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Projected Changes in the Climate Zoning of Côte d'Ivoire

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Abstract

This study assesses the projected changes in the climate zoning of Côte d'Ivoire using the hierarchical classification of principal components (HCPC) method applied to the daily precipitation data of an ensemble of 14 CORDEX-AFRICA simulations under RCP4.5 and RCP8.5 scenarios. The results indicate the existence of three climate zones in Côte d'Ivoire (the coastal, the centre and the north) over the historical period (1981-2005). Moreover, CORDEX simulations project an extension of the surface area of drier climatic zones while a reduction of wetter zones, associated with the appearance of an intermediate climate zone with surface area varying from 77,560 km^2 to 134,960 km^2 depending on the period and the scenario. These results highlight the potential impacts of climate change on the delimitation of the climate zones of Côte d'Ivoire under the greenhouse gas emission scenarios. Thus, there is a reduction in the surface areas suitable for the production of cash crops such as cocoa and coffee. This could hinder the country's economy and development, mainly based on these cash crops.

Keywords

Climate Projection, Climate Zone, Principal Component Analysis, Hierarchical Classification on Principal Components, CORDEX, Côte d'Ivoire

1. Introduction

Climate change is one of the greatest challenges faced by mankind nowadays. Surface air temperature is characterized by an upward trend [1] while precipitation regimes are still uncertain and their projections vary from one climate model to another. Many activity sectors (economy, transportation, livestock farming, tourism, etc.) are affected by the advent of climate change phenomenon at global, regional and local scales, particularly in Africa [2] [3] [4] [5]. Moreover, the impacts of climate change in sub-Saharan regions can vary from one country to another, and even within different regions of the same country, due to the diversity of the ecosystem. Côte d'Ivoire is one of the West African countries most vulnerable to the effects of climate change [6]. Potential impacts include variability of the precipitation regimes [7], the occurrence, frequency and intensification of extreme weather events [6] [8] [9] [10] [11] and changes in the hydrological cycles [12] [13]. In addition, previous studies, using weather station data, have highlighted changes in climatic zones in Côte d'Ivoire [14] [15] [16]. These changes have negatively impacted some activities sectors including agriculture, livestock farming and natural resources due to their dependence on the climate. On the other hand, these studies have also used various methods to characterize the variability of the climate zones in Côte d'Ivoire, including principal component analysis (PCA) [14], normalized principal component analysis (NPCA) [15] and ascending hierarchical clustering (AHC) [15] [16]. The results revealed the variation in the number and structures of the climate zones, depending on the methods used, the data type and the study periods. In order to understand the challenges related to the variability in climate zones for short and long terms, it is thus necessary to define the delimitation of the climate zones in Côte d'Ivoire involving climate projections (*i.e.*, RCP4.5 and RCP8.5). This study assesses future modifications in the climate zoning of Côte d'Ivoire with respect to the present climate conditions. To address this concern, this study analyses future projections of the climate zoning of Côte d'Ivoire using high-resolution (about 50 km) regional climate models from the Coordinated Regional Climate Downscaling EXperiment (CORDEX-Africa) program [17].

Indeed, regional climate models play an essential role in assessing future changes at regional and local scales. The CORDEX-Africa simulations provide detailed information on Africa's regional climate at high resolution (about 50 km) to produce reliable climate scenarios, specific to an area (*i.e.*, Côte d'Ivoire), taking into account its geographical and climatic features.

Therefore, the study also analyses the impacts of climate change on the climate zoning of Côte d'Ivoire for different periods using the method of combination of multivariate analyses applied to the daily precipitation data from CORDEX, used as variables.

Section 2 of the paper describes the material and methods. Sections 3 and 4 present the results and discussion while section 5 gives the concluding remarks.

2. Materials and Methods

2.1. Study Area

This study investigated over Côte d'Ivoire, a West African country located between (4˚N-11˚N, 8˚W-2˚W), covering a surface area of 322,462 km^2 (about 1% of the total surface area of the African continent). The country is bordered to the south by the Gulf of Guinea, to the east by Ghana, to the west by Liberia and Guinea, and to the north by Mali and Burkina Faso. There are three main types of climate in Côte d'Ivoire equatorial, tropical and mountainous [18]. The equatorial climate, located in the southern part of the country, is characterized by a high humidity (82% in Abidjan), a mean temperatures (about 26˚C) and abundant rainfall (about 1922 mm/year in Abidjan) [19]. This region is governed by two dry and wet seasons during the year. The tropical climate predominates in the northern part of the country. With mean annual temperatures varying around 26˚C, with a relatively higher daily temperature ranges around 32˚C

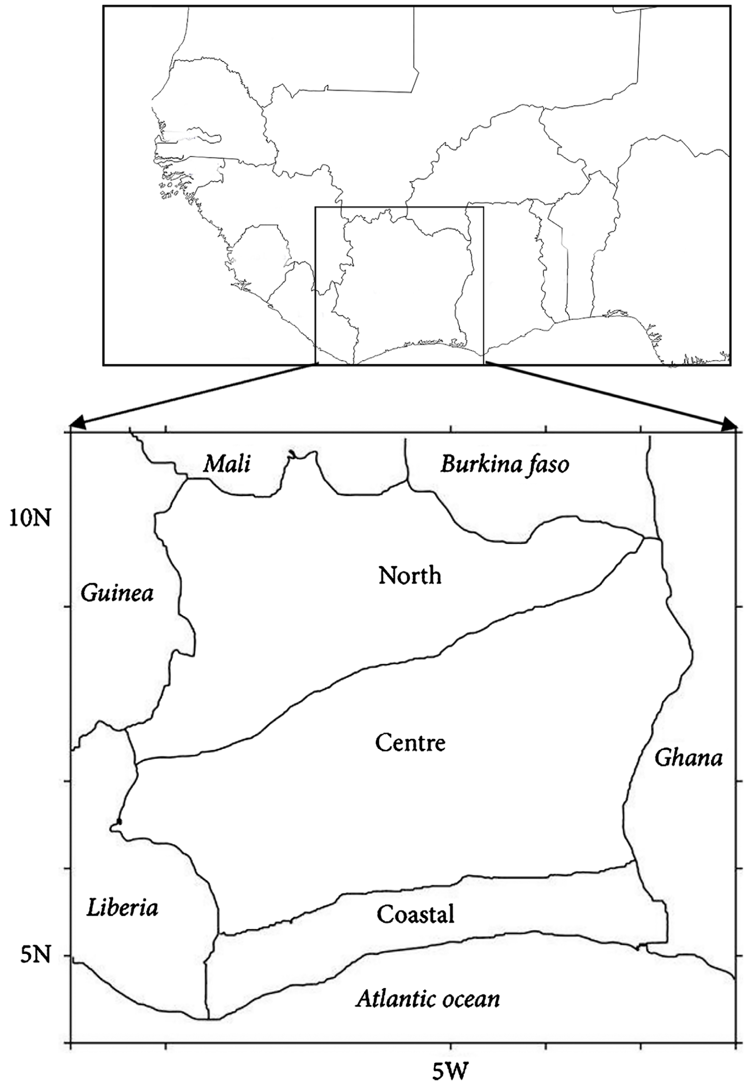

Figure 1. Map of Côte d'Ivoire displaying the three climatic areas (Coastal, Centre and North), adapted from [14].

and low humidity (63% in Korhogo) compared to the southern region. This region is dominated by a long dry season and a short rainy (wet) season, as well as the presence of a cool and dry wind originating from the Sahelian regions known as the "harmattan" blowing during December-February. Mean annual rainfall is generally less than 1300 mm/year. The mountainous climate in the western part of the country is characterized by abundant annual rainfall, compared to the northern region with two seasons: a rainy and a dry season. Mean annual temperatures vary around 24˚C, and relative humidity remains very high throughout the year, reaching about 98% in Man [20].

2.2. Data

In this study, we used simulated daily precipitation data derived from an ensemble of 14 simulations of the Coordinated Regional Climate Downscaling EXperiment (CORDEX) phase 2 [21] [22] available at the Earth System Grid Federation (ESGF) website (https://esg-dn1,nsc,liu,se/projects/esgf-liu/) with a horizontal resolution of 0.44˚ (about 50 km). These simulations are composed of 8 Regional Climate Models (RCMs) forced by 7 Global Climate Models (GCMs) from the Coupled Intercomparison Project phase 5 (CMIP5) (see **Table 1**). The data span the historical (1950-2005) and future (2006-2100) periods, under RCP4.5 and RCP8.5 radiative forcing scenarios. They are useful for providing a regional climate analysis for many meteorological parameters (temperature, precipitation, etc.,) for a given region (e.g. Africa) and at different periods [23] [24]. Moreover, CORDEX simulations have been evaluated in terms of their ability to simulate mean climate (precipitation and temperature) as well as climate extremes

Table 1. List of the 14 CORDEX-Africa Phase 2 simulations used in the study. The simulations include the RCMs and the GCMs used as boundary data ([6] [10]).

RCM	GCM	RCP	Status
SMHI-RCA4	CanESM2	4.5, 8.5	ESGF
	CNRM-CM5	4.5, 8.5	
	ES-EARTH-r12	4.5, 8.5	
	IPSL-CM5A-MR	4.5, 8.5	
CLMcom-CCLM4-8-17	MPI-ESM-LR	4.5, 8.5	ESGF
	ES-EARTH-r12	4.5, 8.5	
	HadGEM2-ES	4.5, 8.5	
	CNRM-CM5	4.5, 8.5	
DMI-HIRHAM5	EC-EARTH-r3	4.5, 8.5	ESGF
KNMI-RACMO22E	EC-EARTH-r1	4.5, 8.5	ESGF
CCCma-CanRCM4	CanESM2	4.5, 8.5	CCCMA ftp
MPI-CSC-REMO2009	MPI-ESM-LR	4.5, 8.5	RCM group
CNRM-ALADIN52	CNRM-CM5	4.5, 8.5	RCM group (not all vars)
BCCR-WRF331	NorESM1-M	4.5, 8.5	RCM group

in Africa with satisfactory results [23] [24] [25] [26]. In addition, high resolution (about 5 km) daily precipitation data from the "Climate Hazards Infrared Precipitation" (CHIRP) of the University of California [27] covering the period 1981-2005, are also used as observation data. These data have the advantage of providing reliable information on the climatic variability over the study area due to their high resolution [5] [6].

2.3. Methods

The analysis of climate zoning and its projections in Côte d'Ivoire is carried out using the multi-model ensemble mean of the 14 CORDEX simulations based on the grid clustering method. The multi-model ensemble approach consists of using the mean of an ensemble of simulations to reduce the difficulties associated with characterizing the uncertainties existing between them. Clustering is a multivariate statistical technique designed to explore structures within a data set whose prior properties are unknown [28]. This technique is regularly used in various forms to determine rainfall structures and climatic regions in West Africa, particularly in Côte d'Ivoire [14] [15] [29]. This technique aims to assign data to significant classes by increasing the similarity within each cluster while maximizing the differences between clusters. Although various clustering algorithms exist, we used hierarchical clustering on principal components (HCPC). The advantage of this approach is to combine the three standard methods used in multivariate data analysis, in particular, the principal component analysis (PCA), the hierarchical clustering and the k-means [30]. Taken individually, k-means and hierarchical clustering are less effective when applied to a large number of dimensions. However, the results are better as the dimensions decrease [31]. In the HCPC, PCA is used to reduce the dimensions of the multivariate input data for two or three principal components, or even more, depending on the selected criterion, while losing as much information as possible. PCA axes use the Kaiser criterion [32] stipulating that only axes associated with eigenvectors and eigenvalues greater than or equal to 1 are considered significant. The hierarchical classification of the variables deduced from the PCA will define the different clusters over the historical (1981-2005), the near future (2031-2060) and the far future (2071-2100) periods under RCP4.5 and RCP8.5 scenarios. The similarity between the variables for the different climatic zones derived from CORDEX and CHIRPS during the historical period is evaluated using Spearman correlation coefficients. The similarity is significant if the p-value associated with the correlation coefficient is less than 0.05 [33]. Spatial variability of the climate zones over future periods is estimated by the variation rate (in percentage %), following Equations (1) and (2):

$$\text{Rate}(\%) = \frac{\text{Pop}_{\text{zone(i)}_{\text{projection}}} - \text{Pop}_{\text{zone(i)}_{\text{historical}}}}{\text{Pop}_{\text{Total}}} * 100 \tag{1}$$

$$\text{Variation} = \left(\text{Pop}_{\text{zone(i)}_{\text{projection}}} - \text{Pop}_{\text{zone(i)}_{\text{historical}}}\right) * \text{surface}_{\text{grid}} \tag{2}$$

Rate: rate of change in the area of zone i, for a given period,

$Pop_{zone(i)_{projection}}$: number of grids in zone i, over the projection period,

$Pop_{zone(i)_{historical}}$: number of grids in zone i, over the historical period,

Pop_{Total} : total number of grids over the study area,

Variation: variation in the area of zone i, for a given period,

$surface_{grid}$: surface area of a grid (50 km * 50 km).

3. Results

3.1. Statistical Description of the Variables

The statistical descriptions of the variables are summarized in Table 1(a) and Table 1(b). The results reveal that monthly rainfall over the period 1981-2005 varies between 0.95 and 462.81 mm for CHIRPS variables (respectively between 0.17 and 432.9 mm for CORDEX variables) while monthly mean rainfall varies between 9.62 and 184.07 mm for CHIRPS (respectively between 6.59 and 244.1 mm for CORDEX).

3.2. Identification of the Climate Zones over the Historical period (1981-2005)

1) Principal component analysis (PCA)

Table 3(a) and Table 3(b) present the eigenvalues and variances of the various factors (axes) obtained from the principal component analysis (PCA) of the mean daily cumulative precipitation over the period 1981-2005. Principal components with eigenvalues equal or greater than 1 were considered significant according to the Kaiser criterion [32]. Only the first ten components fulfil this criterion for CHIRPS variables and the first seven for CORDEX. The results indicate that these components explain 81.81% and 92% of the total variance of CHIRPS and CORDEX rainfall, respectively. The principal components of the axes dim.1 to dim.10 for CHIRPS and dim.1 to dim.7 for CORDEX are retained for analysis (see Table 2).

2) Hierarchical Classification of Principal Components (HCPC)

The hierarchical classification of principal components (HCPC) of CHIRPS and CORDEX variables during the period 1981-2005 defines three (3) distinct major classes in Côte d'Ivoire (Figure 2(a) and Figure 2(b)). The first class (C1) includes 23 grids for CHIRPS and 18 grids for CORDEX, located along the coast between latitudes 4.75˚N and 6.25˚N for CHIRPS and latitudes 4.75˚N and 5.25˚N for CORDEX. The second class (C2) comprises 50 grids for CHIRPS and 39 grids for CORDEX. This class includes the central grid for CORDEX with a maximum latitude of 7.75˚N, and the central and northeastern grids with a maximum latitude of 8.75˚N. Finally, the third class (C3) consists of 39 grids for CHIRPS and 55 grids for CORDEX. It contains grids in the northern zone with minimum latitudes of 8.75˚N and 7.75˚N respectively.

Figure 3 shows the spatial distribution of the homogeneous climatic zones obtained from the CHIRPS (a) and CORDEX (b) principal components hierarchical classification analysis. These representations show that Côte d'Ivoire can be subdivided into three (3) homogeneous climatic zones:

Table 2. Descriptive statistics for CHIRPS (a) and CORDEX (b) rainfall during the historical period (1981-2005).

(a)

Variables	Minimum	Average	Maximum
Longitude	−8.75	−5.50	−2.25
Latitude	4.25	7.50	10.75
January	0.950	9.619	37.080
February	4.21	31.07	78.61
March	18.37	81.10	185.23
April	58.92	124.40	199.21
May	86.52	149.48	301.45
June	94.73	184.07	462.81
July	81.29	159.22	354.62
August	39.51	166.97	366.18
September	74.82	182.00	361.15
October	77.85	138.85	249.54
November	6.48	51.83	172.66
December	1.990	22.384	107.520

(b)

Variables	Minimum	Average	Maximum
Longitude	−8.75	−5.50	−2.25
Latitude	4.25	7.50	10.75
January	0.280	6.586	27.980
February	1.500	15.137	61.850
March	9.92	51.34	166.64
April	39.69	98.55	200.78
May	97.74	140.19	224.11
June	124.5	188.7	342.0
July	144.1	237.7	432.9
August	166.0	244.1	385.0
September	149.4	207.5	300.0
October	104.2	152.4	273.6
November	12.20	60.77	174.62
December	0.170	11.269	52.070

Table 3. Eigenvalues and variances of the principal axes of CHIRPS (a) and CORDEX (b) variables for the historical period (1981-2005).

(a)

Axis	Eigen value	Variance (%)	Cumulative variance (%)
Dim.1	176.54	48.24	48.24
Dim.2	46.3	12.65	60.89
Dim.3	33.61	9.18	70.07
Dim.4	11.2	3.06	73.13
Dim.5	8.2	2.24	75.37
Dim.6	5.85	1.6	76.97
Dim.7	5.19	1.42	78.38
Dim.8	4.49	1.23	79.61
Dim.9	4.16	1.14	80.75
Dim.10	3.89	1.06	81.81
Dim.11	3.39	0.93	82.74

(b)

Axis	Eigen value	Variance (%)	Cumulative variance (%)
Dim.1	197.93	54.23	54.23
Dim.2	60.67	16.62	70.85
Dim.3	53.36	14.62	85.47
Dim.4	8.18	2.24	87.71
Dim.5	7.92	2.17	89.88
Dim.6	5.29	1.45	91.33
Dim.7	3.96	1.08	92.41
Dim.8	3.06	0.84	93.25
Dim.9	2.77	0.76	94.01
Dim.10	2.37	0.65	94.66
Dim.11	1.74	0.48	95.13

- The first region corresponds to the sub-equatorial climate (zone1) including grids at low latitudes along the coast. The abundant rainfall in this region can be explained by a combination of factors linked to its proximity to the Atlantic Ocean, such as the strong influence of the West African monsoon [12].

- The second climate zone is the humid tropical climate (zone 2), located in the centre of the country. The rainfall in this zone is relatively lower compared to the rainfall in the zone 1.

- The third zone represents the transitional tropical climate (zone 3), including grids located at higher latitudes. This climate zone dominates the northern part of Côte d'Ivoire influenced by Harmattan with the lowest cumulative rainfall during a year. Indeed, the air masses coming from the Atlantic Ocean towards the Sudanian zone of Côte d'Ivoire (zone 3) warm up, as they cross the

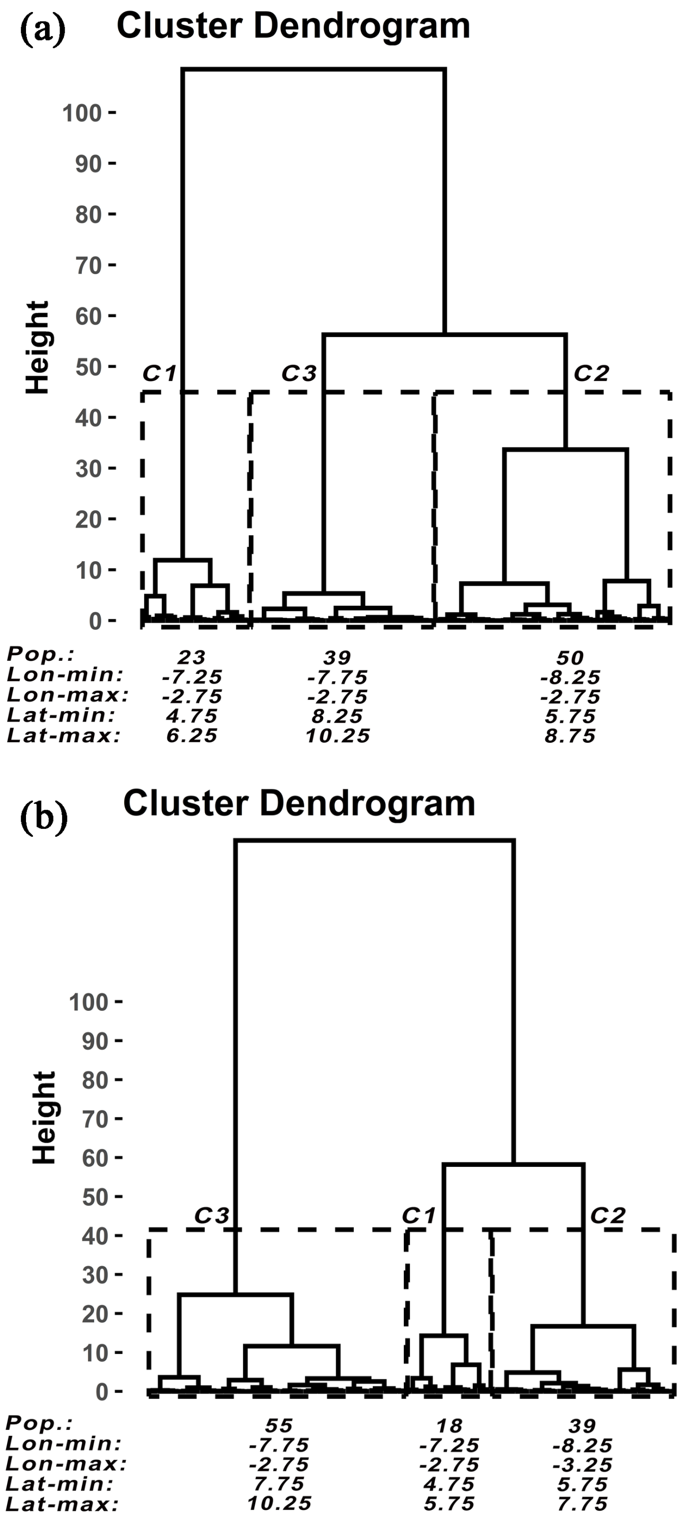

Figure 2. Hierarchical classification on the principal components (HCP) for CHIRPS (a) and CORDEX (b) during the historical period (1981-2005).

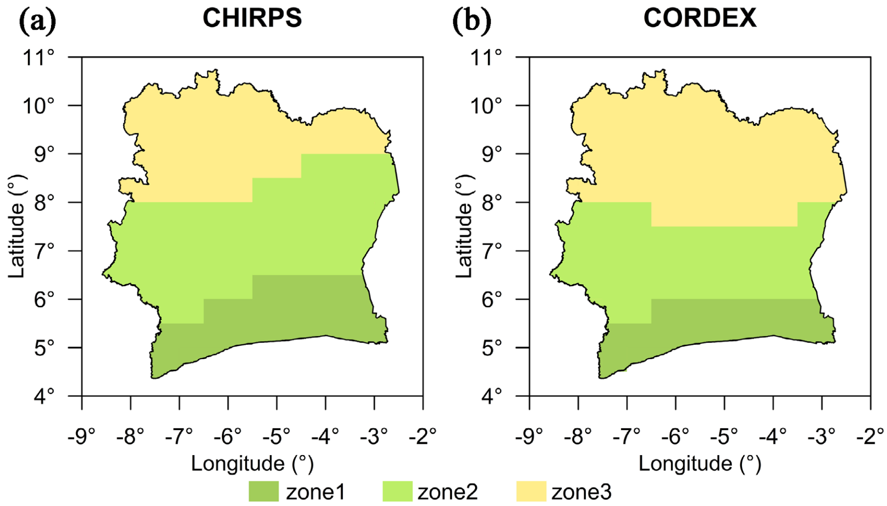

Figure 3. Climate zoning of Côte d'Ivoire based on HPC: CHIRPS (a) and CORDEX (b) over the historical period (1981-2005).

Sahelian zone, leading to a reduction in condensation and relative humidity resulting in an increase in temperature in this climate zone.

3) Analysis of the mean daily cumulative rainfall derived from CHIRPS and CORDEX over the period 1981-2005

The box-and-whisker plots of mean daily rainfall for each climate zone obtained from the hierarchical classification of the principal components of CHIRPS and CORDEX over the period 1981-2005 are illustrated in Figure 4(a) and Figure 4(b). The important climatic feature is the same number of zones three (3) for each of the climate profiles derived from CHIRPS and CORDEX. In addition, a comparison of the box plots of mean daily precipitation for the climate zones shows small interquartile differences between CHIRPS and CORDEX. For all the climate zones derived from the HCP, CORDEX simulations overestimate the median of daily precipitation with relatively smaller biases about 1.9% for the south (zone 1); 4.8% for the centre (zone 2) and 3.8% for the north (zone 3).

Furthermore, analysis of Spearman correlation coefficients between accumulated daily rainfall from CHIRPS and CORDEX for the different climate zones over the historical period (1981-2005) reveals the significant similarity between them (see Table 3) with p-values lesser than 0.05.

3.3. Climate Zoning Projection under the RCP4.5 and RCP8.5 Scenarios

1) Principal component analysis (PCA)

Table 5(a) and Table 5(b) show the PCA for the projected variables derived from CORDEX under RCP4.5 and RCP8.5 scenarios over the near future period (2031-2060). The PCA for the far future period (2071-2100) is also reported in Table 6(a) and Table 6(b). Following Kaiser criterion (see section 2.3), the first fifteen and fourteen components for CORDEX variables under RCP4.5 and RCP8.5

Table 4. Speadman correlation coefficients between CORDEX and CHIRPS in simulating daily rainfall over the different climate zones during the historical period 1981-2005.

Climate zones	Spearman correlation coefficients	p-values
Zone 1	0.5	4.5×10^{-20}
Zone 2	0.8	7.76×10^{-75}
Zone 3	0.9	2.1×10^{-206}

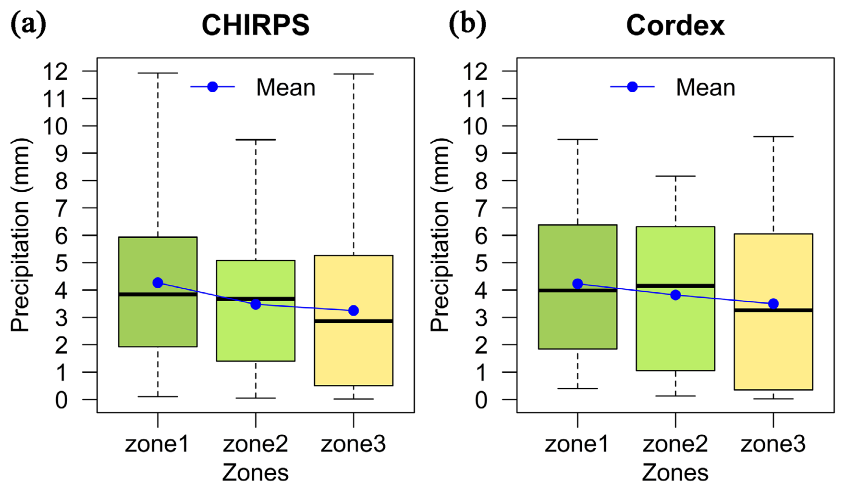

Figure 4. Box-and-whisker plots of mean daily precipitation associated with each zone resulting from the hierarchical classification on principal components (HCPC) for CHIRPS (a) and CORDEX (b) over the historical period (1981-2005).

Table 5. Eigen values and variances of the principal axes for RCP4.5 (A) and RCP8.5 (B) variables over the near future (2031-2060) period

(a)			
Axis	**Eigen value**	**Variance (%)**	**Cumulative variance (%)**
Dim.1	207.58	56.87	56.87
Dim.2	60.93	16.69	73.56
Dim.3	48.68	13.34	86.9
Dim.4	8.17	2.24	89.14
Dim.5	6.48	1.77	90.92
Dim.6	4.51	1.24	92.15
Dim.7	3.9	1.07	93.22
Dim.8	2.74	0.75	93.97
Dim.9	2.49	0.68	94.65
Dim.10	1.9	0.52	95.17
Dim.11	1.53	0.42	95.59
Dim.12	1.46	0.4	95.99
Dim.13	1.43	0.39	96.39

Continued

Dim.14	1.2	0.33	96.72
Dim.15	1.04	0.29	97
Dim.16	0.85	0.23	97.23

(b)

Axis	Eigen value	Variance (%)	Cumulative variance (%)
Dim.1	208.7	57.18	57.18
Dim.2	59.44	16.29	73.46
Dim.3	52.66	14.43	87.89
Dim.4	7.82	2.14	90.04
Dim.5	5.29	1.45	91.48
Dim.6	3.92	1.07	92.56
Dim.7	3.32	0.91	93.47
Dim.8	2.89	0.79	94.26
Dim.9	2.31	0.63	94.89
Dim.10	1.96	0.54	95.43
Dim.11	1.46	0.4	95.83
Dim.12	1.32	0.36	96.19
Dim.13	1.09	0.3	96.49
Dim.14	1.05	0.29	96.77
Dim.15	0.99	0.27	97.05
Dim.17	0.74	0.2	97.47

Table 6. Eigen values and variances of the principal axes for RCP4.5 (A) and RCP8.5 (B) variables over the far future period (2071-2100) period.

(a)

Axis	Eigen value	Variance (%)	Cumulative variance (%)
Dim.1	213.61	58.52	58.52
Dim.2	61.44	16.83	75.36
Dim.3	45.28	12.41	87.76
Dim.4	7.6	2.08	89.84
Dim.5	5.38	1.47	91.32
Dim.6	4.43	1.21	92.53
Dim.7	3.08	0.84	93.38
Dim.8	2.59	0.71	94.08
Dim.9	2.38	0.65	94.73
Dim.10	1.84	0.5	95.24

Continued

Dim.11	1.67	0.46	95.69
Dim.12	1.32	0.36	96.06
Dim.13	1.18	0.32	96.38
Dim.14	1.11	0.3	96.69
Dim.15	0.99	0.27	96.96

(b)

Axis	Eigen value	Variance (%)	Cumulative variance (%)
Dim.1	210.02	57.54	57.54
Dim.2	58.15	15.93	73.47
Dim.3	48.75	13.36	86.83
Dim.4	8.58	2.35	89.18
Dim.5	5.99	1.64	90.82
Dim.6	3.91	1.07	91.89
Dim.7	3.28	0.9	92.79
Dim.8	2.85	0.78	93.57
Dim.9	2.55	0.7	94.27
Dim.10	2.09	0.57	94.84
Dim.11	1.79	0.49	95.33
Dim.12	1.66	0.46	95.79
Dim.13	1.34	0.37	96.15
Dim.14	1.09	0.3	96.45
Dim.15	0.99	0.27	96.72

scenarios are retained for the near future period (2031-2060). For the far future period (2071-2100), only the first fourteen components are significant for both scenarios, with cumulative variances of 96.69% and 96.45%, respectively.

b) Analysis of the Hierarchical Classification of Principal Components (HCP)

Figure 5 and **Figure 6** show the HCP of the projected variables derived from CORDEX for the near (2031-2060) and far (2071-2100) future periods. The structure and composition of the classes vary according to the scenarios and the period. For the near future, four (4) different classes are identified for RCP4.5 and three (3) classes for RCP8.5, with numbers ranging between eleven (11) and fifty-seven (57), while during the far future (2071-2100), both scenarios (RCP4.5 and RCP8.5) indicate four classes with the number varying between twelve (12) and fifty-four (54) grids.

The spatial distribution of climate zones of Côte d'Ivoire under RCP4.5 and RCP8.5 scenarios for 2031-2060 and 2071-2100 periods is presented in **Figure 7** and **Figure 8**.

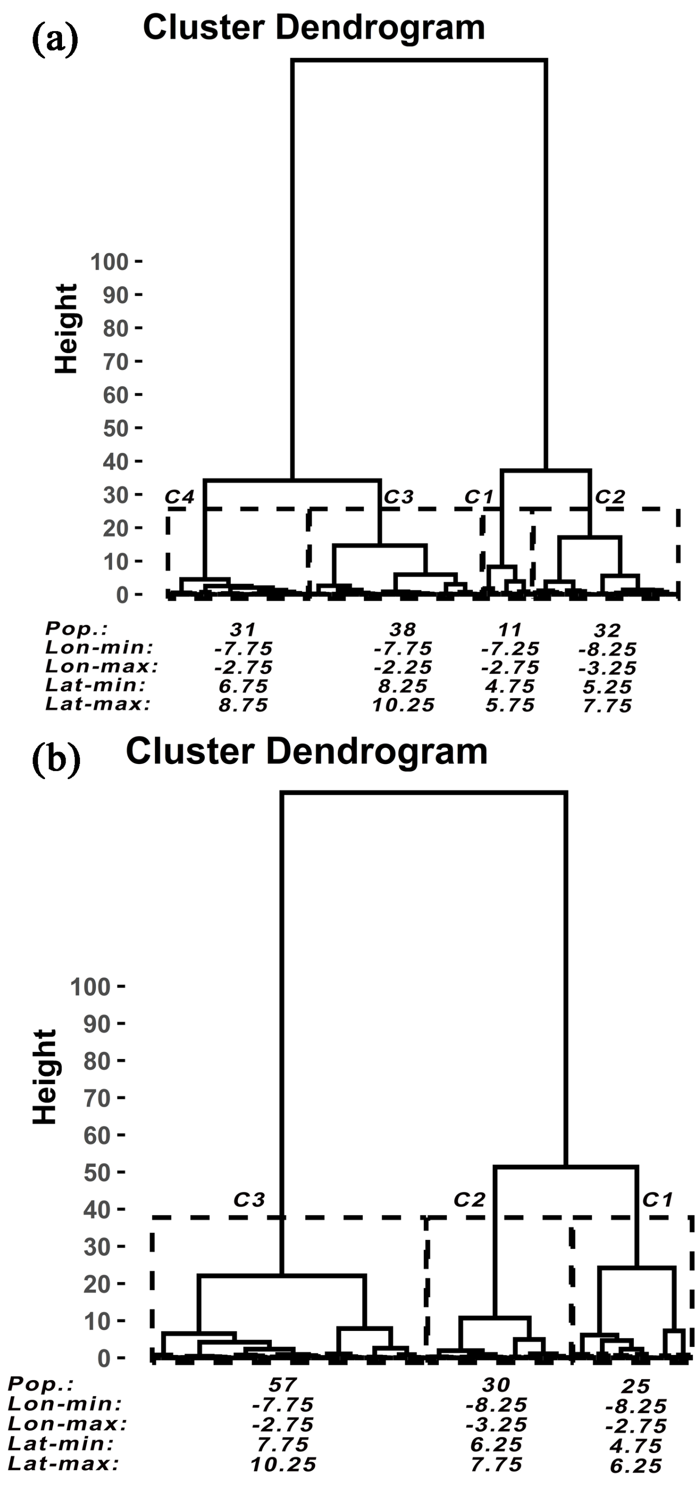

Figure 5. Hierarchical classification on the principal components (HCP) for RCP4.5 (a) and RCP8.5 (b) over near future (2031-2060) period.

There are four (4) climate zones resulting from the hierarchical classification of principal components (HCPC), which are maintained over the two future periods under the RCP4.5 scenario, while under RCP8.5 there are three (3) and four (4) climate zones over the near and far future periods, respectively. Thus, except

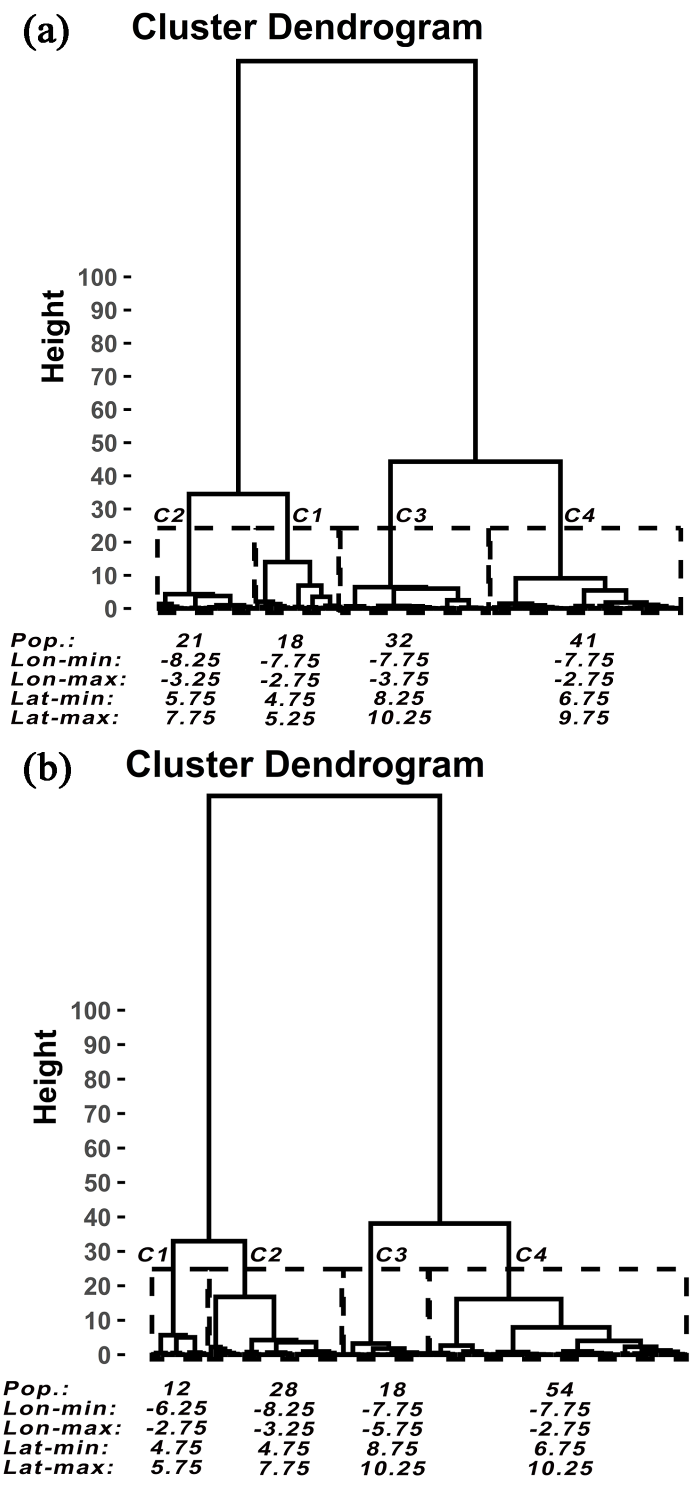

Figure 6. Hierarchical classification on principal components (HCP) for RCP4.5 (a) and RCP8.5 (b) scenarios over far future period (2071-2100)

RCP8.5 scenario for the near future period, the coastal climate zone (zone 1), the humid tropical mountainous climate zone (zone 2), the transitional tropical climate zone (zone 3) and a new climate zone (zone 4) combining the humid tropical and transitional tropical climates are found for each scenario from the south

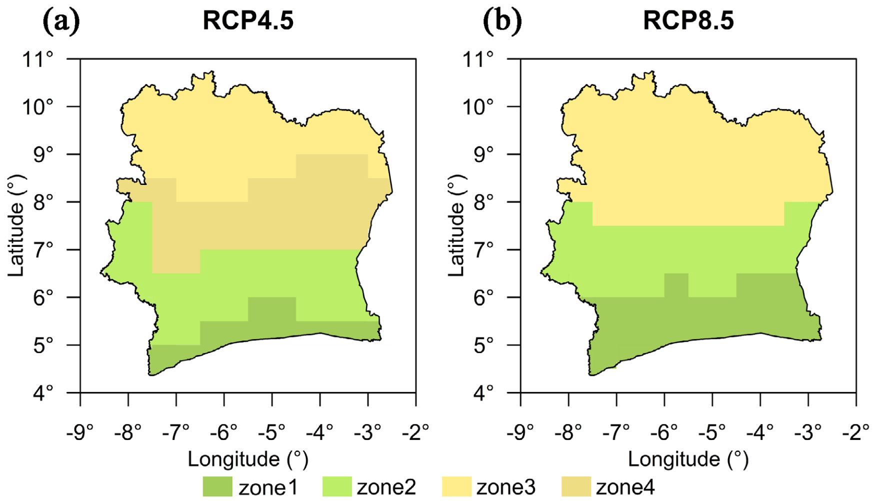

Figure 7. Future projections of climate zoning in Côte d'Ivoire based on HPC results under RCP4.5 (a) and RCP8.5 (b) scenarios for the near future (2031-2060).

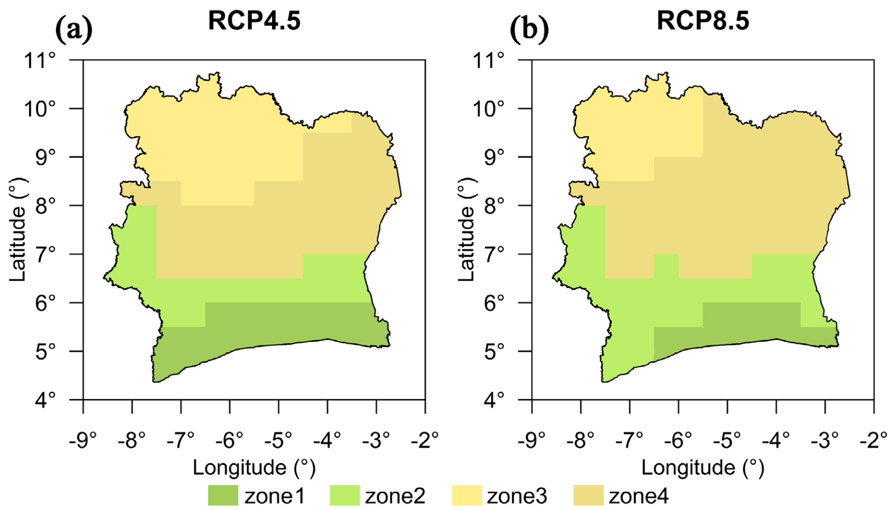

Figure 8. Future projection of climate zoning in Côte d'Ivoire based on HPC results under RCP4.5 (a) and RCP8.5 (b) scenarios over the far future period (2071-2100).

to the north. The main observed changes in the surface areas of the different climate zones over the future periods are due to the latitudinal displacement of the inter-zone boundaries and the appearance of the fourth climate zone. These changes are the results of a reduction or an extension of the surface area of the climate zones, depending on the scenario and the period. Extended surface areas are generally observed in the northern climate regions. The climate zone 4 reaches its maximum extension over the period 2071-2100 under RCP8.5 scenario (Figure 8(b)). Surface area reductions are more marked in the southern climatic regions of Côte d'Ivoire. The maximum reduction is observed over zone 1 during far future period (2071-2100) and under RCP8.5 scenario (Figure 7(b)).

3) Trends in climate zones for short (2031-2060) and long (2071-2100) terms

Figure 9 illustrates the projected rates of spatial changes of the climate zones derived from CORDEX simulations under RCP4.5 scenario over the near and

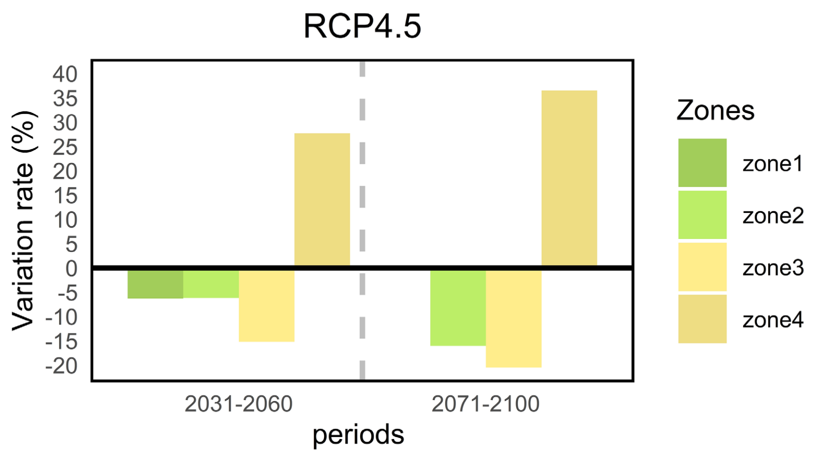

Figure 9. Projected changes in the surface rates of the climate zones of Côte d'Ivoire under the RCP4.5 scenario over the near and far future periods.

the far future periods. Analysis reveals significant changes in the surface areas of the different climate regions of Côte d'Ivoire. During the near future period, climate zones 1, 2 and 3 will experience a reduction of their surfaces areas with negative rates of changes estimated about −6.3%, −6.2% and −15.2%, respectively; corresponding to 17,640 km^2, 17,360 km^2 and 42,560 km^2, surface areas, respectively. This situation favors the appearance of a fourth intermediate climatic zone (zone 4) with an appearance rate of 27.7% (*i.e.*, 77,560 km^2). This zone extends from west to east, between the northern and central zones. In the far future, zones 2 and 3 will experience a significant reduction of their surface areas, with respective rates of −16% and −20.4%, corresponding to surface reduction of about 44,800 km^2 and 56,000 km^2, respectively. Zone 1, with a zero rate of change, preserves the same surface area as during the historical period. Zone 4, in addition to the centre, will extend to the northeast with a rate of appearance of 36.5%, corresponding to 102,200 km^2.

These results clearly indicate that climate change will result in changes in the extent (surface area) and structure of Côte d'Ivoire's climate zones. Northern and central zones are the most impacted, with the appearance of an intermediate fourth zone with a surface area varying between 77,560 km^2 and 102,200 km^2, depending on the period.

Figure 10 shows the projected rates of spatial changes of the climate zones derived from CORDEX simulations under RCP8.5 scenario over the near and far future periods. Under RCP8.5, Zones 1 and 3 experience an increase in their surface area of 6.2% and 1.8%, corresponding to 17,360 km^2 and 5040 km^2, respectively, while Zone 2 will experience a reduction of 8%, corresponding to 22,400 km^2. During the far future period 2071-2100, zones 1, 2 and 3 will experience a decrease of their surface areas estimated about −5.4%, −9.8% and −33%, corresponding to 15,120 km^2, 27,440 km^2 and 92,400 km^2, respectively. Moreover, Zone 4 will appear at a rate of 48.2% (*i.e.*, 134,960 km^2). In addition, RCP8.5 scenario projects a reduction of the surface area of the southern zone, particularly in the south-western part, over the far future period.

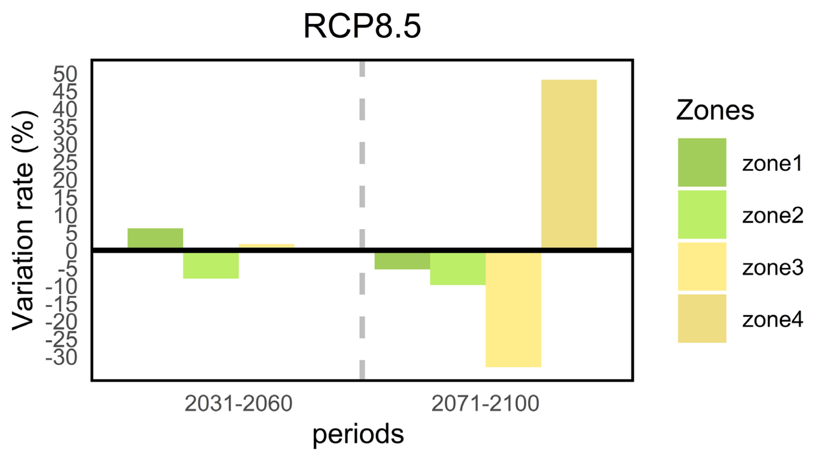

Figure 10. Projected changes in the surface rates of the climate zones of Côte d'Ivoire under RCP8.5 scenario over the near and far future periods.

4. Discussion

The comparison of the hierarchical classification of principal components (HCPC) applied to CHIRPS and CORDEX over the historical period (1981-2005) revealed some similarities and dissimilarities. Both data sets (CHIRPS and CORDEX) indicate the existence of three (3) climate zones in Côte d'Ivoire including the southern climatic region bordering the oceanic coasts (zone 1), the central climatic region dominated by the humid tropical climate (zone 2) and the northern climatic region identified as the transitional tropical climate (zone 3). A comparison of average daily accumulations for each zone reveals similarities with significant correlation coefficients (p-values less than 0.05) and low interquartile range between 1.9% and 4.8% for CORDEX and CHIRPS configurations. One of the dissimilarities is the overestimation of the cumulative daily mean precipitation for each zone by CORDEX. These disparities could be explained by the loss of information for the interpolation method used to regrid data at different spatial resolutions (CORDEX 0.44˚ and CHIRPS 0.05˚) onto the same grid, that of CORDEX (0.44˚). The climate zoning results obtained from the hierarchical classification of CORDEX principal components are in agreement with the results found by [14] [15] [16]. Indeed, the work of [14], based on a principal component analysis (PCA) of average monthly rainfall for 22 stations in Côte d'Ivoire over the period 1964-1997, identified three climatic zones including the coastal zone (bordering the Gulf of Guinea), the central zone (in the centre) and the northern zone (in the north). The results obtained using CORDEX hierarchical classification on principal components during the period 1981-2005 are similar to those of [14] (**Figure 11**).

Furthermore, the work of [15] (**Figure 11**), based on a hierarchical classification of monthly rainfall totals from 44 rainfall stations over the period 1961-2016, identified five climate zones over Côte d'Ivoire. These results could be consistent with those obtained using the HCPC of CORDEX under RCP4.5 scenario for the near future period (2031-2060) by combining the fifth climate zone (R5) and the

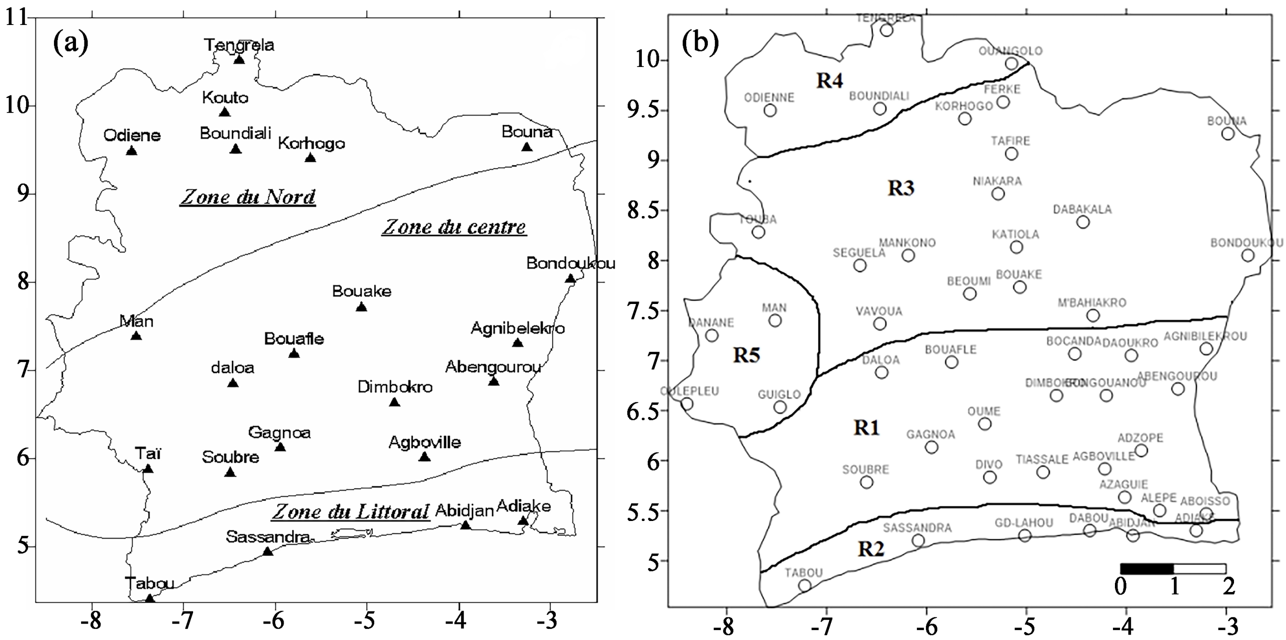

Figure 11. Climate zoning of Côte d'Ivoire based on the results of PCA [14] (a) and the PCNA [15] (b).

first zone (R1) to a single climate zone.

The HCPC results of the CORDEX projections under RCP4.5 and RCP8.5 radiative forcing scenarios over the near and far future periods reveal variability in the structure and the surface area of the climate zones as a function of the periods and scenarios. These variations are characterized by the appearance of a fourth climate zone which surface area will increase depending to the periods. Consequently, this will result in a gradual increase in the surface area of drier zones and a reduction of wetter ones. Under stabilization scenario RCP4.5, the appearance of the fourth climate zone (zone4) during the near-future period (2031-2060) is due to a reduction in the surface area varying from 17,360 km^2 to 42,560 km^2 overall climate zones during the historical period. RCP4.5 scenario projects a recovery of zone 1 in the south and an accentuation of the expansion of drier zones over the period 2071-2100, with a reduction in the surface area of zone 4 about 36.5%. High greenhouse gas emission scenario RCP8.5 indicates a reduction in the surface area of the central zone (zone 2) about 22,400 km^2 over the near future due to the expansion of the climate zones (zone 1 and 2). There is an appearance of zone 4 over 2071-2100 with a surface area of 134,960 km^2 representing 41.8% of the total surface area of the country. In addition, RCP8.5 scenario projects a reduction of surface area of the southern zone (zone1) about 15,120 km^2 (*i.e.*, 4.6% of the territory), particularly in the south-western part.

The increase in the surface area of drier climatic zones and the decrease of wetter climate zone surface area projected by CORDEX simulations could be explained by the work of [6] on the changes in extreme precipitation in Côte d'Ivoire. Indeed, the study of [6] analyzed projected changes in the intensity of seasonal rainfall extreme and the duration of drought periods in Côte d'Ivoire under RCP4.5 and RCP8.5 forcing scenarios. Their results indicate an increase in the duration of dry spells about 12% and 17% over the near future period and 20% and 30% over the far future period over the entire country. This study also reveals that these variations will be accentuated in the southwestern part of the country, which is also the area most affected by the decreases in surface area projected by RCP8.5 scenario over the far future period.

5. Conclusions

In this work, we assessed the projected changes in the climate zoning of Côte d'Ivoire using hierarchical classification of principal components (HCPC) method applied on daily mean cumulative precipitation under RCP4.5 and RCP8.5 scenarios from CORDEX-AFRICA simulations. The results show a variation in the structure and surface area of the climate zones as a function of the periods and scenarios. During near future 2031-2060, RCP4.5 projects a reduction in the surface area of the present climate zones (south, centre and north) in benefit to a new transition zone with a surface area of about 77,560 km^2, located between the centre and the north zones, with longitudes ranging between 7.75˚W to 2.75˚W. RCP8.5 scenario projects a reduction of the central zone of 22,400 km^2 due to the extension of the southern and northern zones. During the far future 2071-2100 period, CORDEX simulations agree to an intensification of the variability in the surface area of the different zones. Under RCP4.5, an increase in the surface area of zone 4 about 24,640 km^2 is projected, particularly in the northeast. In addition, under RCP8.5 scenario a reduction about 15,120 km^2 is projected in the surface area of the southern zone.

Projected changes in the surface areas of the different climatic zones of Côte d'Ivoire under RCP4.5 and RCP8.5 scenarios show an extension of the surface area of drier regions associated to a reduction of wetter climate zones' surface areas. This could be explained by increasing trends in projected temperatures and dry spells with disruption of the seasons, particularly the dates of onset, end and duration. As a result, cash crop production and the development of new crops could be compromised. In addition, a complementary analysis of the climate zones using finer resolution simulations (around 5 to 10 km) including other parameters (*i.e.*, humidity, evapotranspiration, temperature, wind speed, etc.) could improve our understanding and provide more detailed information on the projected changes specific to each climate zone of Côte d'Ivoire. Moreover, the characterization of the climate zones of Côte d'Ivoire could be focused on their rainfall regime and changes during different periods. This study is a contribution to a better understanding of the dynamics in the climate zoning of Côte d'Ivoire and to the formulation of appropriate adaptation and mitigation measures aimed at protecting natural resources and strengthening food security for a sustainable development.

Conflicts of Interest

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

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