variability, with turning points in 1940 and 1980. Desert and arid areas have experienced a large number of breaks from 1901 to 2016 while in Nigeria, wetlands and non-desert areas experienced several breaks.

1 Introduction

Projection by the Intergovernmental Panel on Climate Change (Smith et al. 2014; IPCC 2013) based on all proposed emission scenarios indicates an increase in surface temperature

✉ Oudah Yobom
oudah.yobom@inra.fr

[1] Centre of Rural Economy and Sociology Applied to Agriculture and Rural Areas (CESAER UMR1041), AgroSup Dijon, French National Institute for Agricultural Research (INRA), University of Burgundy Franche-Comté, Dijon, France

during the twenty-first century. Changes will be observed in air temperature, water cycle, and sea level. The average global increase in surface temperature for the period 2016–2035 will be between 0.3 and 0.7°C. Changes in precipitation will not be uniform in the world with decreasing average precipitation in arid subtropical regions and in most mid-latitude regions, while an increase will be observed in wetlands following sea level rise at the end of the twenty-first century. Climate change is a threat to the development of the entire planet, although in some countries the effects seem slow to appear.

The political response to climate change has evolved over time. Prior to the Paris 2015 (COP21) and Marrakech 2016 (COP22) meetings, several international climate summits and conferences have been organized, but COP21 is considered to be the only agreement of a universal and global nature. It is also historical because of its content, as this agreement recognizes climate justice through the principle of differentiation between countries (developed countries, emerging and polluting countries, developing countries, and Island states). On the other hand, COP22 is an action conference whose aim is to contribute to the implementation of the results of COP21 by increasing the mobilization of state and non-state actors. All parties pledged to respect the Paris Agreement, but the exit of Donald Trump announcing the withdrawal of the USA constitutes an important turning point in the fight against global warming. For the current US president, the Paris Agreement, the key of which is to limit global warming to 2 °C by 2100 (COP21), is a brake for economic growth (decline in employment and US economic recovery). For the World Meteorological Organization, 2016 was the warmest year ever and the years ahead will be warmer if there is no quick reaction. In response, European countries, other economic powers and other signatory countries are organizing and remain united for the implementation of the Paris Agreement, under the slogan advocated by French President Emmanuel Macron, "Make Our Planet Great Again". For instance, the United Nations Framework Convention on Climate Change (UNFCCC) is an institution characterized by a balance of power between States, but observers and actors struggling to implement the Paris Agreement hope that a consensus will be reached and that the USA will return in the game as they represent the second largest CO_2 emitter in the world. COP24 was held from 2 to 15 December 2018 in Katowice, just after Brazil refused to organize COP25 because of President Bolsonaro's position in the fight against global warming. One of the most important achievements of COP24 is the finalization of the text on the full implementation of the Paris Agreement, in accordance with the decisions adopted in Paris and Marrakech. In addition, the specificity of COP24 is to have included the "facilitation dialogue" whose purpose is to facilitate the implementation of national commitments. Overall, this COP24 helped to endow the Paris Agreement with tools, especially a clarity on financing, but the limit is that the international community has not committed to do more and faster against global warming.

In this context, this paper addresses the issue of climate change in the economies of the Sahelian belt. Like other African countries, the countries that form the Sahelian belt are confronted with an extremely variable and uncertain climate (Lumbroso et al. 2015). The Sahel is known for its fragility due to climatic variability (CILSS 2010). The Sahel is a strip located between the isohyet 200 mm and the isohyet 600 mm, sometimes 150 mm and 500 mm (CILSS 2010) and a small difference with the Midlands of Sudan which were between the isohyet 200 mm and the 800-mm isohyet (Kassas 2008). Thus, we have adopted the following definition of the extended Sahel: it is composed of the countries of Burkina Faso, Chad, Djibouti, Eritrea, Ethiopia, Mali, Mauritania, Niger, Nigeria, Senegal, Somalia, and Sudan. The Sahelian population is mainly rural, and its agriculture depends heavily on weather conditions. Then, any climatic variation affects the agricultural and financial

performances of this segment of the population. Lack of water is the main problem of the Sahelian countries.

Earlier work has already been done in West Africa (Ozer et al., 2003, 2010; Mahé et al. 2001; L'Hôte et al. 2002; Adeniyi 2016) but is confined to the West African Sahel. It was thought that droughts were statistically over at the level of these countries, but that the rainfall deficit would remain persistent until the end of the 2000s (Ozer et al. 2010). Their effects in the 1970s and 1980s were catastrophic for the West African Sahelian population. For instance, Mahé et al. (2001) analyzed the rainfall of 23 countries of Central and West Africa over the period 1910 to 1989. The results showed that a first rupture appeared in the 1950s in several units of West Africa. The main break-up period is between 1968 and 1970, followed by a second in the early 1980s. L'Hôte et al. (2002) also analyzed the annual rainfall index in the West African Sahel from 1896 to 2000 using data provided by the Agrhymet Regional Center of Niamey. They find that the drought began in the 1970s and was not over until the late 2000s, although the years 1994 and 1999 brought some humidity. Failing to stop, climate change through its effects is spreading and affects the entire Sahelian band. Based on IPCC scenarios, Adeniyi (2016) shows that the projected rainfall increase over subregion in West Africa (Western West Africa, Central Guinea Coast, Eastern Guinea Coast, Lower Eastern Sahel, and Eastern Sahel) is based on average rainfall as he estimates that extreme precipitation is expected to decrease significantly.

Accordingly, it is important to focus today on the extended Sahel. To the best of our knowledge, such a study has never been done and it is important to know whether the changes detected in West Africa 10 years ago are starting to be seen in East Africa today, thus justifying this new definition of the Sahelian band as part of this work. Our analysis is also unique because it is the first to be interested in climate change and variability at a more disaggregated level, that of agroecological zones. Although the West African Sahel has been the subject of several studies, its agroecological zones have not been explored in details yet. This disaggregated analysis is important as agroecological zones represent consistent areas from an agronomic point of view, where the agricultural practice of these countries is determined by the characteristics of these areas. To do so, we have constructed an original database including temperature and precipitation at the agroecological zone level which is available on the author's website (XXX[1]).

To analyze this dataset, we do not perform projections but perform a retrospective analyse. For that purpose, we do not use calibration and simulation models often used in climate change studies (Hulme et al. 2001; Sylla et al. 2018; Maharana et al. 2018; Adeniyi 2016). Instead we base our analysis on linear regression models (Fahrmeir et al. 2013; Bingham and Fry 2010) where the climate variables (temperature and precipitation) are regressed on a linear trend, eventually allowing for structural change. The assessment of climate change then proceeds by evaluating the sign and statistical significance of the estimated parameter related to the trend. We believe that using econometric methods further allowing for structural change to analyzing climate change and variability provides new insights into this issue.

This paper is organized as follows. We first present our study area and the databases. Then, we perform a statistical analysis on both the Sahelian countries and agroecological zones levels. Finally, we conclude.

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[1]Deleted for blind review.

2 Study area and data

2.1 Study area

This section presents the countries and the agroecological zones of the Sahelian band.

2.1.1 Definition and construction of the Sahelian band

The Sahel, as defined by the Permanent Interstate Committee for drought control in the Sahel (CILSS), covers nine countries: Mauritania, Senegal, Gambia, Guinea-Bissau, Mali, Burkina Faso, Niger, Chad, and Cape Verde, with a total area of 5,400,000 km^2 and a population of nearly 60 million (Sissoko et al. 2011). However, the Sahel is difficult to delimit because it is composed of several subSaharan African countries bordered by a similar climatic zone. The West African Sahel is defined as a semi-arid range of grasslands, shrubs, and small thorny trees located just south of the Sahara desert (Nicholson 2013; Sissoko et al. 2011). According to Nicholson (2013), the Sahel extends about 5000 km from the east-west extent of Africa and the Sahara to the wet savanna at about 10 ° North. It includes Mauritania, Senegal, Mali, Niger, Chad, Sudan, and the northern parts of Burkina Faso and Nigeria.

Our definition of Sahel is different from that of the CILSS, and consists of the sum of the two definitions given by Nicholson (2013) and Sissoko et al. (2011). More precisely, we have selected countries with the same climatic characteristics (variation of weather conditions, variable and hot climate, uncertain rainy seasons, famine, food insecurity, regular occurrence of floods and droughts) and countries bordered by the desert and those whose sensitivity to climatic shocks is similar. Thus, our extended Sahel (see Fig. 1) includes 6 countries in West Africa (Burkina Faso, Mali, Mauritania, Niger, Nigeria, and Senegal), 5 East African countries (Djibouti, Eritrea, Ethiopia, Somalia, and Sudan), and 1 country in Central Africa (Chad). In these countries, agriculture and livestock are the main sources of economic wealth and agricultural activity remains the main source of subsistence for the majority of people living in the region (Sissoko et al. 2011). The 12 countries forming
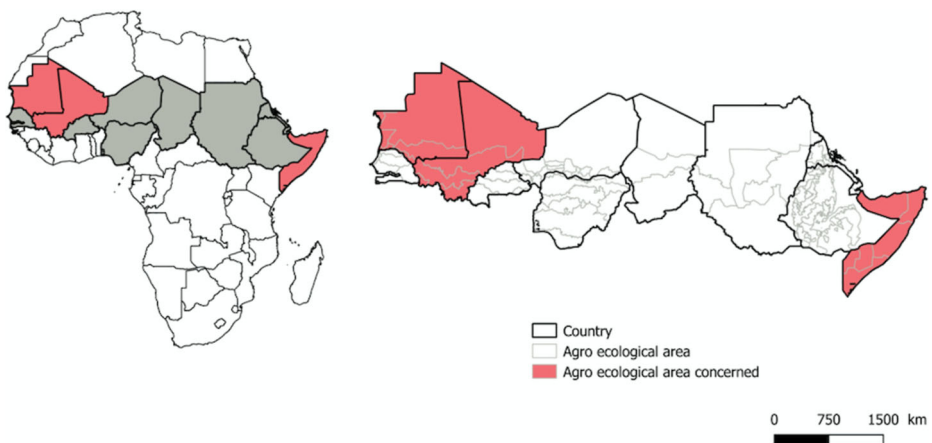

Country
Agro ecological area
Agro ecological area concerned

0   750   1500 km

Fig. 1 Perimeter of the study area. Source: Author

the Sahelian band are the most vulnerable in the world. In addition to the great climatic variability, they face civil wars, mass migration (internal or external), and terrorism that create lasting instability. Faced with all these difficulties, the fields are deserted and the farmers take flight and take refuge far from their field. As in recent decades, these countries have seen unprecedented population growth, and their economic inconsistency accentuates the problem of food self-sufficiency.

2.1.2 Agroecological zones

The analysis of climate change and variability is also interesting at a smaller scale: the agroecological zone. Since 30 years, the Food and Agriculture Organization (FAO) of the United Nations has put in place a global system of agroecological zones which is defined as a method to measure the potential of agricultural land productivity. In other words, it characterizes climate, soil, and land conditions relevant to agricultural production. This method has led to the design and identification of agroecological zones. We share FAO's definition of agroecological zones as country-specific land resource mapping units in the world. They are built on the basis of country-specific climate, soil, and vegetation cover characteristics. This characterization is specific because it also looks at the potentials and constraints for land use. Within each country, there are agroecological zones, the number and characteristics of which vary from one country to another. Table 3 gives the names and number of agroecological zones for each country.

Despite belonging to the Sahelian belt, the 52 agroecological zones have specific individual characteristics. As we will see, they are distinguished by their area, the temperature recorded, and the seasonal precipitation or the quantities of water received annually. They can also be distinguished by the start and end dates of the rainy seasons and by their agricultural practices, the cropping system (irrigated or rainy) and the types of crops used.

The analysis of rainfall and temperature at the level of the 52 agroecological zones makes it possible to study, on the one hand, climate change and variability in the 12 countries. On the other hand, it is also a question of establishing a ranking of the countries, in other words to establish a distinction between the countries in which there are no marked differences between the zones and those which present remarkable differences. We are then able not only to detect trends in climate irrespective of the spatial scale used but also to detect heterogeneity in the phenomenon of climate change within each country.

2.2 Data

We use two main climate variables, temperature and precipitation, that we study for two different scales distinguished by the study period and the sources of the data.

The first analysis covers 12 countries (Burkina Faso, Chad, Djibouti, Eritrea, Ethiopia, Mali, Mauritania, Niger, Nigeria, Senegal, Somalia, and Sudan) for the period 1901–2012 and the second one covers the 52 agroecological zones of the countries selected (except Eritrea, see below) for the period 1901–2016. Our climate data sources come from the Climate Research Unit (2016). We use an updated gridded climate dataset (referred to as CRU TS 4.02 (land) 0.5°, 1.0°, 2.5°) from monthly observations at meteorological stations across the world's land areas especially in Sahelian countries.

While the CRU data are of good quality, we are aware of the low number of stations in the Sahel countries available at the beginning of the century. At the country level, the number of stations may be less problematic than at the scale of the areas where the number of stations can be crucial especially in the countries of East Africa. However, if we go back

to the beginning of the century, we can see that the number of stations is small but our study is suitable as the analyses that have already been done by Hulme et al. (2001) and the information provided by Harris et al. (2014) on the robustness of CRU data reinforce the results of our analysis. All sets of observation have this problem. Hence, there are accepted thresholds to allow missing observations: in CRU TS for instance, each station must have 75% of the values between 1961 and 1990 for each month. Some datasets specify thresholds for each decade (Harris et al. 2014).

At the country level, we extracted monthly average data from the World Bank Climate Change Knowledge Portal. The monthly data for pixels are extracted from the database of the Royal Netherlands Meteorological Institute (KNMI).

The temperature and precipitation data available from these two databases are expressed as monthly averages. Regarding the analysis of agroecological zones and in the absence of data at this level, we used R and QGIS to process, construct, and map the agroecological zones of each country in the Sahel based on the information provided by the FAO. After their construction, we obtained the masks of the geographical coordinates of each agroecological zone of each country which allowed the reconstruction of the temperature and precipitation data at the level of the agroecological zones. However, we were not able to produce agroecological maps of the Eritrea due to the lack of data and information on the shapes and perimeters of agriecological zones for this country.

Given the scope of this paper, we constructed climatic variables that can be linked to agriculture because this sector is dominant in these countries.[2] In particular, we focus on temperatures and precipitations during the dry and the rainy seasons. In the Sahel, the dry season is variable but is between September and May in most countries. It is characterized by the absence or the weakness of rains. On the other hand, the rainy season is the growing season which is the period when agriculture is practiced in the Sahel. Indeed, the soil is wet because of the high rainfall. Seasonal rainfall therefore plays a crucial role (Maharana et al. 2018).

Specifically, from the average monthly temperature, we computed 6 temperature variables built according to the seasons specific to each country: minimum annual temperature (i.e., in our case, the average monthly temperature of the coldest month of the season), annual median temperature (i.e., the average monthly temperature of the season), maximum annual temperature (i.e., the average monthly temperature of the hottest month of the season) for both the dry and rainy seasons. The computation and analysis of the annual median temperature, the annual minimum temperature, and the annual maximum temperature provide a good idea of the distribution of this variable both in terms of central tendency and dispersion. From the average monthly precipitations, we computed total annual precipitation and seasonal mean precipitation.

In total, at the country level, we have 112 annual observations for precipitation and temperature variables and 116 annual observations for agroecological zones. Table 4 describes the variables used in the analysis of climate change in the Sahel. It also provides an overview of precipitation and temperature indicating the source, period, and frequency of these variables.

Table 1 presents the descriptive statistics of our 8 climates variables.

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[2]The agricultural sector employs about 80% of the Sahelian population and is the main source of consumption and income of Sahelian households. Agricultural activities account for between 60 and 100% of the income of the poorest African households (Davis et al. 2008).

Table 1 Descriptive statistics of climate data

Climate variables	Country level		Agroecological level	
	Mean	Std. dev.	Mean	Std. dev.
Precipitation				
Total precipitation	468.09	320.38	619.37	444.52
Seasonal precipitation	80.73	51.69	103.08	70.11
Temperature				
Mean temp. of the coldest month; rainy season	27.63	2.90	26.66	3.65
Median monthly temp.; rainy season	29.01	2.55	27.84	3.68
Mean temp. of the hottest month; rainy season	30.42	2.42	29.68	3.79
Mean temp. of the coldest month; dry season	22.29	2.12	22.73	2.84
Median monthly temp.; dry season	26.18	1.64	26.05	3.01
Mean temp. of the hottest month; dry season	30.01	2.54	29.87	4.00
Countries	12			
Agroecological zones	52			

3 Methodology

Recall that our aim is to see whether countries have experienced phenomenon of climate change and the period from which these countries began to register these climatic variations. The aim is not to predict future precipitations and temperatures but to observe the evolution of the temperatures and precipitation during the period (1901 to 2012 for countries and 1901 to 2016 for agroecological zones) and to detect subperiods using econometric (statistical) techniques to find endogenous ruptures in the model's coefficients. To that purpose, we present in this section the methodology of linear models with fixed effects and structural change models.

3.1 Pooled model with country effects

In order to detect climate change, we first use a simple pooled panel linear statistical model with a measure of climate as the dependent variable and time as the single independent variable associated to a heterogeneous coefficient, so that we are able to estimate one coefficient for each country and each agroecological zone. The implementation of this model is done on two spatial scales: 12 countries with annual observations ranging from 1901 to 2012 and 52 agroecological zones with annual observations ranging from 1901 to 2016. The specification is as follows:

$$y_{it} = \sum_{i=1}^{N} \alpha_{1i} + \sum_{i=1}^{N} \alpha_{2i} \, \text{year}_t + \epsilon_{it} \tag{1}$$

where y_{it} is the dependent variable (annual median temperature, annual minimum temperature, annual maximum temperature of the dry and rainy seasons, total annual precipitation and seasonal annual precipitation) for area (country or agroecological zone) i at time t; year_t is the variable representing the year of observation. We then have $N = 112$ observations $\cdot$ 12 countries $= 1344$ global observation at the country level

and $N = 116$ observations $\cdot$ 52 zones $= 6032$ global observations at the agroecological zones level. ϵ_t represents the error term. This model is estimated using ordinary least squares (OLS), which allows to recover estimates for α_{1i} and α_{2i}. Climate change is then assessed by the sign and the statistical significance of the marginal effect of y_{it} over $year_t$, i.e., α_{2i}. This marginal effect varies over areas if the estimates of α_{2i} are significantly different from each other, which can be tested for by a simple F-test. Furthermore, if the area fixed effects α_{1i} are significantly different from each other, then the intercept significantly differs between areas.

3.2 Structural change model

The structural change model allows endogenous detection of structural breaks in the coefficients in time series. We base our analysis on Bai and Perron (1998, 2003) who developed procedures for detecting ruptures in the longitudinal data and the necessary associated statistical tests.

Generally, the structural change test is defined naturally for longitudinal data (Bai and Perron 1998); the principle is to estimate the relationship between the dependent and the independent variables and to verify whether the nature of the relationship changes over the period. Wald-type tests are used to test models with multiple structural changes by formulating the null structural non-change hypothesis ℓ versus the alternative hypothesis containing an arbitrary number of changes denoted $\ell + 1$. This procedure then corresponds to a specific general modeling strategy that allows to endogenously determine the appropriate number of changes in the data. One drawback of this procedure is the problem associated with hypothesis testing under multiple changes (Bai and Perron 2003) as is the case with the present empiric application.

Formally, consider the regression for a single area (country or agroecological zone, therefore omitting the index i) over the period. We then consider the following linear regression with m breaks ($m + 1$ regimes):

$$y_t = z_t' \delta_j + \epsilon_t \qquad\qquad t = T_{j-1} + 1, ..., T_j \qquad\qquad (2)$$

for $j = 1, ..., m+1$. In this model, y_t is the observed dependent variable at time t; $z_t (q \times 1)$ is the vector of covariates (corresponding to the constant term and the coefficient associated to the trend in our case) and δ_j ($j = 1, ..., m + 1$) is the corresponding vector of unknown coefficients to be estimated including α_1 and α_2; ϵ_{it} is the disturbance for area i and at time t. The indices $(T_1, ..., T_m)$, or the break points, are explicitly treated as unknown (we use the convention that T_0 and $T_{m+1} = T$). The purpose of this econometric approach is then to estimate the unknown regression coefficients with the break points when the T observations on (y_t, x_t, z_t) are available. Moreover, the variance of u_t need not be constant: breaks in variance are possible provided that they occur on the same dates as the breaks in the regression parameters. For each possible partition of the data, the model is then estimated using OLS and the best model is selected via a cross-validation procedure. This procedure then allows to detect both changes in the intercept and in the trend.

4 Application at the country level

In this section, we first estimate model (1) for the various climatic variables and test whether the intercepts and trends are significantly different across countries. We also produce graphs for each climatic variable and each country to show their evolution over time (available in

the online Appendix) and empirically verify the existence of climate change in the Sahelian countries using a simple linear model and a structural change model. In addition, we discuss the results obtained with the structural change model proposed by Bai and Perron (2003) in order to identify breaks or subperiods in the countries of our sample, which is, to the best of our knowledge, the first analysis of this type in this context.

4.1 Pooled model with heterogeneous coefficients

The estimation results are presented in Table 2. For each indicator, we provide at the bottom of the table the results of the homogeneity tests: homogeneity of intercept across countries ($H_0 : \alpha_{1i} = \alpha_1$) and homogeneity of slopes across countries ($H_0 : \alpha_{2i} = \alpha_2$). The null hypothesis is rejected for all climate variables meaning that both the intercepts and the slopes differ between countries (see Table 2, columns 1 to 6 for temperature and for precipitation, columns 7 and 8). This can be explained by the fact that although we have grouped countries that have a similar climatic situation, forming the Sahelian bloc, these countries still have different configurations and differ from each other in their geographical position and the size of their national territory. For example, some countries are landlocked without access to the sea and some countries have large or small inland water areas and openings to the sea. Furthermore, as we show later, within a country, the climate is very variable and the composition of the landscape is also different. This can be explained by the varying numbers of agroecological zones (see Table 3) within a country. The extent of a country can also be the source of heterogeneity because the climate seems to be contrasted in countries with a large territorial area. For example, Nigeria receives a significant amount of rain because the country has four rainy seasons spread all over its territory. The temperature also varies within the agroecological zones. In Niger, the desert represents a large part of the national territory, which explains the fact that the country records high temperatures and low annual rainfall. This characteristic is also observable in Mauritania, the national rainfall is very low accompanied by intense heat. It should also be noted that the presence of forests or savannas has a significant impact on the average temperature at the country level.

All these elements justify a country-by-country analysis that we carry out in the following sections.

4.2 Temperature

The graphs (Figs. 2, 3, 4, 5, 6, and 7 in the online appendix) provide a graphical overview of the evolution of the temperature over the period 1901 and 2016 in the Sahelian countries. These graphical representations concern the median, minimum, and maximum temperatures, respectively, during the dry and rainy seasons.

Looking first at temperature in the rainy season, the series of graphical trends illustrated in Figs. 2, 3, and 4 show the evolution and interannual variability of the minimum, median, and maximum temperatures during the rainy season from 1901 to 2016 in the Sahelian countries. They show that the temperature displayed an upward trend over the entire period and globally at the country level. Figures 5, 6, and 7 show the evolution of the 3 variables related to temperature during the dry season. This increase is also confirmed by our statistical results in columns (1) to (6) of Table 2 which show that indeed there is a significant rise in temperature trend (in both seasons) for all countries and for the entire period as in almost all cases, the coefficients associated to the trend (shown by the rows year.country) are positive with varying extents and statistically significant.

Table 2 Regressions results with country fixed effects

| | Temperature | | | | | | Rainfall | |
	TempminRain (1)	TempmedRain (2)	TempmaxRain (3)	TempminDry (4)	TempmedDry (5)	TempmaxDry (6)	RainSum (7)	RainSeason (8)
Burkina	15.693***	23.992***	20.227***	15.222***	11.258***	18.567***	2,138.647***	420.053***
	(3.531)	(3.104)	(3.212)	(4.387)	(3.945)	(3.657)	(345.252)	(70.512)
Chad	9.728***	10.386***	11.909***	22.721***	15.335***	10.859***	443.341	89.890
	(3.531)	(3.104)	(3.212)	(4.387)	(3.945)	(3.657)	(345.252)	(70.512)
Djibouti	31.401***	22.148***	23.516***	17.810***	18.353***	17.431***	−16.364	117.699*
	(3.531)	(3.104)	(3.212)	(4.387)	(3.945)	(3.657)	(345.252)	(70.512)
Eritrea	7.775**	11.788***	16.410***	14.739***	12.302***	4.723	855.250**	11.912
	(3.531)	(3.104)	(3.212)	(4.387)	(3.945)	(3.657)	(345.252)	(70.512)
Ethiopia	12.822***	14.340***	6.643**	11.035**	12.371***	9.543***	1,607.414***	247.479***
	(3.531)	(3.104)	(3.212)	(4.387)	(3.945)	(3.657)	(345.252)	(70.512)
Mali	12.547***	25.599***	13.446***	4.447	−2.703	10.375***	1,284.374***	314.934***
	(3.531)	(3.104)	(3.212)	(4.387)	(3.945)	(3.657)	(345.252)	(70.512)
Mauritania	18.336***	21.196***	16.286***	3.719	−9.030**	8.505**	393.009	100.260
	(3.531)	(3.104)	(3.212)	(4.387)	(3.945)	(3.657)	(345.252)	(70.512)
Niger	15.455***	20.209***	19.740***	20.551***	16.174***	21.987***	368.249	106.570
	(3.531)	(3.104)	(3.212)	(4.387)	(3.945)	(3.657)	(345.252)	(70.512)
Nigeria	18.449***	22.285***	22.563***	25.639***	16.862***	17.379***	2,445.411***	260.903***
	(3.531)	(3.104)	(3.212)	(4.387)	(3.945)	(3.657)	(345.252)	(70.512)
Senegal	19.772***	23.784***	20.510***	7.900*	13.782***	7.905**	4,398.572***	1,134.395***
	(3.531)	(3.104)	(3.212)	(4.387)	(3.945)	(3.657)	(345.252)	(70.512)
Somalia	26.161***	24.097***	20.957***	20.018***	27.699***	21.485***	−11.388	0.729
	(3.531)	(3.104)	(3.212)	(4.387)	(3.945)	(3.657)	(345.252)	(70.512)

Table 2 (continued)

	Temperature						Rainfall	
	TempminRain (1)	TempmedRain (2)	TempmaxRain (3)	TempminDry (4)	TempmedDry (5)	TempmaxDry (6)	RainSum (7)	RainSeason (8)
Sudan	8.902** (3.531)	11.943*** (3.104)	13.011*** (3.212)	9.120** (4.387)	−0.112 (3.945)	2.721 (3.657)	729.066** (345.252)	165.253** (70.512)
year.Burkina	0.005*** (0.002)	0.002 (0.002)	0.005*** (0.002)	0.005** (0.002)	0.009*** (0.002)	0.007*** (0.002)	−0.682*** (0.176)	−0.129*** (0.036)
year.Chad	0.009*** (0.002)	0.010*** (0.002)	0.010*** (0.002)	−0.001 (0.002)	0.006*** (0.002)	0.010*** (0.002)	−0.049 (0.176)	−0.004 (0.036)
year.Djibouti	−0.0001 (0.002)	0.005*** (0.002)	0.005*** (0.002)	0.003 (0.002)	0.004** (0.002)	0.007*** (0.002)	0.108 (0.176)	−0.046 (0.036)
year.Eritrea	0.008*** (0.002)	0.008*** (0.002)	0.007*** (0.002)	0.004* (0.002)	0.007*** (0.002)	0.012*** (0.002)	−0.310* (0.176)	0.008 (0.036)
year.Ethiopia	0.005*** (0.002)	0.005*** (0.002)	0.009*** (0.002)	0.005** (0.002)	0.005** (0.002)	0.008*** (0.002)	−0.445*** (0.176)	−0.081** (0.036)
year.Mali	0.009*** (0.002)	0.003** (0.002)	0.010*** (0.002)	0.008*** (0.002)	0.015*** (0.002)	0.012*** (0.002)	−0.480*** (0.176)	−0.120*** (0.036)
year.Mauritania	0.007*** (0.002)	0.006*** (0.002)	0.009*** (0.002)	0.008*** (0.002)	0.018*** (0.002)	0.012*** (0.002)	−0.148 (0.176)	−0.040 (0.036)
year.Niger	0.007*** (0.002)	0.006*** (0.002)	0.007*** (0.002)	−0.001 (0.002)	0.005** (0.002)	0.005*** (0.002)	−0.093 (0.176)	−0.029 (0.036)
year.Nigeria	0.003* (0.002)	0.002 (0.002)	0.004** (0.002)	−0.001 (0.002)	0.004** (0.002)	0.005*** (0.002)	−0.656*** (0.176)	−0.068* (0.036)
year.Senegal	0.004** (0.002)	0.002 (0.002)	0.005*** (0.002)	0.008*** (0.002)	0.007*** (0.002)	0.012*** (0.002)	−1.842*** (0.176)	−0.492*** (0.036)

Table 2 (continued)

	Temperature						Rainfall	
	TempminRain	TempmedRain	TempmaxRain	TempminDry	TempmedDry	TempmaxDry	RainSum	RainSeason
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
year.Somalia	−0.0001	0.002	0.004**	0.003	−0.0004	0.004*	0.136	0.019
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.176)	(0.036)
year.Sudan	0.010***	0.009***	0.009***	0.006***	0.014***	0.14***	−0.147	−0.041
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.176)	(0.036)
Observations	1,344	1,344	1,344	1,344	1,344	1,344	1,344	1,344
R^2	1.000	1.000	1.000	0.999	0.999	1.000	0.989	0.984
Model	OLS	OLS	OLS	OLS	OLS	OLS	OLS	OLS
Test of homogeneity of intercept								
Fischer-test	3.9661***	3.2159***	2.4829***	2.7014**	6.641***	3.1578***	13.755***	18.787***
P-value	(<0.001)	(<0.001)	(0.0044)	(0.0019)	(<0.001)	(<0.001)	(<0.001)	(<0.001)
Test of homogeneity of slope								
Fischer test	3.5839***	3.0556***	2.1068***	2.4968***	6.7388***	3.3793***	9.134***	14.253***
P value	(<0.001)	(<0.001)	(0.0174)	(0.00418)	(<0.001)	(<0.001)	(<0.001)	(<0.001)

Note: *p<0.1; **p<0.05; ***p<0.01

We now turn to the analysis of structural change using the six variables we have constructed. The results of our structural analysis are graphically represented in Figs. 11, 12, 13, 14, 15, and 16 in the online appendix. They allow to identify the periods of breaks in the regression coefficient for the models with the 6 variables. We show that the structural changes and the number of breaks vary from one country to another. Focusing first on the temperature analysis during the growing season, we show that the evolution of the variables related to the seasonal temperature experienced periods of rupture over the whole period. The results of the graphs (Figs. 11, 12, and 13) show that all countries experienced periods of breaks that sometimes occur on the same dates or at different times. The results of the minimum temperature show during the growing season (Fig. 14) that Chad and Djibouti individually experienced three shocks related to but at different times, with a periodically similar shock around the 1980s. Figure 13 shows the ruptures related to the maximum temperature during the rainy season in all countries. Chad, Mali, Mauritania, Eritrea, Niger, Nigeria, and Somalia each had three shocks that occurred at different times. Unlike other countries where the year 1980 is an important starting point, Somalia has experienced two shocks before the 1980s. All the shocks related to the different variables associated with the temperature during the season have been summarized in the Table 6 but by analyzing our graphical results (Figs. 11, 12, and 13), we clearly see that for most countries the year 1980 is a year of reference in the explanation of climate change. In other words, the year 1980 is a turning point in explaining the phenomenon of climate change (Tables 4 and 5).

Structural change model results identifying temperature-related breaks during the dry season are presented in Figs. 14, 15, and 16. Overall, all countries experienced breaks that are distinguished by their number (see Table 6) and their date of occurrence over the entire period (Figs. 14, 15, and 16). Analysis of Fig. 14 indicates that most countries recorded these shocks after the 1980s, with the exception of Burkina Faso, Ethiopia, Somalia, and Djibouti, which all had a shock at the beginning of the period. Chad and Sudan experienced the same shock at the same time. Nigeria is the only country that has not experienced any temperature change shock during the dry season. In addition, analysis of Fig. 16 shows that Burkina Faso, Djibouti, and Ethiopia suffered only one shock identified in 1980.

The summary of shocks related to the evolution of temperature variables during the dry season is given in Table 6. Countries have experienced more shocks in the rainy season than in the dry season. From an economic point of view, this poses socioeconomic problems because the Sahelian economies are very dependent on rainfed agriculture.

Overall, our results allow us to confirm the hypothesis according to which the temperature has increased over the whole period and for the whole period. They also show that the level of temperature rise is different from one country to another. These results are consistent with those obtained by Masih et al. (2014), Rajaud and Noblet-Ducoudré (2017), Auffhammer (2018), Norrgård (2014), Brown et al. (2017), Tierney et al. (2015), Wagena et al. (2016), Sylla et al. (2018) on different geographical scales. For instance, Masih et al. (2014) indicate that a large number of shocks occurred after the 1980s in most African countries. In particular, they pointed out that Ethiopia is the country with the highest number of droughts (15 droughts) from 1900 to 2013 and these are climate-related (Brown et al. 2017).

4.3 Precipitation

Precipitation is the second variable chosen to characterize climate change in the Sahelian countries. Precipitation and temperature are strongly bound in this area. Rainfall sometimes depends on temperature during the rainy seasons (Nicholson 2013). We focus on the annual precipitations, i.e., the total annual quantity of rain since the important issue is the total

amount of water for a year at a given area. We also focus on seasonal rainfall. With respect to total precipitations, the same graphical and statistical analyses are applied on this variable, and Fig. 8 in the online appendix shows sequences marked by decreases or increases in annual precipitation, varying from country to country and independently while Table 2 provides the estimation results (columns 7 and 8).

There was a statistically significant decline in annual precipitations in Burkina Faso, Eritrea, Ethiopia, Mali, Nigeria, and Senegal (see the coefficients year·country in columns (7) and (8) of Table 2). For all the other countries, the slope coefficients are not significant.

Overall, the graph series in Fig. 8 show that annual precipitation has varied strongly over the entire period for all countries. Around the 1980s, they fell sharply before regaining some recovery for all countries. Nicholson et al. (1997, 2000) and Ozer et al. (2010) reported that the West African Sahel recorded above-average rains from 1961 to 1990 which could indicate the end of the severe period of aridity that began in the 1960s. Moreover, over the same period, the same situation is observable in the countries of East Africa (of the extended Sahel). The thesis that Sahelian dry matter seems to be over in the 1990s (Host et al. 2002) is to be refuted because even if there is a slight rise in rainfall in the early 2010s. After 10 years, rainfalls are still low in West African countries and this trend is also spreading in East Africa (Nicholson 2013; Olsson et al. 2005).

The series of precipitation graphs also show that the Sahelian countries experienced periods of rainfall variability. Even though the latter are not very obvious, they are a good reflection of global warming. The rainfall of this band is generally limited to the summer months, with maximum precipitation in August. After presenting this analysis on annual rainfall, we focus on seasonal variability to explain the evolution of the annual rainfall quantity during the rainy season (see Figs. 9 and 10) which corresponds to the period of agricultural activities for a rainfed "agricultural system". With respect to temperatures, the question is more crucial and essential, because the annual average mixes the temperatures of dry season and that of vegetative (agricultural) season, but it is only these last that matter. In addition, we do not seek to substitute the annual rainfall with precipitation from the rainy season, because the two variables are almost equal in countries where rainfall is highly concentrated over time (in the case of Sahelian countries in our sample such as Burkina Faso, Chad, Mali, Niger, Sudan); this explanation is less true in countries with more complex rainfall patterns, such as Nigeria and East African countries such as Ethiopia, Somalia, and Eritrea (in these cases, there is several seasons to consider).

We see that countries differ strongly. There are countries that have two seasons during the year, a dry season and a rainy season. Generally, the dry season (7 to 9 months, October to June) is longer than the rainy season. The month of August is generally the most watered and the arid climate which varies according to the agroecological zones of each country. The environment of these two-season countries is influenced by a tropical climate and dry, they are arid countries. We selected for the rainy season the months of June, July, and August. To our knowledge, the length of the rainy season has not and does not evolve practically in these countries. Then we have a group of countries that benefit from several rainy seasons, Nigeria, Ethiopia, Djibouti, Eritrea, and Somalia. Ethiopia has two rainy seasons, a first with moderate rains (from March and April) and a second rainy season from June to September. Eritrea has a climate that varies according to climate zones, the coast has an arid climate (located in the desert with a dry climate) with low and insignificant rainfall and the plateau area located in the center of the country with two seasons, a short rainy season from February to April and a big rainy season from end of June to mid-September (we keep

the months entirely because we work with monthly data). Thus, Somalia is characterized by a dry climate with two rainy seasons and two dry seasons in the north and south of the country. To the south, the first rainy season extends from April to June and a second season from October to November. The first dry season (December to March) and second dry season (July to September). In northern Somalia, the first rainy season (April to June) and the second season runs from October to November. Finally, Nigeria has a tropical and varying climate, semi-arid in the north of the country and wetter to the south. The country receives a longer rainy season from June to September in the north, another from April to October in the center, a third from March to October in the south and a last from March to November in the south east precisely in the region Calabar which is the rainy area of the country.

Globally, countries with a single rainy season are likely to receive less rainfall than countries with several rainy seasons. However, Eritrea and Somalia receive less water than a portion of countries with a single rainy season, except for Nigeria and Ethiopia. There is a problem of rainfall distribution at the national level of each country.

The results of the annual precipitation estimates presented in column 7 of Table 2 show that the coefficients associated to trend are negative and statistically significant for most countries. In addition, in the case of seasonal precipitation (column 8 of Table 2), these coefficients are negative and very significant for Burkina Faso, Ethiopia, Mali, and Senegal. On the other hand, they are negative and insignificant for Chad, Mauritania, Niger, and Somalia except in Eritrea where it is positive and not significant. Hence, countries experienced rainfall declines but in a distinct way: the second group of countries did not record a significant decrease in average rainfall over the entire period as the first group. For Djibouti and Somalia, unlike other countries, rainfall did not recover at the end of the period and both countries had irregular and low rainfall.

The results of endogenous breaks analyses related to precipitation variables are presented in Figs. 10 and 17 in the online appendix. Figure 17 illustrates the ruptures related to the evolution of total annual precipitation in the Sahelian countries over the entire analysis period. The graphs show that Chad, Mali, and Niger each had three shocks at different times. However, the last two shocks occurred in the same period, i.e., after the 1980s. In addition, Chad and Niger experienced their first break-up at the same period, at the end of the 1980s. Burkina Faso, Mauritania, and Somalia each suffered two shocks that occurred in the same period in the late 1940s and early 1960s. Ethiopia, Senegal and Sudan each experienced a single break in the early 1990s. Djibouti did not record breaks over the entire period. The results in Fig. 8 show the different breaks associated with the evolution of seasonal average rainfall in the Sahelian countries. Chad and Eritrea experienced three shocks throughout the period. The first shock occurred at a different time while the last two occurred at similar times. Mauritania and Niger each experienced two shocks that occurred at different times. Burkina Faso, Djibouti, Ethiopia, Mali, Nigeria, Senegal, and Sudan recorded only one shock, which globally occurred during the same period. Somalia has not contained periods of ruptures related to the evolution of seasonal average rainfall. Overall, precipitation decreased at the country level while recording periods of ruptures. This global warming trend could significantly alter rainfall patterns and water availability in different parts of the world. Gan et al. (2016) point out the fact that many parts of Africa, such as the Sahel, the Greater Horn of Africa, and Western and Southern Africa, have been affected by severe droughts in recent decades and millennia and are vulnerable to the adverse effects of climate change. By analyzing recent rainfall patterns in the Sahel, Norrgård (2014) shows that there was great interannual and inter-decadal variability in West African rainfall patterns in

the eighteenth century. These results are in line with our analyses, which indicate that all the Sahelian West African countries from Senegal to Nigeria have experienced a significant decline and interannual rainfall variability over the entire period. Rising rainfall and falling rainfall are both effects of climate change. An increase in precipitation leads to floods. They are considered as one of the main expected impacts of climate change (Dittrich et al. 2016).

Several studies (Sylla et al. 2018; Ford et al. 2018; Lebel et al. 2009; Ali and Lebel 2009; Gbangou et al. 2018) have also shown changes in precipitation in West African countries and that under current climatic conditions, West African countries will experience significant water stress (Ali and Lebel 2009; Sylla et al. 2018): this situation is obviously due to the high inter-decadal rainfall variability recorded in West Africa, with the droughts of the late 1970s and early 1980s and the recent upturn of the 1990s. Our results show that East Africa also experienced periods of water stress during this period, as also shown by the results of Gizaw et al. (2017) and Tierney et al. (2015) that support the existence of water stress in the countries of this part of the Sahel.

5 Application at the agroecological zone level

This section is devoted to analyzing climate change and variability at the level of agroecological zones. We identified 52 agroecological zones distributed differently among the 11 countries. Given the high number of agroecological zones, we first propose a global analysis of heterogeneity and then focus on three countries in which we find significant difference between agroecological zones composing them (see Fig. 1).

Table 5 provides the tests of homogeneity of intercepts and slopes between the agroecological zones for each country and each climate variable. Several categories of countries can be formed. The first category is composed of countries (Burkina, Chad, Djibouti, and Nigeria) in which there are no significant differences for any climatic variables between agroecological zones. This lack of heterogeneity leads us to say that although the zones have different configurations, the climate distribution is almost similar. The second group is formed by countries (Ethiopia, Mali, Mauritania, Senegal, Somalia, and Sudan) where there are significant differences for some but not all variables between agroecological zones. For example, there are countries where there are significant differences between agroecological zones only for temperature variables and not for precipitation variables (Ethiopia, Somalia, Sudan) and other countries where there are significant differences between zones for some temperature variables and rainfall variables (Mali, Mauritania, Senegal). Finally, the last category is formed only by Niger where only the slope for the minimum annual temperature during the dry season is significantly different between the agroecological zones. The results do not indicate that there is perfect homogeneity between the different zones at the country level but that there is obvious but weak heterogeneity.

For the focus, we consider three countries: 2 countries where there are significant differences for temperature and precipitation (Mali, Mauritania, Senegal) and 1 country from the group of countries where there are no significant differences except for temperature (Ethiopia, Somalia, Sudan). We choose Mali and Mauritania because there are more significant differences compared with Senegal. We also choose Somalia in order to have in our focus a country in the Horn of Africa, specifically West Africa and two countries bordering West Africa (see the red part of Fig. 1).

We performed the same statistical analysis at the level of agroecological zones. We report here the main results; the complete results are available in Appendix to save space.

5.1 Case of Mali

Mali has four agroecological zones (Saharan zone, Sahelian zone, Sudanian zone, Sudano Guinean zone) distributed throughout its territory. These areas are distinguished by their area, climatic conditions, agricultural practices, and type of breeding.

Overall, temperature-related variables increased at the level of agroecological zones in Mali in both the dry and vegetative seasons. On the other hand, both total and seasonal precipitation experienced a decline and a large year-to-year variability over the period. For example, total precipitation is marked by great variability in Mali (Sahelian zone and Sudano-Guinean zone). Conversely, it has low variability in Mali (Saharan zone). These facts are confirmed by our statistical analysis, thus validating the hypothesis according to which the phenomenon of climate change has started at the level of the agroecological zones of the countries. In addition, these periods started well before the 1980s. These results are confirmed by those on the identification of breaks (see Appendix) on the evolution of the eight climatic variables exploited. For all variables, the Sahara zone records 18 shocks compared with the other zones. This result is logical because the sahara is a desert zone characterized by a very random and varying climate.

5.2 Case of Mauritania

Mauritania is the second country on which we focus. It also has four agroecological zones distributed throughout its territory. However, all four zones differ in their terrestrial, climatic, and agricultural characteristics.

Overall, analyses of temperature variables show an increase in the temperature of the agroecological zones of Mauritania over the two seasons and this increase is observed throughout the period. This bullish situation confirms the hypothesis that the phenomenon of change has also begun in the agroecological zones of Mauritania. The results related to the two rainfall variables showed that in most agroecological zones there was a significant decrease in rainfall accompanied by high variability except in the Sahelian zone where the decline is not significant. The results on the identification show that the arid zone records globally 14 shocks for all the variables combined in comparison with other agrolecological zones of Mauritania.

5.3 Case of Somalia

Somalia is a country in the Horn of Africa whose national territory is composed of five heterogeneous agroecological zones that are distinguished by their size, climate, and agricultural practices.

Analyses show that agroecological zones recorded an increase in temperature variables and a decrease in precipitation over the entire period. However, Somaliland and Central Coast and Southern Somalia did not experience a decline in rainfall over the entire period. In addition, the results clearly show a large interannual variability of precipitation and temperature. For example, total rainfall is marked by high variability in Somalia (Bay and Bakool, central and southern Somalia, Shabelle and Juba valleys, Somaliland). Conversely, it has low variability in Somalia (*Bari*, constant linear and end of period). It is also apparent that climate change began in the agroecological zones of Somalia well before the 1980s. Results on breakage identification show that the *Bari* area has 14 shocks for all variables combined compared to other agroecological zones of Somalia.

6 Conclusion

This paper shows that global warming has started and exists in the Sahelian countries and also in their agroecological zones with varying extents. This assessment highlighted the causes and effects of climate change on economies. While the estimates of the existence of climate change and its consequences may be full of uncertainties, it is clear that the Sahelian countries (and their agroecological zones) have experienced a large variation in climate variables. As a result, several points can be raised:

- Graphical and statistical analyses showed that the Sahelian countries experienced a large change in temperature (+) and precipitation (−) over the period from 1901 to 2012. Beginning in the 1980s, the climatic consequences were enormous with low-frequency drylands weakening countries.
- Most Sahelian countries experienced a prolonged period of low rainfall in the mid-twentieth century, with annual average precipitation below that of the twenty-first century. On the other hand, there was an improvement in the late 1990s and from 2003, rainfall increased on average.
- From the end of our study period (year 2010), all countries in the Sahel experienced a slight increase in rainfall.
- The rainfall analysis during the vegetative period has shown that rainfall amounts have varied annually over the period. This trend strongly explains why countries have had a hard time responding to a rainy farming practice.
- The analysis of agroecological zones shows that those receiving a large amount of rainfall are the same with the greatest interannual variability over the entire analysis period. This reasoning is also valid for the temperature of agroecological zones. The hottest areas with high temperatures are those with very variable temperatures over the period.
- It also shows a contrasted result far from the idea that a high temperature is a source of precipitation. Otherwise, the hottest years are those that record a great deal of rain. Indeed, the graphical and econometric results show that an increase in temperature is not always accompanied by a rise in total and seasonal precipitation.
- It also shows that desert areas are the warmest but have the lowest annual minimum temperatures for all agroecological zones and for all countries.

This analysis shows that there were more shocks to temperature in agroecological zones than precipitation. Desert and arid areas are those that recorded a large number of shocks over the period, with the exception of Nigeria with wetlands and non-desert areas that have experienced several shocks. In general, periods of heat wave were frequent as floods or droughts.

At the level of agroecological zones, we show that the Sahara or desert areas have experienced early climate shocks. As a result, climatic changes began with desert areas before reaching slightly humid areas given the contrasting initial conditions of the dry zones.

The analysis at the level of agroecological zones made it possible to say that climate change started very early at the level of the agroecological zones however this precocity is not observed in the analysis at the level of the countries. Climate change started early in climate zones before being felt at the level of countries and agroecological zones.

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