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Climate Services Elaboration for Cocoa Cultivation in Côte d'Ivoire: Contribution of CORDEX Climate Projections

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Abstract

This study assessed the contribution of climate projections to improving rainfall information for cocoa crops in the central and southern regions of Côte d'Ivoire. Particular attention was paid to fourteen localities in these two climatic zones. Simulation data were obtained from the CORDEX ensemble and observation data from CHIRPS. They cover the period 1991-2005 for the reference period and the future period from 2021 to 2050 for the RCP4.5 and RCP8.5 scenarios. In addition, the study was based on the water requirements necessary during the critical phase of the cocoa tree (the flowering phase) for a good yield from the cocoa production chain on the one hand, and on a selection of three climate indices CDD, CWD and r95PTOT to study their spatio-temporal changes over two future periods 2021-2035 (near future) and 2036-2050 (medium-term) on the other. These climatic indices influence cocoa cultivation and their use in studies of climatic impacts on agriculture is of prime importance. The analysis of their spatio-temporal changes in this work also contributes to providing climate services based on rainfall, to which cocoa crops are highly sensitive. Our results show that the CDD and CWD indices vary from one region to another depending on latitude. For the fourteen localities studied, the number of consecutive dry days (CDD) could increase between now and 2050, while the number of consecutive wet days (CWD) could decrease over the period 2021-2035 and then increase over the period

2036-2050. The localities of Tabou, Aboisso and San-Pedro record high numbers of CDD index and CWD index for both projection scenarios. In comparison with the RCP4.5 and RCP8.5 scenarios, these results show that the RCP8.5 scenarios are having an impact on cocoa growing in Côte d'Ivoire.

Keywords

Cocoa, RCP4.5, RCP8.5, Climate Indices, Côte D'ivoire

1. Introduction

Côte d'Ivoire with an estimated population of 28,000,000 [1] is the world's leading producer of cocoa beans, with average annual production of 2.1 million tonnes, or 41% of world supply in 2020-2021, according to the Conseil Café-Cacao (CCC) and the International Cocoa Organisation (ICO) [2]. At national level, cocoa farming contributes around 40% of export earnings according to the World Bank, and 10% to 15% of Gross Domestic Product (GDP) [3]. Some 600,000 farmers are involved in the production chain, providing a livelihood for around 6,000,000 people, according to the World Bank. However, the droughts observed over the last twenty years in the Sahelian countries (Burkina Faso, Mali, Niger, Chad) are also being felt further southward of West Africa in regions with wetter climates. This drop in rainfall amount which has led to a reduction in the supply of surface water, is likely to (i) reduce agricultural production [4] and (ii) lead to population migrations in search of areas suitable for cocoa cultivation, resulting in conflicts between populations, increased deforestation and so on. In addition, the increase in climatic risks means that communities, particularly those in rural areas, are vulnerable to impoverishment and a reduction in their purchasing power. This situation is exacerbated by the inadequacy of adaptation and resilience measures. People are made vulnerable by the availability of unsuitable and non-modern infrastructure, but also by the lack of dedicated climate services to help them plan adaptation measures. Consequently, this situation, which is general in West Africa, has led the scientific community to take an interest in climate impact studies [5]-[10] through climate modelling [11], the determination of the beginning and end of rainy seasons [12] [13] and, finally, the development of strategies for adapting to the effects of climate change in order to achieve food security objectives [14]. Thus, the contribution of climate change scenarios (RCP4.5 and RCP8.5) in this region is of crucial importance in understanding and assessing impacts and potential changes, as they are supposed to represent the future climate under certain conditions. Thanks to these climate projections, we will be able to assess the vulnerability of the regions, and thus anticipate the adverse consequences that may result, and put in place effective prevention and adaptation strategies against climate change [11].

In the context of climate change, cocoa production, which is Côte d'Ivoire's main financial resource, is increasingly affected by variations in a number of climate indices (CDD and CWD) established by the UNFCCC (United Nations Framework Convention on Climate Change), to which it is sensitive. It is also essential to analyse the spatio-temporal changes in these indices to help political decision-making in support of agricultural policies. The question is therefore whether the localities covered by this study will still be suitable for cocoa farming in 2050, according to the climate index projections under the RCP4.5 and RCP8.5 scenarios of CORDEX simulations.

The aim of this study is therefore to provide climate services dedicated to cocoa growing and based on rainfall. More specifically, the aim is to identify precipitation-related climate indices that are highly sensitive to cocoa growing, and to study their spatio-temporal variations using the RCP4.5 and RCP8.5 projection scenarios.

This work is structured as follows: Section 2 is devoted to a description of the study area, the equipment and the method used. Section 3 shows the results and the discussion is given in Section 4. Finally, the conclusion and outlook are provided at the end.

2. Study Area, Data and Methods

2.1. Study Area

This study focuses on cocoa production areas in the central and southern regions of Côte d'Ivoire. The central region is the area between 6˚N - 8˚N and 9˚W - 3˚W, and the southern region is the area between 4.5˚N - 6˚N and 9˚W - 3˚W (**Figure 1**). The black dots in **Figure 1** represent the main towns of the cocoa-producing regions, departments or districts. The large central and southern regions are characterised by a sub-equatorial climate with two rainy seasons. Cocoa growing in these regions is highly dependent on climatic factors, particularly temperature [7], rainfall and relative humidity, as well as soil and pest factors [15]. Studies [16] have shown that the best climate for cocoa growing is tropical regions with temperature condition from 18˚C to 32˚C and annual precipitation in between 1200 mm and 2000 mm. It is important to note that rainfall is the most significant factor in cocoa growing, as a prolonged lack of water during the flowering phase can lead to a drop in cocoa production.

Vegetation cover is provided by two dynamic physiognomic units: forest and savannah. The southern region is characterised by evergreen and semi-deciduous forest [17] with an average annual rainfall of around 1700 mm and an annual water deficit of no more than 300 mm. The central region is characterised by a strip of land stretching either side of the town of Bouaké, where annual climate forecasts are particularly difficult because of the mosaic of vegetation, which is dominated by open forest or wooded savannah.

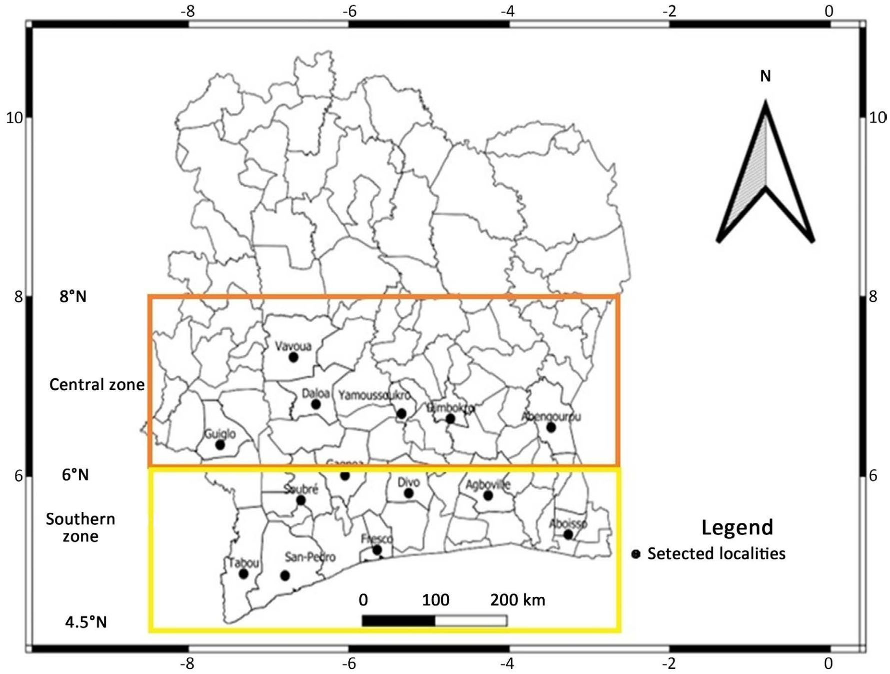

Figure 1. Presentation of the study area, with the southern regions (4.5˚N - 6˚N; 9˚W - 3˚W) in yellow and the central regions (6˚N - 8˚N; 9˚W - 3˚W) in red and the selected cities cocoa-producing localities in black.

2.2. Data

2.2.1. Observation Data

The Climate Hazards Group's CHIRPS (Climate Hazard Infrared Precipitation with Station data) observational data [18] is a near-global rainfall dataset over more than 30 years (1981-2021) covering 50˚S to 50˚N and all longitudes. From 1981 to almost the present day, CHIRPS integrates 0.05˚ resolution satellite imagery with ground observation data from stations to create gridded rainfall time series [18]. The rainfall data used for this work have a time series from 1991 to 2005. The choice of this period depends on the availability of ground observation data for the validation of the simulations.

2.2.2. Rainfall Data from Climate Models

The model rainfall data come from seven simulations in the CORDEX-Africa database. These different simulations are carried out with Regional Climate Models (RCMs) under the forcing of three Global Climate Models (GCMs) (**Table 1**). These GCMs, taken from the CMIP5 database, are used and forced for the future period by RCP4.5 and RCP8.5 scenarios. The precipitation simulated by these climate models is based on two periods, namely the historical period from 1951 to 2005 and the future period from 2006 to 2100. Let's mention that the dryness and wetness of models can be affected by several factors such as: 1) West African Monsoon which is among the dominant climatic features. It is characterized by a seasonal shift in wind patterns and precipitation. 2) The sea surface temperature anomalies in the Atlantic Ocean, which can influence rainfall

Table 1. List of CORDEX simulations carried out with RCMs forced by GCMs.

Simulations	RCM	GCM	Code
CLMcom-CCLM4_CNRM-CERFACS-CNRM-CM5	CLMcom-CCLM4	CNRM-CERFACS-CNRM-CM5	S1
CLMcom-CCLM4_ICHEC-EC-EARTH	CLMcom-CCLM4	ICHEC-EC-EARTH	S2
CLMcom-CCLM4_MPI-M-MPI-ESM-LR	CLMcom-CCLM4	MPI-M-MPI-ESM-LR	S3
KNMI-RACM022T-ICHEC-EC-EARTH	KNMI-RACM022T	ICHEC-EC-EARTH	S4
SMHI-RCA4_CNRM-CERFACS-CNRM-CM5	SMHI-RCA4	CNRM-CERFACS-CNRM-CM5	S5
SMHI-RCA4_ICHEC-EC-EARTH	SMHI-RCA4	ICHEC-EC-EARTH	S6
SMHI-RCA4_MPI-M-MPI-ESM-LR	SMHI-RCA4	MPI-M-MPI-ESM-LR	S7

variability in the Sahel. 3) The Gulf of Guinea Convergence Zone which is part of key features of the West African climate system. Variations in the position and intensity of the Convergence Zone can lead to fluctuations in rainfall across West Africa. 4) We also notice the region's diverse topography, including the Guinea Highlands, Niger River Basin, and coastal plains, can create local variations in precipitation patterns through orographic effects and land-sea breezes. 5) Land Cover Changes (Deforestation, agricultural expansion, and land degradation) influence the regional precipitation patterns in West Africa. Also, Saharan Dust and Aerosols can affect cloud formation and precipitation processes, potentially leading to changes in dryness and wetness [19] [20]. These are some of the phenomena affecting models' behaviour.

2.3. Methodology

To validate the simulations, three statistical parameters were calculated: mean rainfall, standard deviation (STD) and maximum rainfall for each model over the 1991-2005 historical period and for the 14 selected locations. These parameters were compared with those of the CHIRPS observation data over the same period in order to assess the degrees of similarity and quantify the differences between the data. The RCP4.5 and RCP8.5 projection scenarios for extreme rainfall events are analysed over two future periods, 2021-2035 and 2036-2050. In addition, the average rainfall calculated is an arithmetic mean, which is defined as the sum of the terms in a list, divided by the number of terms in the list. Thus, for any list (x_i, ..., x_n) of real numbers, its arithmetic mean is defined by the formula below

$$M = \frac{\sum_{i=1}^{n} x_i}{N} \tag{1}$$

which takes no account of the order of the terms and is always between the minimum and maximum values in the list. This average is linear, meaning that addition or multiplication by a constant on the values in the list results in the same operation on the average. The standard deviation is defined as the square root of the variance or, equivalently, as the root mean square of the deviations from the mean. It is homogeneous to the variable measured and its expression is given by the relationship below.

$$\sigma = \sqrt{V} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}x_i^2 - \bar{x}^2} \tag{2}$$

Climatic indices (e.g. CDD and CWD) associated with rainfall were also used to assess the degree of sensitivity of the cocoa crop to rainfall conditions and projections of future yields under the constraints of the RCP4.5 and RCP8.5 emission scenarios. The CDD index represents the number of consecutive days on which cumulative rainfall over at least 30 days is less than 70 mm (CP < 70 mm). Cocoa growing does not tolerate a dry period exceeding 3 months (90 days) [13]. The critical period is between November and March before the start of leaf growth and flowering in the cocoa tree. For the CWD index, on the other hand, the software (CDO) counts all periods with cumulative rainfall greater than or equal to 5 mm (CP ≥ 5 mm) over a 5-day period. To assess the change in extreme rainfall events over the two periods (2021-2035 and 2036-2050), we used the following equation:

$$\text{Changement}(\%) = \frac{(\text{projection} - \text{référence})}{\text{référence}} \times 100 \tag{3}$$

3. Results and Discussions

3.1. Results

3.1.1. Statistical Analysis

Table 1 shows the standard deviation values obtained by comparing the precipitation simulated by the models and that obtained from observations in the southern and central regions (**Figure 1**). These values were calculated over the period 1991-2005. We have also combined the mean, maximum and minimum annual precipitation. The standard deviations in the central and southern regions range from 87 to 150 and from 98 to 290 respectively. These low standard deviations from the mean highlight a low dispersion of rainfall around the annual mean, annual rainfall values tend to be close to the mean. As a result, rainfall variability in the central and southern regions shows smaller inter-annual fluctuations. With regard to the average rainfall value of the seven simulations in the CORDEX database over the historical period 1951-2005, the calculations show that it is fairly close to that of the CHIRPS data. The rainfall from the CORDEX simulations is therefore fairly well in line with that from CHIRPS. The ensemble model appears to perform well in terms of mean precipitation, as highlighted in the work of [11]. The author has shown that the average rainfall of fourteen regional climate models (RCMs) accurately represents the rainfall fields observed in West Africa. On the other hand, some simulations in our case are much wetter, in particular simulations S4, S5, S6 and S7, then others that are drier, such as S3, S2 and S1, which leads to biases in the representation of rainfall when the models are considered individually. The average of all the models could then compensate for the biases of each model, and thus make it possible to get closer to the CHIRPS observation data. Furthermore, with the exception of the period from June to September, when we can observe an increase in the ensemble mean rainfall compared with the CHIRPS data, the other months of the annual rainfall pattern are characterised by fairly identical trends between these two databases (Figure 2, a and b). The short dry season from July to August of the rainfall regime in the central and southern regions is not well represented by the average set of CORDEX models. However, most of the models (taken individually) are able to capture the bimodal nature of the rainfall regime in the central and southern regions, unlike the ensemble mean.

In the southern and central regions, the annual rainfall totals are respectively 1523 mm and 1299 mm for the average of all the models and 1704 mm and 1279 mm for the CHIRPS observations, which shows that the annual rainfall totals over the historical period are fairly well reproduced. In both regions and for both databases, these accumulations are higher than 1200 mm, the accepted annual rainfall threshold for cocoa in Côte d'Ivoire [21]. This result indicates that rainfall conditions in the central and southern regions are suitable for cocoa growing.

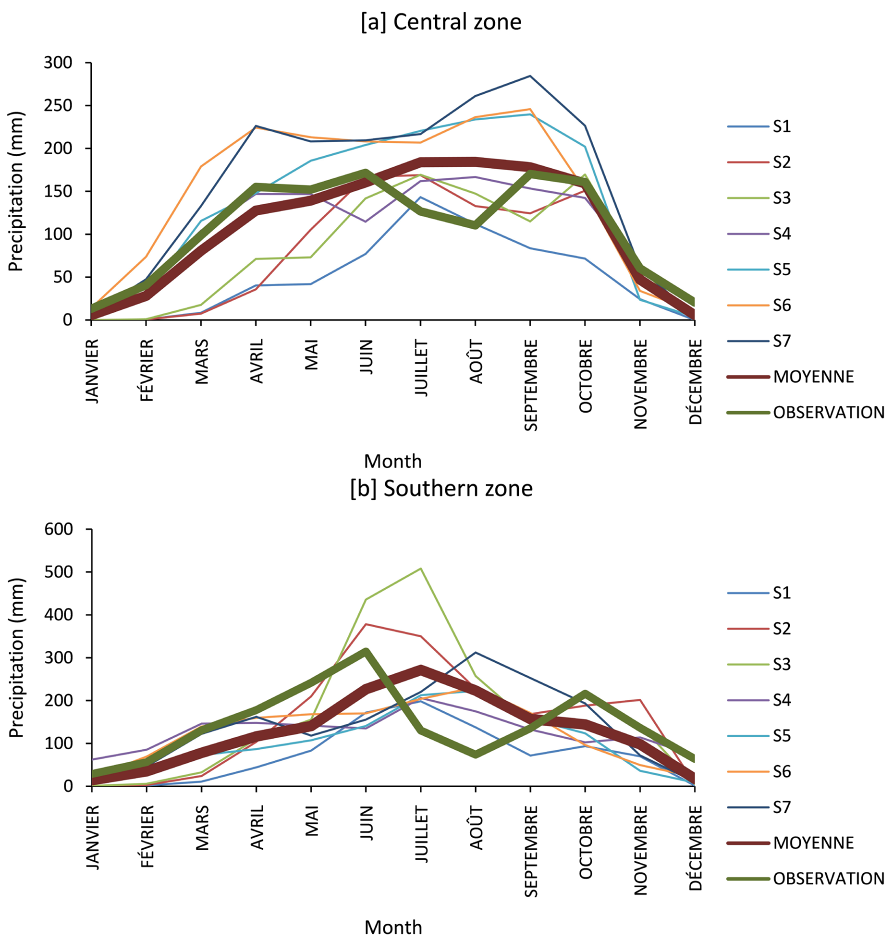

Figure 2. Intra-annual trends in mean monthly precipitation for the seven CORDEX models (S1, S2, S3, S4, S5, S6 and S7), their overall mean (brown) and observations for the central [a] and southern [b] regions over the period 1991-2005.

3.1.2. Determining Climate Indices: CDD and CWD

1) Index of consecutive dry days (CDD)

The CDD climatic index was used in this study to assess the impact of drought on cocoa production using seven CORDEX simulations. The results in **Table 2** were obtained for each grid point corresponding to the cocoa production zones in the central and southern regions of the study area, on the basis of cumulative rainfall of less than 70 mm over a period of 90 days (tolerance threshold accepted by the cocoa tree during the dry season). The results show that the CDD index varies from one locality to another and from one model to another. The mean values of all seven models indicate the presence of moderate or severe drought in all cocoa-producing localities in the study area. The majority of the localities studied are strongly affected by drought, particularly Tabou, San-Pedro, Aboisso, Fresco, Divo and Agboville, with an average of nine, eight, seven and six dry events respectively over the period 1991-2005. These results support the current observation on rainfall trends in West Africa, which many studies [22] emphasise are declining significantly and could be accompanied by rising temperatures over the coming decades. This significant drop in rainfall could alter the growth of plant species such as cocoa, leading to changes in the areas suitable for cocoa farming.

2) Changes in the CDD index for the RCP4.5 scenario

Figure 3 shows that there is little variation in the CDD index with increasing georeferenced latitudes in the different study areas. This result suggests that variations in the CDD index are not strongly impacted by latitude. These variations highlight the effect of local factors in the areas studied, such as temperature and rainfall variability, which show specific spatial behaviour. However, for the RCP4.5 scenario, there is a significant increase in the CDD index over the period 2021-2035 in the localities of San-Pedro, Agboville, Gagnoa, Abengourou, Tabou and Vavoua. For the other localities, the increase is relatively small.

On the other hand, over the period 2036-2050, the CDD index increases in areas such as Gagnoa, Abengourou and Tabou, while in other localities such as Yamoussoukro, Aboisso and Guiglo, where the increase was low, the trend is reversed with a significant increase in the CDD index. Aboisso is the locality with

Table 2. Annual precipitation (models and observations) calculated over the central and southern regions using STDs over the period 1991-2005.

ZONES		S1	S2	S3	S4	S5	S6	S7	Mean	OBS
	STD	147	150	145	87	133	124	109	131	104
CENTRE	Moy (mm)	602	956	966	1278	1607	1796	1884	1298	1279
	Max (mm)	857	1240	1190	1472	1868	2089	2046	1537	1451
	STD	153	221	290	98	135	152	207	175	171
SOUTH	Moy (mm)	884	1858	2013	1521	1207	1502	1677	1523	1704
	Max (mm)	1144	2364	2453	1729	1575	1841	1993	1871	2072

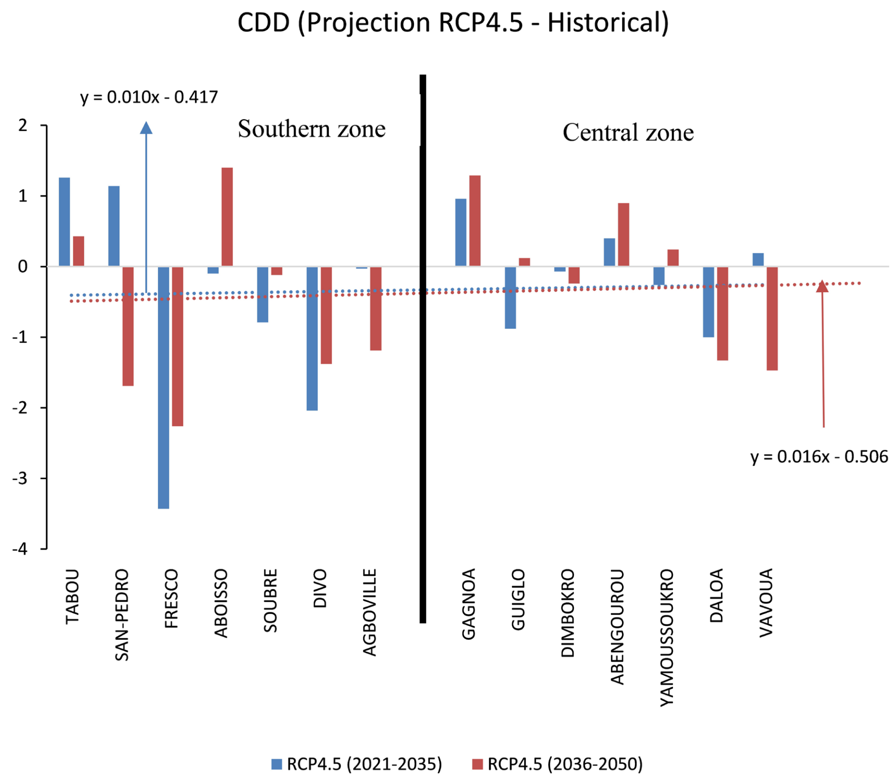

Figure 3. Latitudinal trends (south-central) in the difference in CDD indices between the RCP4.5 scenario (projection) and historical data (1991-2005) with associated trend curves.

the highest CDD index value and Fresco is the one with the lowest CDD index value. In the southern and central regions (**Figure 4**), there is also a negative difference in the number of consecutive dry days between projections and historical data in most locations. Overall, the RCP4.5 scenario results in a decrease in the CDD index, and hence a decrease in drought periods, in all areas of the southern and central regions, with the exception of Yamoussoukro, Abengourou, Guiglo and Gagnoa in the central region and Aboisso in the southern region, which are likely to experience an increase in the CDD index and hence in drought periods. Drought is therefore more likely to occur in the central region than in the southern region for the RCP4.5 scenario, which could have a considerable impact on the mortality of young cocoa trees in the central region, as highlighted by the work of [21]. The work carried out by these authors in Côte d'Ivoire has shown clear signs of the onset of drought in Gagnoa and Divo. This situation of reduced rainfall must be accompanied by replanting with drought-resistant hybrids in association with tree legumes or banana trees to reduce the mortality rate.

3) Changes in the CDD index for the RCP8.5 scenario

In the case of the RCP8.5 scenario (**Figure 4**), there is a gradual decline in the values of the CDD index in the Tabou-Vavoua latitudinal trinsect, from the southern region towards the central region. This weakening of the drought state

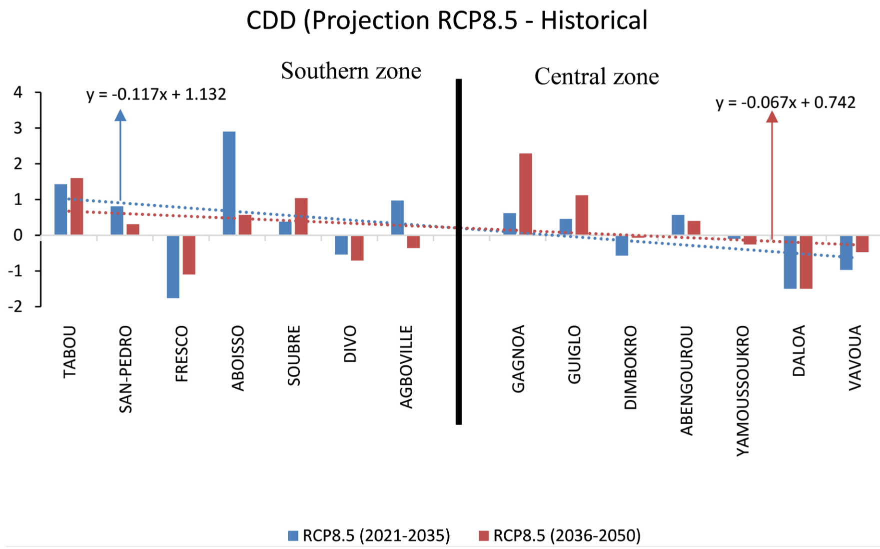

Figure 4. Latitudinal trends in the difference in CDD index values between the RCP8.5 scenario (projection) and historical data (1991-2005) with associated trend curves.

is much more pronounced in the 2021-2035 period than in the 2036-2050 period. Over the period 2021-2035, the localities of San Pedro, Agboville, Soubré, Gagnoa, Abengourou, Guiglo and Tabou experience an increase in CDD index values, whereas in the other zones this increase is marginal. Over the period 2036-2050, CDD index values continue to increase in the San-Pedro, Soubré, Abengourou, Guiglo and Tabou zones. An upward trend in consecutive dry days (CDD index) can be seen overall in both the southern and central regions and for both the 2021-2035 and 2035-2050 periods. This increase is more pronounced in the central region, particularly in the areas of Guiglo, Dimbokro, Vavoua and Gagnoa over the 2036-2050 period. However, the locality of Daloa is not affected by this upward trend, and the Yamoussoukro area experiences a return to humid conditions over the 2035-2050 period. These results could be explained by an increase in extreme events in certain areas in the RCP8.5 scenario, leading to heavy rainfall.

3.1.3. Consecutive Rainy Days (CWD Index)

The CWD index was calculated in this section to assess wet periods and their impacts on all fourteen zones mentioned in Figure 1, based on climate scenarios derived from the simulations in Table 3. The parameter used is cumulative rainfall greater than or equal to 5 mm over a consecutive period of 5 days (the threshold representing the rainy season for cocoa). The results show that some models S1, S2 and S3 are drier than others and record half the number of consecutive rainy days for all the locations studied, unlike models S4, S5, S6 and S7. However, the overall average of the seven models shows the presence of a good series of rainy events for the majority of locations. The highest values were recorded in the southern region for San-pédro (67 consecutive wet day events) and Aboisso (64 consecutive wet day events), in contrast to Guiglo (31 consecutive

Table 3. CDD Index values calculated for each CORDEX model and for the different localities over the historical period 1995-2005.

Localities	S1	S2	S3	S4	S5	S6	S7	Mean
YAMOUSSOUKRO	6	6	10	3	3	1	2	4,4
ABOISSO	10	15	20	1	2	5	6	8,4
SAN-PEDRO	10	14	21	2	1	4	10	8,8
FRESCO	10	17	14	2	2	1	6	7,4
ABGBOVILLE	11	11	14	1	1	3	7	6,8
DIVO	8	13	18	2	1	1	4	6,7
SOUBRE	5	10	12	3	1	1	5	5,3
GAGNOA	4	9	5	3	1	1	3	3,7
ABENGOUROU	10	10	12	1	1	2	2	5,4
GUIGLO	5	10	6	4	1	2	5	4,7
DALOA	5	6	9	4	3	2	6	5
DIMBOKRO	6	8	8	4	2	2	2	4,6
TABOU	8	23	17	1	2	6	10	9,6
VAVOUA	8	5	6	4	3	5	5	5,1

wet day events), Daloa (37 consecutive wet day events), Dimbokro (44 consecutive wet day events), Vavoua (36 consecutive wet day events) and Fresco (38 consecutive wet day events), which recorded the lowest average rainfall events over the period 1991-2005.

- Number of consecutive rainy days (CWD)

Figure 5 shows the latitudinal profile of CWD index differences for the periods 2021-2035 (Period 1) and 2036-2050 (Period 2) for the RCP4.5 scenario and the historical period (1991-2005). The differences calculated show a latitudinal trend towards an increase. This distribution of differences between RCP4.5 and the historical period is therefore influenced by latitude. This highlights the latitudinal nature of the distribution of the CWD index and, consequently, that of rainfall variability from south to north. For the first period (2021-2035), the central zone saw an increase in the CWD index compared with the historical period (1991-2005) in most zones, with the exception of Guiglo and Vavoua, where the differences were negative. The southern region, on the other hand, is subject to a decrease in the CWD index in the 2021-2035 period, and four localities (Aboisso, San-pédro, Fresco and Agboville) out of seven have negative index differences, which means that there will probably be more rainfall events in the historical period than in the 2021-2035 period. For the period 2036-2050, only the localities of Guiglo and Vavoua have negative CWD index differences, as in the period 2021-2035 for the central region. For the southern region, there is a significant variation in consecutive rainy days compared with the period 2021-2035, and CWD index values are significantly higher than those for the

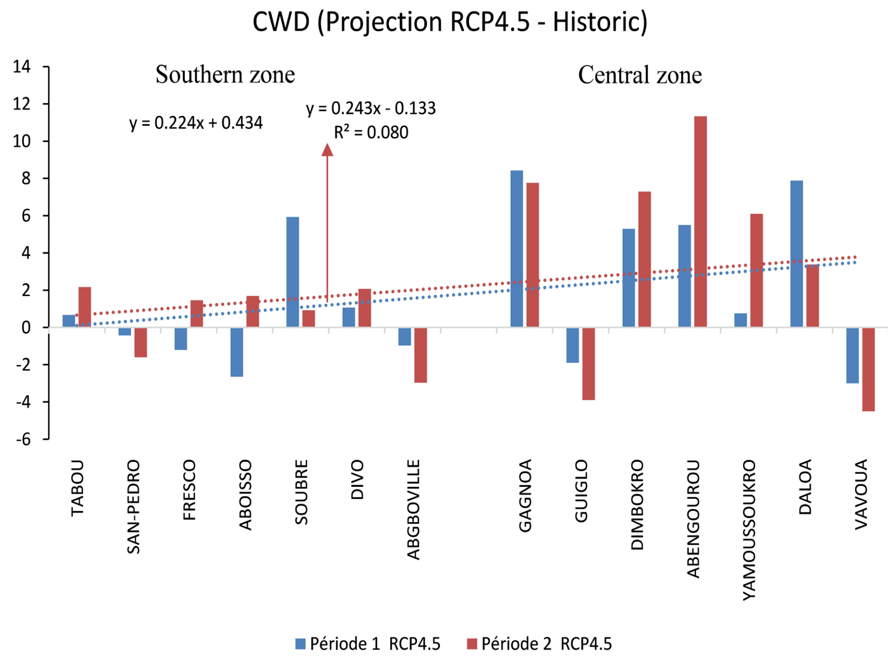

Figure 5. Differences between CWD index values for the periods 2021-2035 and 2036-2050 in the RCP4.5 scenario and the historical period 1991-2005 for the various cities selected.

historical period (1991-2005), as all localities experience positive CWD index differences except for the localities of Agboville and Aboisso. For the period (2036-2050), the differences are higher in the central zone than in the southern zone, although the southern zone as a whole experience less variation in rainfall events.

- Difference between RCP8.5 projection and Historical for consecutive rainy days.

There is a latitudinal upward trend in the consecutive rainy days index (CWD) from the south to the centre. This trend is present over the two future periods 2021-2035 and 2036-2050 in the RCP8.5 projection scenario, although it is less pronounced in the southern region, where only four localities (San-Pédro, Agboville, Divo and Fresco) show negative CWD index differences over the future period 2021-2035. The same is true for Vavoua and Guiglo in the central region. The 2021-2035 period shows that there could be a greater increase in rainfall in the central region than in the southern region due to an increase in CWD.

Furthermore, over the period 2036-2050, the southern and central regions will experience an overall increase in consecutive wet spells, and this increase will be greater in the central region, with high positive differences (of up to 10) in the CWD index between the RCP8.5 projection scenario and the historical period (1991-2005). Only the Guiglo and Vavoua areas in the central region, and the Aboisso and Agboville areas in the southern region, show negative differences in CWD index values.

3.1.4. Difference in CWD between RCP4.5 and RCP8.5 Scenarios

Over the period 2021-2035, the CWD index remains high for most localities, with the exception of Yamoussoukro, Aboisso, Dimbokro and Tabou (**Figure 6**). The CWD values calculated show that the RCP4.5 scenario has a wetter climate than the RCP8.5 scenario. Indeed, the implications of the RCP4.5 scenario (*i.e.* lower greenhouse gas (GHG) forcing) could lead to an increase in the number of consecutive rainy days (CWD), unlike the RCP8.5 scenario, which has a higher GHG forcing. Furthermore, the impact of GHGs on the spatiotemporal variability of the CWD index is well observed in the southern and central regions over the period 2021-2035. Over the period 2036-2050 (**Figure 7**), as the years go by, there will be more localities with a negative difference in CWD index values between the RCP4.5 and RCP8.5 scenarios. These negative values reflect a probable

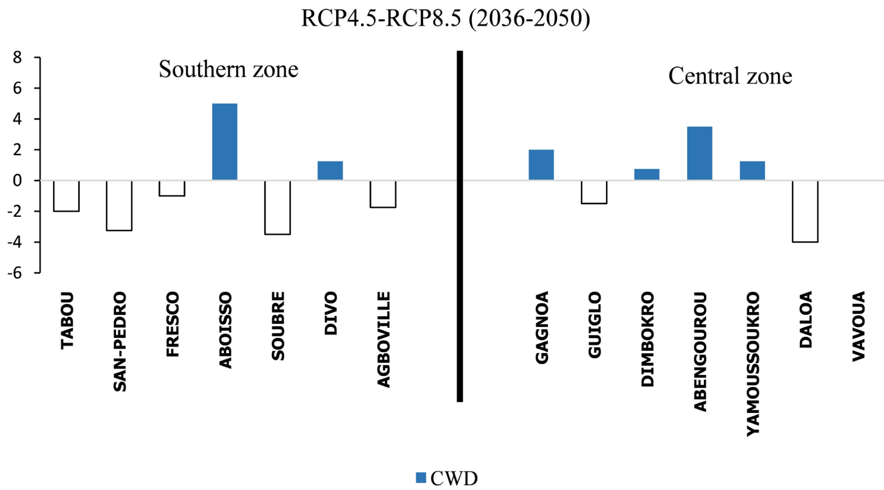

Figure 6. Difference in the CWD climate index between the different RCP4.5 and RCP8.5 projections for the near future (2021-2035) in the different towns in the southern and central zones.

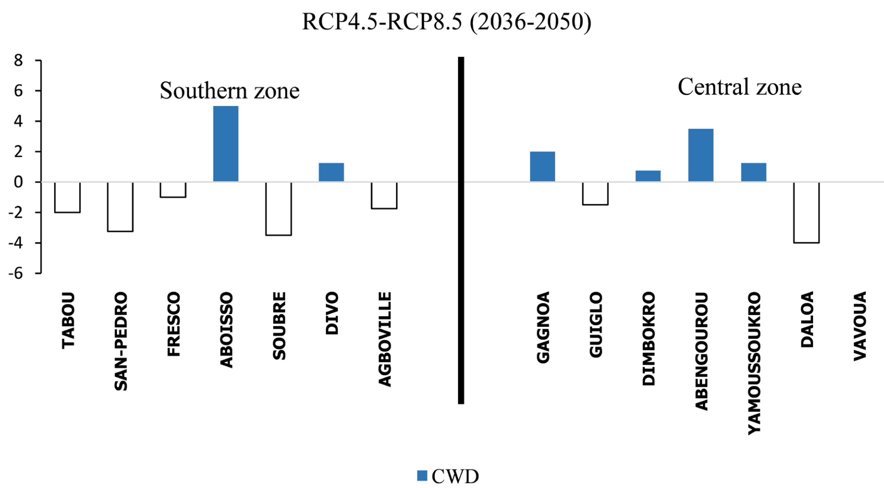

Figure 7. Difference in the CWD climate index between the different RCP4.5 and RCP8.5 projections for the distant future (2036-2050) in the different cities in the southern and central zones.

rainfall deficit in the southern and central regions. This could lead to an excessive increase in rainfall patterns, *i.e.* extreme rainfall events over the period 2036-2050. The frequency of these rainfall extremes could, on the one hand, asphyxiate the roots of young plants in areas where the soil is less water-absorbent, and on the other hand cause surface leaching, which would lead to nutrients being washed into run-off water.

- Index difference (CWD) between RCP45 and RCP85 projections over the periods 2021-2035 and 2036-2050.

For the period 2021-2035, a comparison of the RCP4.5 and RCP8.5 scenarios shows that the southern region will be more affected overall by consecutive dry days in the RCP8.5 scenario, which is the most aggressive scenario in the projections of future climate up to 2100. The central region, on the other hand, will experience more consecutive dry days overall in the RCP4.5 scenario than in the RCP8.5 scenario. Over the periods 2021-2035 and 2036-2050, the number of consecutive dry days will increase, resulting in an increase in the dry season, and therefore an increasing reduction in the areas suitable for cocoa cultivation.

3.2. Discussion

The rainfall potential of the southern and central cocoa-growing regions of Côte d'Ivoire (climatic drought index, climatic humidity index, climatic flood index) was determined using the RCP4.5 and RCP8.5 climate projection scenarios. Drought was characterised by an overall increase in the CDD index for the RCP4.5 and RCP8.5 projection scenarios in the various locations studied. These results are in agreement with those observed in the Adaptcoop project [23]. Indeed, more than half of the fourteen localities studied over the periods 2021-2035 and 2036-2050 experience an increase in the CDD index compared with the historical period (1991-2005). The localities of Tabou, San-Pedro, Fresco and Aboisso are more affected by drought, with maximum dry periods of nine days for Tabou and eight days for San-Pedro, Fresco and Aboisso over a fifteen-year period (2021-2035). Nevertheless, for the southern and central regions as a whole, cumulative rainfall over the year exceeds 1200 mm, and the work of [24] indicates that this is the minimum threshold required for cocoa trees every year. This increase in drought, also highlighted by [25] and [26], has resulted in a decline in rainfall since the 1970s throughout West Africa. A dual analysis on the scale of a station on the one hand and on the spatial scale on the other confirmed this observation, particularly for annual rainfall in Côte d'Ivoire, Togo and Benin. The time series of rainfall indices in the work by [27] also confirm the sharp drop in rainfall at the end of the 1960s. Also, the cartographic representation of the results shows the clear southward shift of the isohyet curves and highlights the regional dimension of the phenomenon. The rainfall less than 1200 mm/year can lead to reduced root growth, leaf drop, and reduced plant growth. Cocoa trees must receive at least 700 mm of rain during the rainy season. What's more, for cocoa to ripen properly, the rainy season must last 4 consecutive months, from the flowering phase to the end of the main harvesting season from March to November [16]. However, the CWD climate index has risen for all the localities in the regions under the two projection scenarios RCP4.5 and RCP8.5 and over the periods 2021-2035 and 2036-2050, with an accentuation in the second period. This situation is characterised by the fact that extreme rainfall is increasingly felt in both regions, particularly in the south, with maximums of thirty-three extreme rainfall events over a fifteen-year period. Contrary to what might appear, an increase in CWD index values would promote the growth of young cocoa trees, good foliation and increase productivity. However, this increase could also have repercussions on the survival of cocoa trees due to probable flooding, which would result in the loss of surface layers of soil containing nutrient rudiments for cocoa trees, and a drop in foliation if these rains occur during the flowering period. These results are in line with those of [28], who indicate that Côte d'Ivoire is subject to a significant increase in intense rainfall associated with an amplification of extreme rainfall events during the monsoon period. In particular, during the July-August-September season, a substantial increase in extreme precipitation of up to 50% - 60% relative to the mean reference value prevails in the western and coastal regions in the distant future and under the RCP8.5 scenario.

These results suggest that agricultural production in general and cocoa plantations in the south-western regions in particular could be at risk from flooding, and that water stress remains a threat to cocoa, coffee and other cash crop plantations in the eastern regions for the RCP4.5 and RCP8.5 scenarios respectively, albeit with considerable uncertainties.

In this study, the RCP4.5 and RCP8.5 scenarios showed that the southern and central regions of Côte d'Ivoire may no longer be suitable for cocoa production by 2100 under the RCP8.5 scenario [23]. Authors such as [29] and [30] have shown that the amount of rainfall during the main rainy season (April-May-June) is essential for cocoa growing. These results were obtained even though other exogenous factors such as soil quality, altitude, relief and topography, which also affect cocoa growing, were not highlighted in this study.

4. Conclusion

In this study, the climate indices (CDD, CWD and the index of change) were examined for the time horizons 2035 and 2050 on the CORDEX-Africa database. All the results of the CDD climate index show an increase in drought in the two regions of our study. The rainfall projections produced by the seven different models do not agree individually with the historical results. Some models are too wet and give precipitation values that are too high, while others are too dry, with less precipitation than observed. However, the average of all the models is a good representation of the trend in the observed data. Furthermore, the RCP4.5 scenario has more consecutive dry days than the RCP8.5 scenario in the first period 2021-2035, unlike the second period 2036-2050, when the RCP8.5 scenario has more consecutive dry days. Thus, the RCP8.5 scenario predicts a warmer and drier climate than the RCP4.5 scenario by 2050. The average annual rainfall for the models indicates 1270 mm for the central region and 1523 mm for the southern region over the historical period 1991-2005, showing that these regions are suitable for cocoa growing. However, projections of the CDD and CWD climate indices indicate that these regions will experience a decrease in the number of consecutive rainy days in the rainfall regime, with an increasing number of extreme events. These reductions could have an impact on cocoa tree growth, resulting in the loss of flowers during the flowering period, the impoverishment of soils that are less permeable when flooded, and a drop in productivity. This implies that there will probably be a change in agricultural activities that depend on rainfall. With regard to the seasons of the rainfall regime, the seven models indicate two rainy seasons (one long and one short) and two dry seasons (one long and one short) in the southern and central regions. Furthermore, in order to better assess the contribution of climate projections to improving cocoa yields, other climatic parameters such as temperature and relative air humidity should have been associated, as these climatic conditions have a fairly significant impact on the quality of crop yields. These associated meteorological data could improve the quality of climatic services dedicated to cocoa growing.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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