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Evaluating the Impacts of Climate Variability on Cocoa Production in the Western Centre of Cote d'Ivoire during 1979-2010

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Abstract

Climate variability impacts on cocoa production are evaluated for the first time using 31 years (1979-2010) of data from SODEXAM (climate ground-based observations) and the ex-CAISTAB in three main cocoa production regions (Goh, Marahoué, and Haut-Sassandra) in the west-central part of Cote d'Ivoire. The work is a contribution to improving the quality of climate services dedicated to cocoa cultivation to ensure producers' income and improve the yield of the production in the west-central part of Cote d'Ivoire. The results show that cocoa production is affected by the changes and variability in climate conditions (*i.e.* rainfall and temperature). In the Goh region, the increase in cocoa production seems to be mostly related to the augmentation of rainfall amount while in Marahoué, the increase in temperature is identified to have a more significant impact. Over the Haut-Sassandra region, both temperature and rainfall seem to have a considerable effect on the changes in cocoa production. The analysis based on linear regression by least-squares fit shows two characteristic modes (low and high-frequency variability) in the relationships between cocoa production and meteorological conditions suggesting a strong temporal signal impact related to the changes in the emblazoned surfaces. This leads to an important impact of the short-term variations of climate in cocoa production whereas, the influence of the long-term variability in climate on the cocoa yield seems marginal.

Keywords

Agriculture, Climate, Cocoa, Rainfall, Air Temperature, Cote d'Ivoire

1. Introduction

One of the key features of the West African climate is the variability of its rainfall regime controlled by the dynamic of the monsoon [1]. This variability is characterized by alternate dry and wet phases into the annual and seasonal cycles of rainfall [2]. For example, the dry phase can reduce particularly the available water resources for agriculture and population whereas the wet phase could cause floods with economic and social consequences. Due to these dramatic effects, the recurrence modes of the rainfall phases have stimulated much interest. The works of [3] [4] [5] [6] [7] have shown a drought tendency in the Sahel region which, induced a severe famine from the end of the 60's decade. This drought tendency is also observed in the rainfall time series of the coastal areas of West Africa and, particularly, in Côte d'Ivoire [8]. In the same context, [9] have detected three periods for which, the rainfall variations were strong and alternated between excess and deficit periods of rainfall around Lamto station (6.13˚N and 5.02˚W) from 1962 to 2011. The deficit period (1971-2000) observed in Lamto is related to the spatial extension of the drought scenario discussed previously by [3] [4] [7] over the Sahel. Besides, [10] [11] [12] have shown a similar drought phenomenon in the N'Zi region (Central-East of Cote d'Ivoire) and have found many breaks of tendency in the rainfall time series using statistic methods. These breaks of tendency underlined various alternate drought events and abundant periods. Furthermore, the climate variation in the Eastern Central region has negative impacts on cocoa production, especially in Daoukro which, is considered as the last "loop" of cocoa productions in Côte d'Ivoire [13]. In the same vein, the authors as [13] underlined also that cocoa production is shown to experience a significant interannual variability due to the decrease in rainfall and its irregular distribution. As a result, [14] observed a similarity between the main zones of cocoa production and the areas where precipitations are abundant in the Southwest. On the other hand, some factors like the age of plantations and the depletion of forest resources, and combined with the decrease in rainfall induce a reduction of the cocoa production and thus lead to a high migration of farming population toward the South-Centre zone [14]. This social and economic consequence was also observed in the Western Centre region, which had not been exploited before, and where the cocoa yield is similar to that found in the Eastern Centre region of Côte d'Ivoire. Also, the Western centre region of Côte d'Ivoire is an area where pedological (*i.e.* soil type, soil moisture) and meteorological (*i.e.* rainfall, temperature, insolation, relative humidity) conditions are good for cocoa cultivation. But this region is subject to the variable effects of the changes in climate due to the inconstancy of both rainfall and temperature. For example, in the last few years, the western centre region experienced a poor cocoa yield mostly due to climate change [15].

This study assesses the influence of precipitation and temperature trends on the cocoa production, in three main regions (Goh, Haut-Sassandra, and Marahoué) of Côte d'Ivoire. These regions are considered as the main cocoa production areas of the Western-centre of Cote d'Ivoire. Recently, rainfall and temperature conditions for cocoa production have been evaluated by [16] with statistical analysis based on a multiple regression method in six areas (*i.e.* Abengourou, Agboville, Daloa, Dimbokro, Guiglo, and Soubre) on the south part of Cote d'Ivoire. The relative and individual contributions of these two factors in estimating climate change impacts on cocoa yields have been highlighted and authors found that rainfall amount and its seasonal distribution are the most influencing factors. However, temperature impacts on cocoa production are not negligible although they were not significant over the considered period in their study. They further argued that temperature plays crucial and well-known role in evapotranspiration and water demand. Nevertheless, this previous study on the impact of rainfall and temperature on cocoa production, there is still a need to evaluate these impacts of climate conditions on the yield especially the spatial distribution, and the long-term and short-term trends of these impacts. Also, [16] did not cover all the areas of the new "loop" of cocoa yield. This new area has been identified as category 3 by an expert group in a report on the categorisation of cocoa-producing zones in Cote d'Ivoire [17]. According to this report, this category 3, including 17 departments, is a high marketed production of cocoa, high literacy rate, and high agriculture's share of the economy. This category accounts for 87% of the national cocoa production.

The proposed study focuses on the type of dominant signal of the impact of climate on the variability in cocoa production and discusses the cocoa yield response to rainfall and temperature short and long-term trends in the new "loop" of cocoa production over the period 1979 to 2010. This will provide adequate responses to improve cocoa yields and farmers' incomes. It is structured as follows; Section 2 is dedicated to the description of the study area, the material, and the method used. Section 3 shows the results and, the discussion is given in section 4. Finally, conclusion and perspectives are given at the end.

2. Study Area, Material, and Method

2.1. Study Area

Unlike [16], who focused on six main cocoa production areas (Abengourou, Agboville, Daloa, Dimbokro, Guiglo, and Soubre) on the South part of Cote d'Ivoire, the current work targets three main regions of cocoa production with eight administrative departments (**Figure 1**). The Goh (Gagnoa and Oumé), Haut-Sassandra (Daloa, Issia, and Vavoua) and Marahoué (Bouaflé, Sinfra, and Zuénoula) regions, the new "cocoa loop", have significant socio-economic and agricultural assets mostly based on the non-use of the land. These regions are

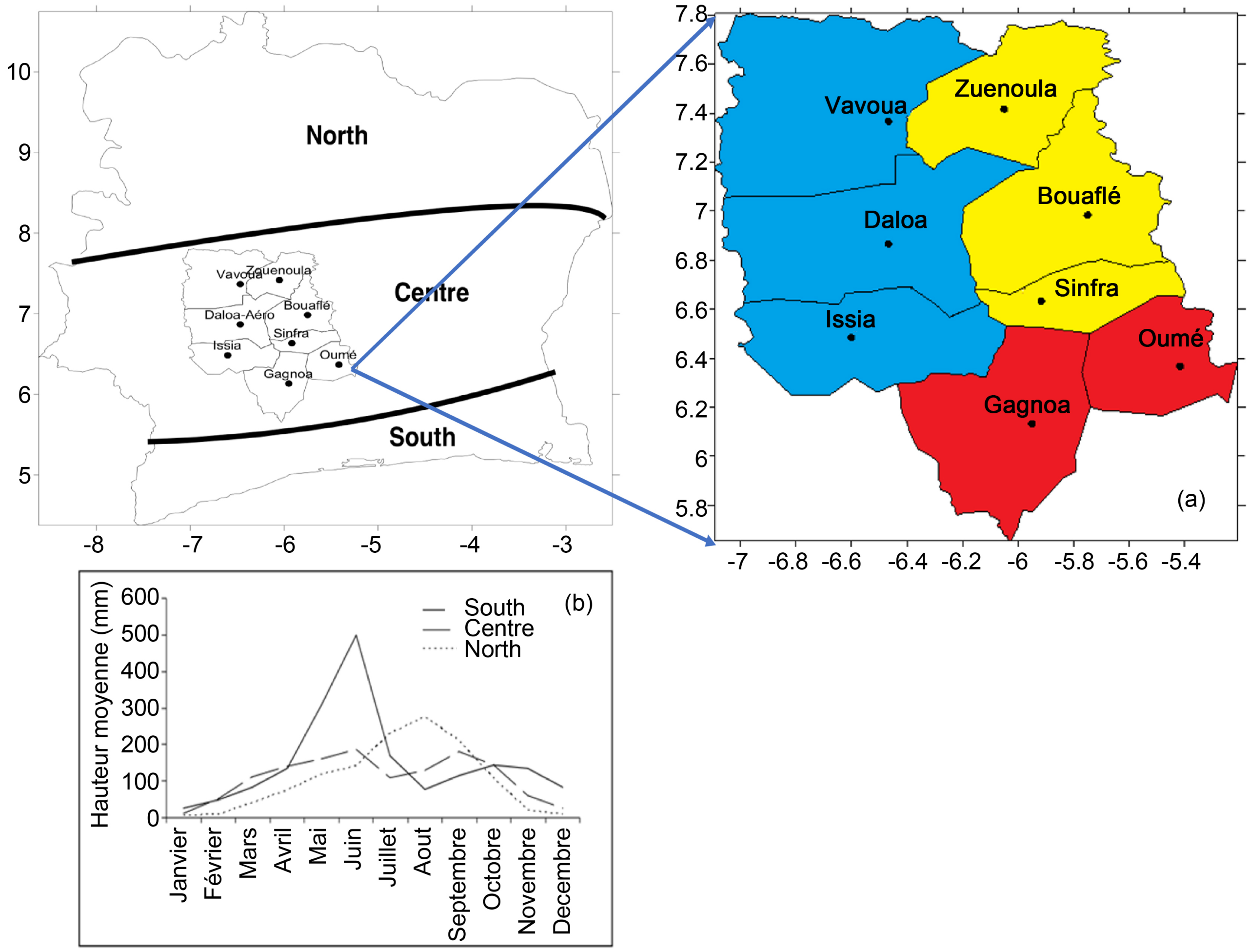


Figure 1. (a) Location of the study area. For simplicity, a color code is associated with each individual region and will be kept in the following: blue for Haut-sassandra, red for Goh, and yellow for Marahoué. (b) Means seasonal cycles of the rainfall during 1964-1997 according to the climate types (Adapted from kouadio *et al.*, 2007).

forest areas belongs to the wet tropical climate with four seasons [11] [18] including two rainy seasons and two dry seasons (**Figure 1(b)**). The main rainy season is from April to July with maximum rainfall in June. The little rainy season extends from September to November with a peak in October [19] [20]. The mean annual rainfall amount is in the range of 1100 and 1800 mm. This rainfall regime is influenced by the West African Monsoon (WAM), modulated by the seasonal migration of the Intertropical Convergence Zone (ITCZ) and three main structures of wind: African Easterly Jet (AEJ) around 700 hPa, Tropical Easterly Jet (TEJ) at 200 hPa and Subtropical Western Jet (STWJ) in the high atmosphere. The cocoa production is estimated at approximately to around 1,727,167 Tons/year in the Gôh region, 2,861,797/year Tons in the Haut-Sassandra, and 1,070,576 Tons/year in Marahoué during 1979-2010 period.

2.2. Material

The current work uses ground-based observations data (rainfall and temperature) from 1961 to 2010 of the National Meteorology of Cote D'Ivoire (hereafter, Société d'Exploitation et de Développement Aéroportuaire et Météorologique, SODEXAM) and cocoa production data from 1979 to 2010 of the ex-Caisse de Stabilisation du Café et du Cacao (ex-CAISTAB). This series of cocoa data is the reliable long-term and with a marginal gap before the socio-political and military crisis that Côte d'Ivoire experienced in 2011 and which disrupted the production chain and then led to a great loss of production. Indeed, a large part of cocoa production has followed circuitous routes to end up in the commercial markets of neighboring countries during that year 2011.

The time series of the climatic parameters data are broadly consistent with those from studies like [3] [7] [21] [22] that explained significant aspects and trends of climate change in West Africa. Here, these data permit to show clearly the amplitude of the relative tendencies of the individual climatic parameters.

2.3. Method

The trends in cocoa production are assessed based on the magnitude of changes in temperature and rainfall during the 1979-2010 period in each of the proposed regions. Climate and cocoa production data from a given region are obtained by averaging the indexes (values) of all stations belonging to this region. In contrast to temperature, which has low year-to-year variability in the context of West Africa, the inter-annual rainfall variability in each major region was analysed to understand the possible causes of changes. Furthermore, the geostatistical analysis (GIS) was used to interpolate the cocoa production and the meteorological parameters to obtain the spatial distributions of these mentioned variables over the entire study area. The mapping tool used was ArcGIS software version 10.2.2 and the inverse distance weighting (IDW) interpolation method was applied to analyse the decadal distributions of the mean annual standardized anomaly of all variables over the 1980-2010 period. This interpolation method was used in [23] and showed better similarity between measured and interpolated values. It also provides a spatial distribution of variables much closer to reality. The spatialization of the data may generate relative bias in the result, however, the relatively limited small size of the areas considered may reduce considerably the impacts of such errors. On the other hand, correlation statistics were used to observe in each region how variations in cocoa production are affected and linked to variations in Rainfall and Temperature at a 90% confidence level established with the Student's t-test. Besides, trends in cocoa production associated with the changes in both rainfall and temperature are depicted and analyzed by a descriptive statistic approach based on the linear regression by the least-squares fit [24]. The trends are calculated by multiplying the slope of linear trends by the length of the time-series. The most significant trends are obtained with a 90% confidence level by the Student t-test. This method shows sufficient and efficient indicators to objectively detect one or more trend breaks in predictor scores and when they occur. It was used in many studies related to climate variability and change in

West Africa [9] [25] [26].

3. Results

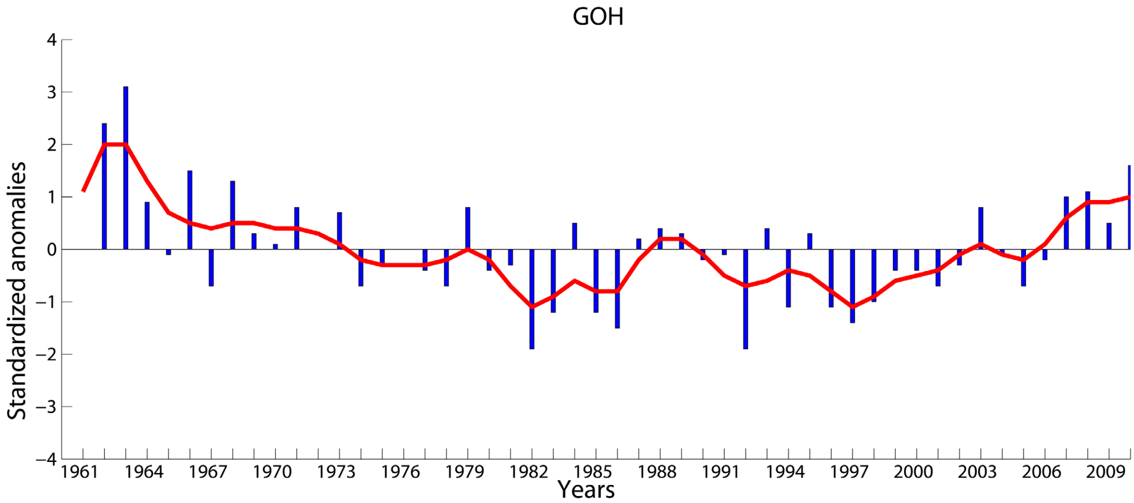
3.1. Interannual Variability of the Rainfall Standardized Anomaly

The yearly standardized anomaly indexes of rainfall (**Figure 2**) related to the regions of Marahoué (**Figure 2(a)**), Goh (**Figure 2(b)**) and Haut-Sassandra (**Figure 2(c)**) highlight significant fluctuation of the values ranging between −1.8 and +3.45 in Marahoué, between −1.8 and +3.2 in Goh and between -1.9 and +3.0 in the Haut-Sassandra. The highest values are observed in 1963 for the regions of the Marahoué and Goh, and during the year 1968 in the Haut-Sassandra while the lowest values appeared in 1982, 1992, and 1990 in Marahoué, Goh and Haut-Sassandra respectively. The moving average curves associated with the interannual variability of each standardize anomaly index show important trends, especially in the Gôh and Haut-Sassandra regions. This suggests a more pronounced interannual variability of rainfall across Goh and Haut-Sassandra regions during the great drought periods from the beginning of the 1970s to the end of 2000. The period before 1973 is marked by a significant excess trend in all regions followed by alternating wet and dry periods of varying lengths. However, in the regions of Goh and Haut-Sassandra, there is a systematic increase in rainfall at the beginning of 2005.

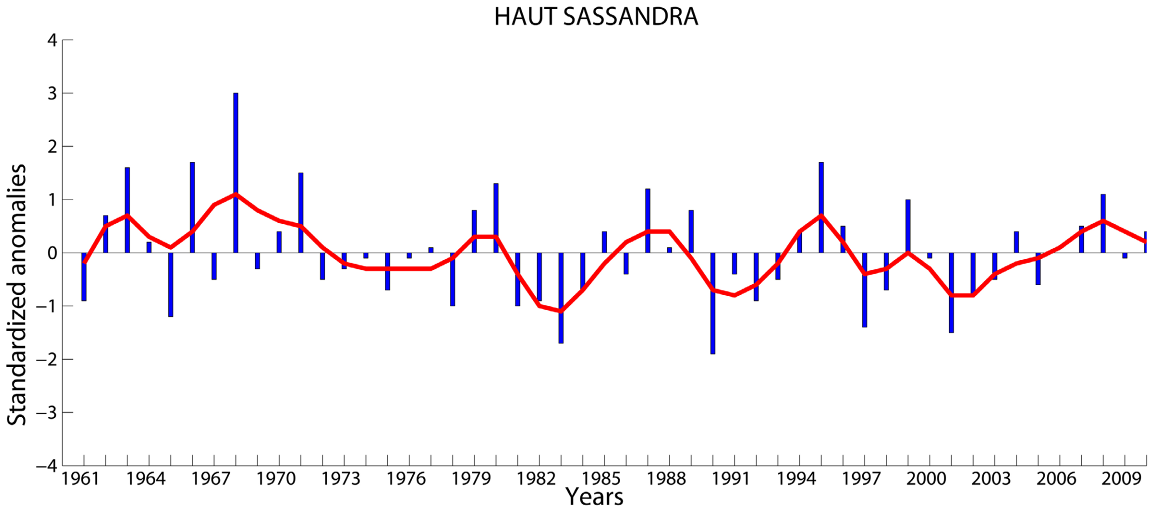
3.2. Spatial and Decadal Variations of the Mean Annual Standardized Anomaly of Cocoa Production, Rainfall, and Temperature

The spatial decadal variations of the mean annual standardized anomaly of the cocoa production, rainfall, and temperature (**Figure 3**) are obtained using the inverse distance weighting (IDW) interpolation method. This kriging method has been variously used to spatialize data much closer to reality. Each decade (*i.e.*, 1981-1990, 1991-2000 and 2001-2010) of the mean spatial standardized anomaly of the parameters has been calculated from the 1980-2010 mean period to evaluate the most significant spatial changes in the study area. The important and positive standardized anomalies of cocoa production are mainly located in the northern part of the study area in 1981-1990 decade (**Figure 3(a)**) with values in the range [0.1; 0.7] contrary to the southern and western zones where values are negatives. In 1991-2000 (**Figure 3(b)**), the anomalies are positive in all stations with values greater than 0.5 in the northern part.

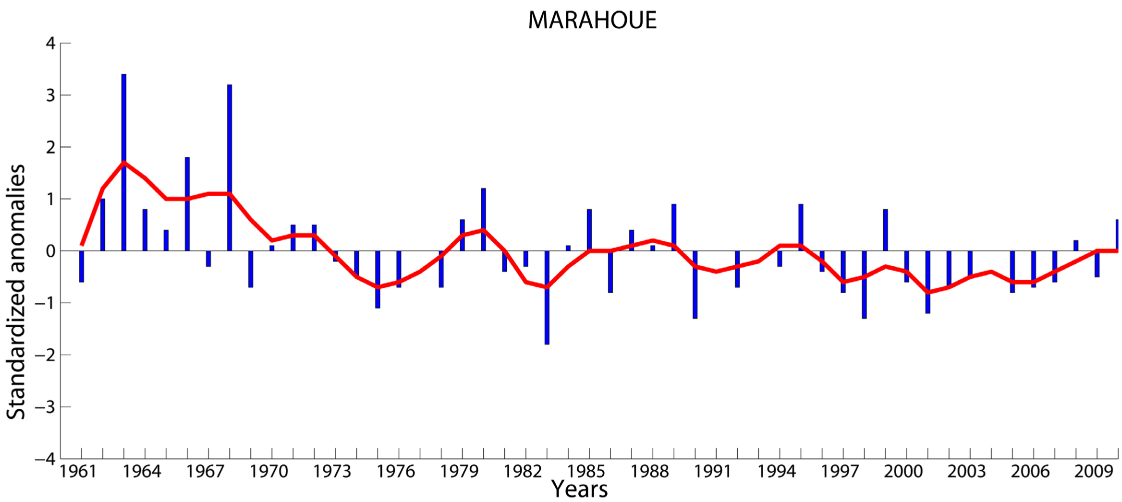
The positive values of these anomalies indicate that cocoa production has been in excess in the 1991-2000 decade compared to the 1981-2010 average period. However, this spatial distribution of anomalies changes from the decade 2001-2010 (**Figure 3(c)**) where positive anomaly values are located in the southern (values >0.5) and south-western parts and negative anomalies in the north and north-eastern parts thus generating a spatial bipolarization. This spatial dynamic shows a positive gradient of the north-south variability in cocoa production. On the over hand, the rainfall standardized anomalies show low values



(a)

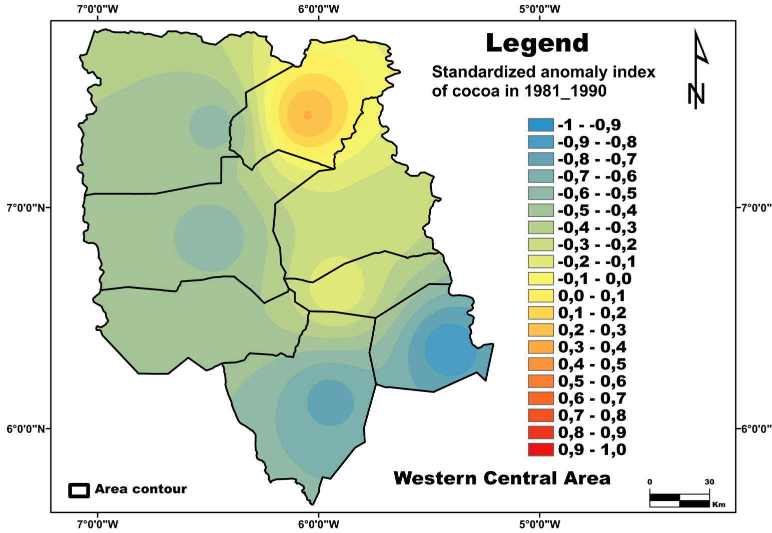


(b)

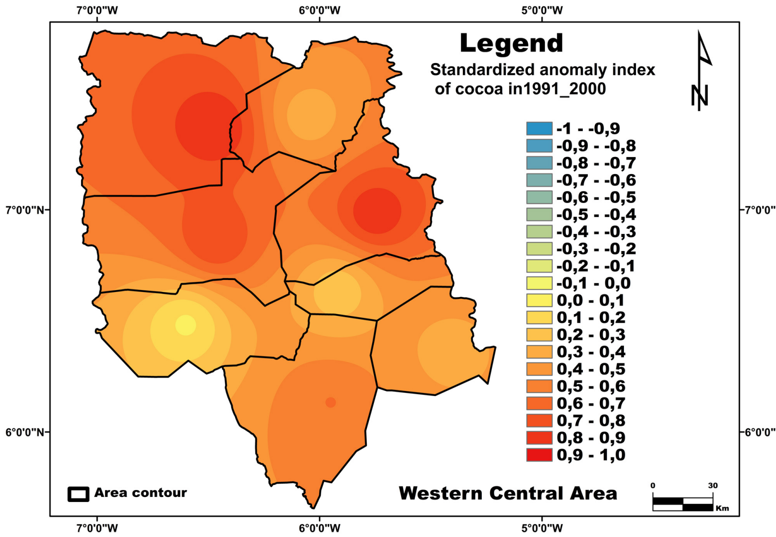


(c)

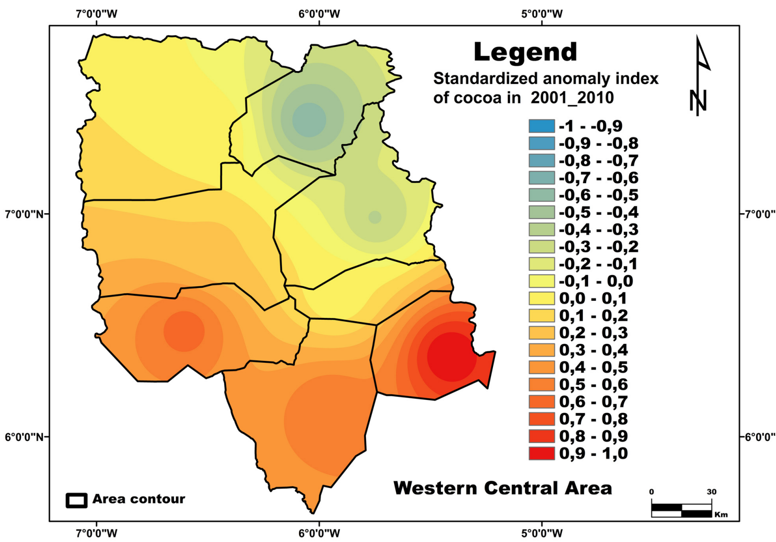
Figure 2. Temporal evolution of the standardized anomalies rainfall index of Marahoue (a), Goh (b) and Haut-Sassandra (c) from 1960 to 2021. The red lines are associated trends curves.


Legend
Standardized anomaly index
of cocoa in 1981_1990
-1 - -0,9
-0,9 - -0,8
-0,8 - -0,7
-0,7 - -0,6
-0,6 - -0,5
-0,5 - -0,4
-0,4 - -0,3
-0,3 - -0,2
-0,2 - -0,1
-0,1 - 0,0
0,0 - 0,1
0,1 - 0,2
0,2 - 0,3
0,3 - 0,4
0,4 - 0,5
0,5 - 0,6
0,6 - 0,7
0,7 - 0,8
0,8 - 0,9
0,9 - 1,0
Western Central Area
Area contour
7°0'0"W
6°0'0"W
5°0'0"W
7°0'0"N
6°0'0"N
0
30
Km

(a)


Legend
Standardized anomaly index
of cocoa in1991_2000
-1 - -0,9
-0,9 - -0,8
-0,8 - -0,7
-0,7 - -0,6
-0,6 - -0,5
-0,5 - -0,4
-0,4 - -0,3
-0,3 - -0,2
-0,2 - -0,1
-0,1 - 0,0
0,0 - 0,1
0,1 - 0,2
0,2 - 0,3
0,3 - 0,4
0,4 - 0,5
0,5 - 0,6
0,6 - 0,7
0,7 - 0,8
0,8 - 0,9
0,9 - 1,0
Western Central Area
Area contour
7°0'0"W
6°0'0"W
5°0'0"W
7°0'0"N
6°0'0"N
0
30
Km

(b)


Legend
Standardized anomaly index
of cocoa in 2001_2010
-1 - -0,9
-0,9 - -0,8
-0,8 - -0,7
-0,7 - -0,6
-0,6 - -0,5
-0,5 - -0,4
-0,4 - -0,3
-0,3 - -0,2
-0,2 - -0,1
-0,1 - 0,0
0,0 - 0,1
0,1 - 0,2
0,2 - 0,3
0,3 - 0,4
0,4 - 0,5
0,5 - 0,6
0,6 - 0,7
0,7 - 0,8
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0,9 - 1,0
Western Central Area
Area contour
7°0'0"W
6°0'0"W
5°0'0"W
7°0'0"N
6°0'0"N
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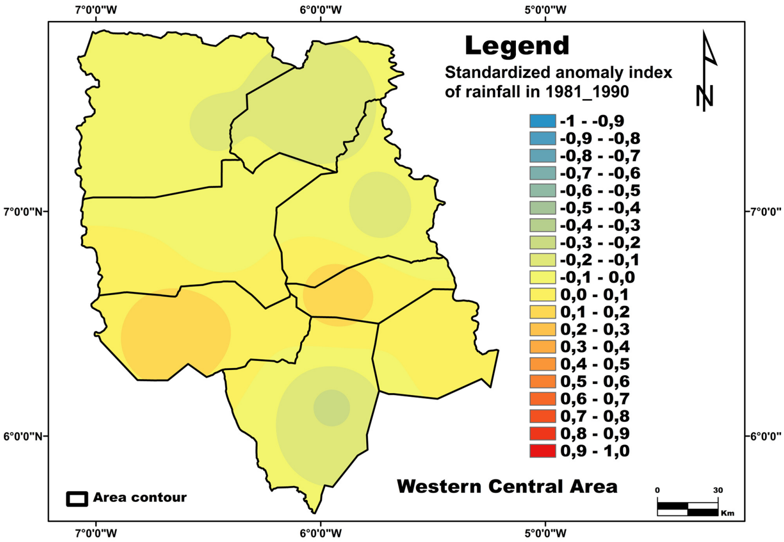
30
Km

(c)


Legend
Standardized anomaly index
of rainfall in 1981_1990
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-0,9 - -0,8
-0,8 - -0,7
-0,7 - -0,6
-0,6 - -0,5
-0,5 - -0,4
-0,4 - -0,3
-0,3 - -0,2
-0,2 - -0,1
-0,1 - 0,0
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Western Central Area
Area contour
7°0'0"W
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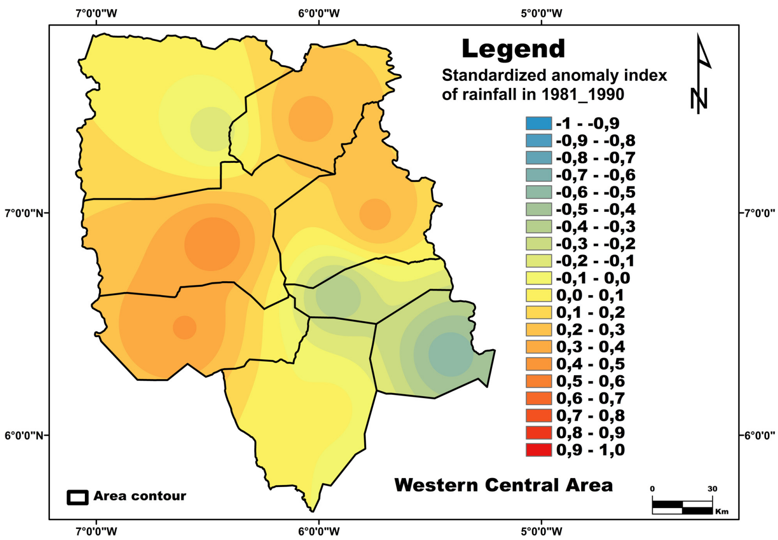
(d)


Legend
Standardized anomaly index
of rainfall in 1981_1990
-1 - -0,9
-0,9 - -0,8
-0,8 - -0,7
-0,7 - -0,6
-0,6 - -0,5
-0,5 - -0,4
-0,4 - -0,3
-0,3 - -0,2
-0,2 - -0,1
-0,1 - 0,0
0,0 - 0,1
0,1 - 0,2
0,2 - 0,3
0,3 - 0,4
0,4 - 0,5
0,5 - 0,6
0,6 - 0,7
0,7 - 0,8
0,8 - 0,9
0,9 - 1,0
Western Central Area
Area contour
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5°0'0"W
7°0'0"N
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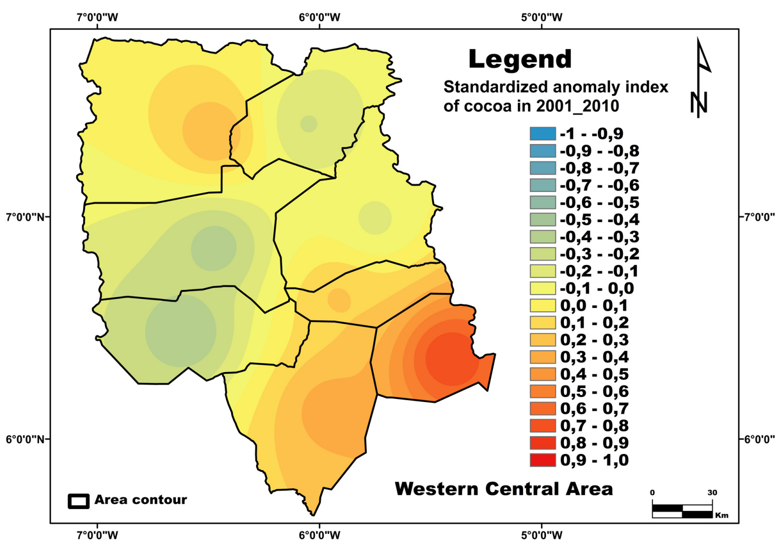
(e)


Legend
Standardized anomaly index
of cocoa in 2001_2010
-1 - -0,9
-0,9 - -0,8
-0,8 - -0,7
-0,7 - -0,6
-0,6 - -0,5
-0,5 - -0,4
-0,4 - -0,3
-0,3 - -0,2
-0,2 - -0,1
-0,1 - 0,0
0,0 - 0,1
0,1 - 0,2
0,2 - 0,3
0,3 - 0,4
0,4 - 0,5
0,5 - 0,6
0,6 - 0,7
0,7 - 0,8
0,8 - 0,9
0,9 - 1,0
Western Central Area
Area contour
7°0'0"W
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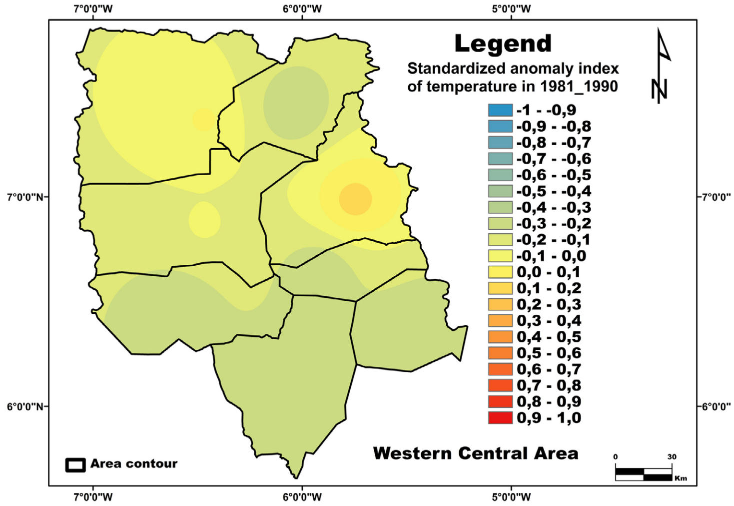
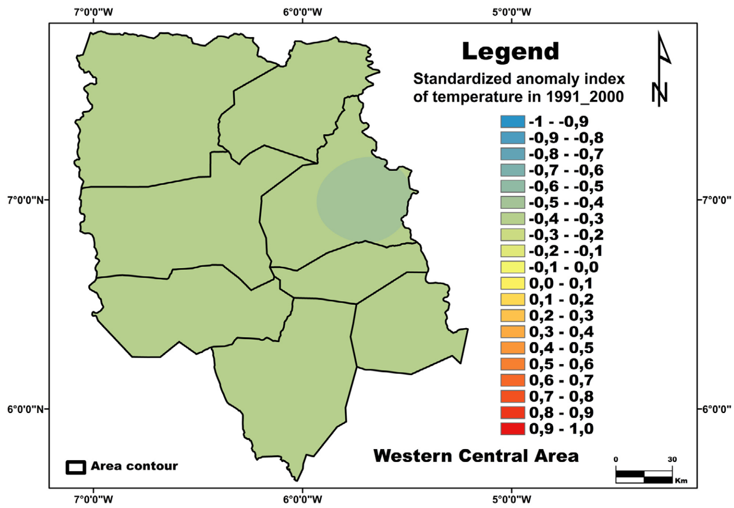
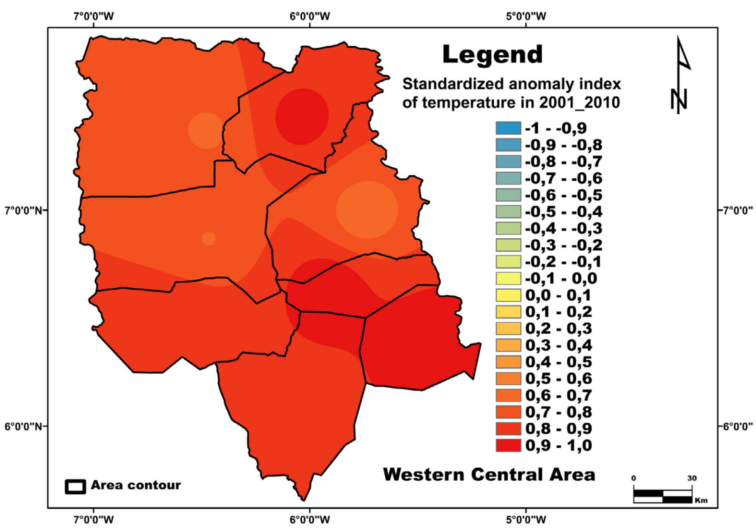
(f)



(g)



(h)



(i)

Figure 3. Spatial and decadal variations of the mean annual standardized anomaly of cocoa production ((a), (b) and (c)), rainfall ((d), (e) and (f)) and temperature ((g), (h) and (i)) for the decade 1981-1990, 1991-2000 and 2001-2010.

between [−0.3; +0.3] over the 1981-1990 period (Figure 3(d)). Over this period, rainfall does not have high spatial variability. All stations appear to have a relatively uniform rainfall distribution, probably due to their proximity and not too large area. However, positive values are systematically observed in Issia and Sinfra while in Zuenoula, Gagnoa and Bouaflé negative values are present. Contrary to the 1981-1990 period, the decade 1991-2000 (Figure 3(e)) shows a clear and remarkable rainfall distribution. This distribution shows two patterns along the North/South-West and North/South-East directions characterized by positive values of anomalies between +0.1 and +0.8 at Zuenoula, Bouaflé, Daloa, and Issia and by negative values of anomalies in the range [−0.8; −0.1]. The regions of Zuénoula, Bouaflé, Daloa, and Issia experienced an excess of mean annual rainfall while those of Vavoua, Oumé, Sinfra, and Gagnoa experienced a rainfall deficit compared to the 1980-2010 period. In addition, the spatial distribution of rainfall over the 2001-2010 period (Figure 3(f)) is in contrast to that of 1991-2000. Indeed, positive values of anomalies in the range [0; 1] are located in the northwest and southeast precisely at Vavoua, Sinfra, Oumé, and Gagnoa while negative values [−0.8; −0.1] are located at Zuénoula, Bouaflé, Daloa, and Issia. These results suggest that the decades 1991-2001 and 2001-2010 had a reversed rainfall variability for the same given stations. These observed rainfall contrasts show the extremely variable patterns of rainfall in West Africa. Concerning the mean spatial variations in temperature over the entire study area, Figure 3(g) shows a relative cooling related to standardized anomalies in the range [−0.5; −0.1] in the stations of Daloa, Issia, Gagnoa, Sinfra, and Oumé that extends to Zuenoula over the 1981-1990 period. In the Vavoua and Bouaflé stations, the standardized anomalies are in the range [0; 0.3] that indicates relative warming compare to the 1981-2010 mean period. In contrast to the 1981-1990 decade, the entire study area is characterized by a generalized cooling over the 1991-2000 period (Figure 3(h)). This cooling indicates that the temperatures recorded at these stations were lower compared to those calculated over the 1981-2010 mean period. A strong cooling is noted particularly in Bouaflé with standardized anomalies lower than −0.7. However, in contrast to the 1991-2000 period, Figure 3(i) shows general warming over the 2001-2010 period in the study area. This warming is illustrated by systematically positive standardized anomalies of temperature in the range [0.1; 1]. This change in temperature pattern between the 1991-2000 and 2001-2010 periods is also visible in the spatial variability of rainfall for the same periods. It seems that these two periods were affected by factors whose variability had alternating effects.

3.3. Statistic Correlation between Cocoa Production, Rainfall, and Temperature

This section discusses the yearly response of cocoa yield related to the changes in rainfall and temperature. Figure 4 shows the standardized anomaly index of rainfall, temperature, and cocoa production in the Goh (a), Haut-Sassandra (b), and Marahoué (c) regions. In the Goh region (Figure 4(a)), cocoa yield seems to

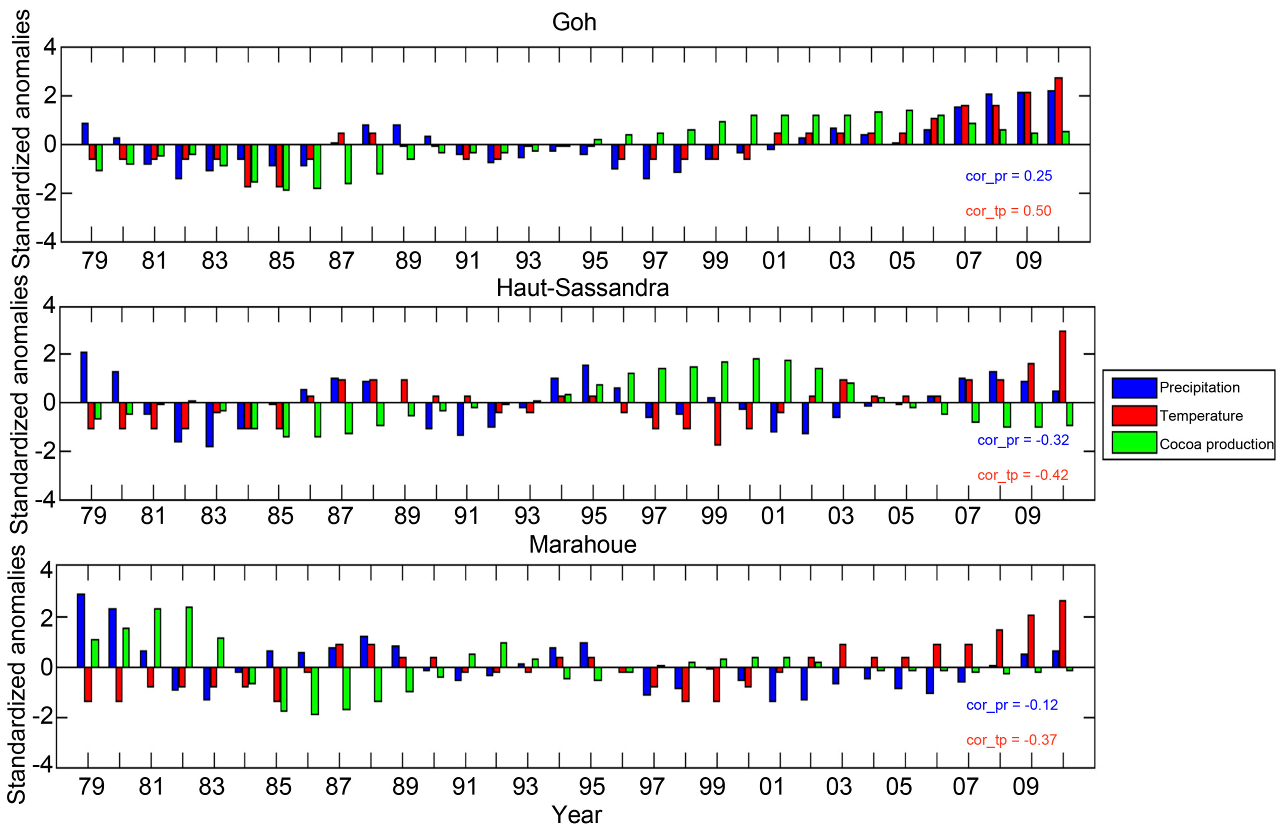


Figure 4. Standardized anomalies of Precipitation (blue), Temperature (red) and cocoa production (green) in Goh (upper), Haut-Sassandra (middle) and Marahoué (below) regions from 1961 to 2010. The calculated correlation coefficients between cocoa production and both precipitation and temperature are in blue and red respectively.

be linked to the temperature variations with a correlation coefficient value of 0.5. Their temporal variations highlight two main periods with negative (resp. positives) standardized anomalies for cocoa production before 1995 (resp. after 1995) and temperature before 2001 (resp. after 2001) except in 1988 and 1989. In this alternation of standardised anomalies (positive and negative), the positive values indicate that temperature variations (warming state) have been favourable to a surplus of cocoa production in the Goh region, while the negative values show that temperature variations (cooling state) have been favourable to a deficit of cocoa production. In addition, the analysis of the correlation between rainfall and cocoa production and the standardized anomalies does not show a clear and systematic impact of the rainfall variability in the cocoa yield. Indeed, the low correlation coefficient (R = 0.25) maybe suggests a lack of direct link between rainfall and cocoa production. This variability in rainfall is therefore not a significant predictor of the response of cocoa yield to changes in meteorological conditions in the Goh region. In the Haut Sassandra region (Figure 4(b)), the cocoa production seems to be anticorrelated to the variations of the thermal conditions (R = −0.42) and also to the precipitation (R = −0.32). There are three phases in the changes in cocoa production that are alternated between deficit and abundant production periods. The period of excess production (*i.e.* positive standardized anomalies values of cocoa production) extends from 1994 to 2004 and the period of deficit in production (*i.e.* negative standardized anomalies values of cocoa production) are recorded from 1979 to 1993 and from 2005 to 2010. During these periods both standardized anomalies of Temperature and Rainfall have the same sign (either positive or negative). However, any positive (respectively negative) variations in these meteorological conditions lead to negative (respectively positive) changes in cocoa production from 1979 to 2010. In the region of Marahoué (**Figure 4(c)**), like the region of the Haut Sassandra (**Figure 4(b)**), the cocoa yield seems also to be anticorrelated to the rainfall (R = −0.12) and temperature (R = −0.37). A surplus in cocoa production is recorded during the 1979-1983 period and from 1991 to 1993 and from 1998 to 2002 while a deficit in the cocoa yield is observed over continuous periods from 4 years (*i.e.*, 1994 to 1997) to more than 6 years (*i.e.*, 1984 to 1990 and 2003 to 2010). Before 1986, the time series show negative temperature anomalies associated with positive precipitation anomalies before 1981 and a negative one between 1981 and 1986. Positive rainfall and temperature conditions from 1987 to 1989 provide negative standardizes anomalies of cocoa production. Also, from 1989 to 2010, variations in cocoa production show alternating positive and negative anomalies with small amplitudes (<0.5). Only rainfall and temperature have significant anomaly values until 2010. Rainfall shows dry sequences from 1990 to 1992 and from 1997 to 2007, but also wet sequences from 1993 to 1995 and from 2008 to 2010 while temperature variations highlight a phase of negative anomalies (*i.e.* cold phase) from 1996 to 2001 followed by a long warm phase from 2001 to 2010. This warm phase is associated with a deficit in cocoa production in the Marahoué area (**Figure 4(c)**). This phenomenon has also spread to the Haut Sassandra region with significant amplitudes. In general, the 2001-2010 period shows a positive temperature anomaly over the three regions indicating warming trends.

3.4. Trends of Cocoa Production, Rainfall, and Temperature

This section focuses on the trends of the cocoa production associated with the variability of both rainfall et temperature which is computed and analysed by statistic approach based on the linear regression by the least-squares fit [24]. This approach was used recently in other climatic studies by [9] [25] [26] to objectively detect one or more tendency breaks in predictor scores and their occurrence. **Figure 5** shows every possible trend for cocoa production and both rainfall and temperature and the corresponding confidence Student's t-test during each time segment from a 2-year to 32 years (*i.e.*, the total length of the time series).

The first column of **Figure 5** shows the trends of cocoa production (a), rainfall (b), and temperature (c) from 1979 to 2010 in the Goh region. There are negative trends from 1979 to 1985 (<2.10^4 Tons in absolute value) in cocoa production for high frequencies (*i.e.*, <10 years) which indicates that during this

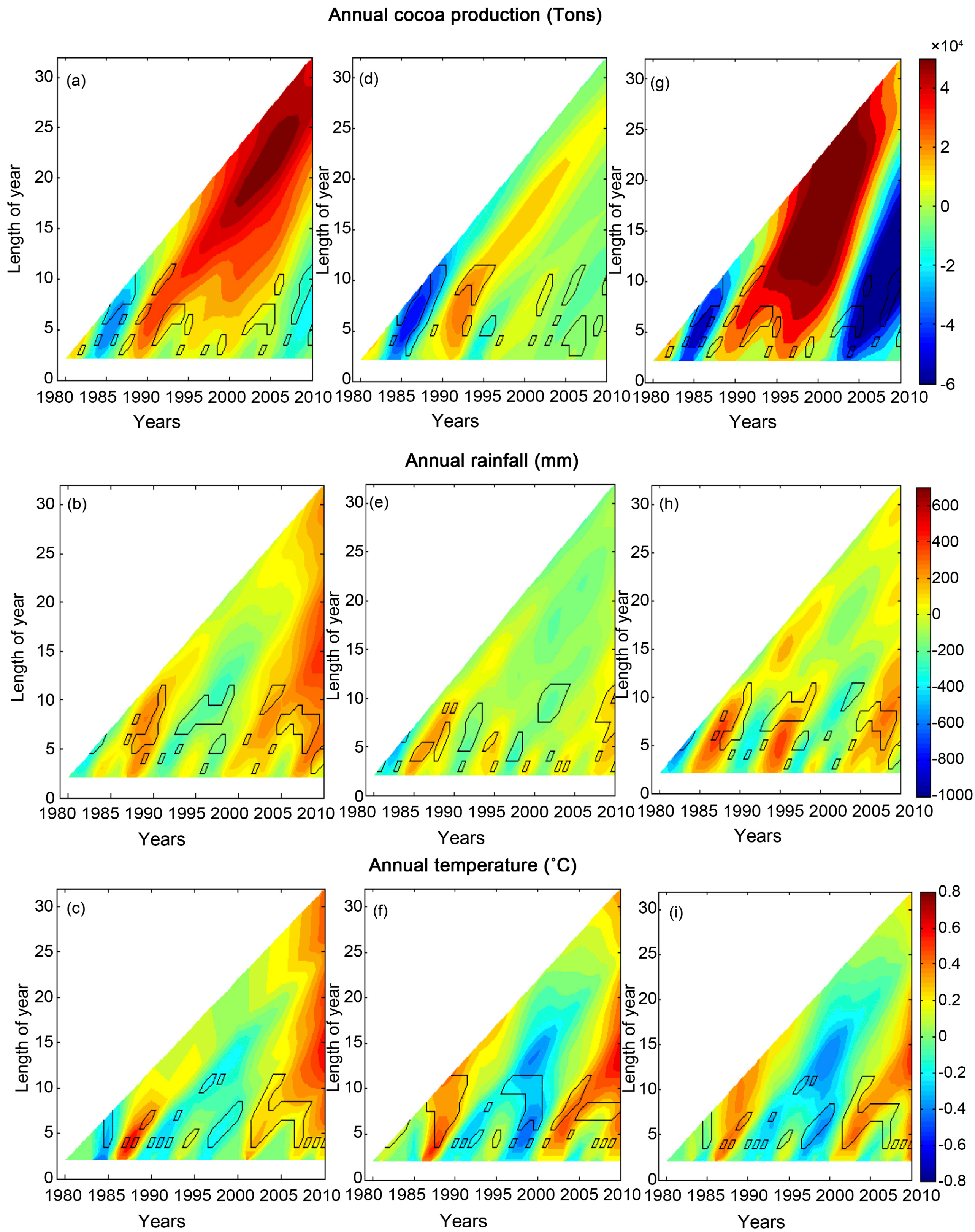


Figure 5. Trends of the Cocoa production (first row), Rainfall (second row) and Temperature (third row) time series from 1979 to 2010 in Goh ((a), (b) and (c)), Haut-Sassandra ((d), (e) and (f)) and Marahoue ((g), (h) and (i)) regions as a function of length of time segment and ending year of calculation; the black contours provide the confidence ranking Student's !-test.

period, cocoa production decreased and the year-to-year change is significant. These trends are associated with high rainfall values (~200 mm) and cooling of 0.2˚C (in absolute value) at the same time. Cocoa production trends are significant from 1987 to 2007 for a time segment less than 5 years with a 95% confidence level of Student's *t*-test and more significant for the length of segment higher than 5 years (*i.e.* low frequencies) where values range between 2×10^4 tons to more than 4×10^4 tons. In the same vein, the trends in rainfall show a decrease during the 1987-1997 period and an increase from 1998 to 2010 for all lengths of a segment. These variations are associated with a significant cooling (<0.2˚C) from 1987 to 2000 for the length of segments less than 20 years. A positive trend in temperature is observed during the 2000-2010 period with high values (>0.3˚C) for lengths of segment ranging between 5 and 31 years. Furthermore, the trends in cocoa production over the Goh region (**Figure 5(a)**) are related to relative similarly trends patterns between rainfall (**Figure 5(b)**) and temperature (**Figure 5(c)**), particularly over the 1987-2000 period, where a cooling and a 20-year drought are recorded.

In the region of Haut-Sassandra, (**Figures 5(d)-(f)**, second column) there are low trends values (<2×10^4 tons) recorded at the middle of the 1980-1985 period in cocoa production for time lengths of segment less than 10 years with a 90% confidence level. This coincides with an increasing tendency of rainfall values of about 200 mm. In addition, important positive trends (>1×10^4 Tons) in the time series of cocoa production appeared from 1985 to 1990. These trends values have a time length of segment extends to 25-year. Beyond the 1990, the trends oscillate between positive and negative values associated with important trends in rainfall variations at high frequencies (*i.e.*, time lengths of segment less than 5 years) with a 90% confidence level. At lower frequencies, the annual rainfall variation exhibits trends values between −200 mm and 100 mm. This is associated with a relative important cooling above 0.2˚C (in absolute value) from 1987 to 2000 for time segments between 5 and 25 years with a 90% confidence level. High trend values (>0.3˚C) in temperature variation are observed at the beginning of the year 1985 and the end of 2000 and 2005. These significant values are recorded with a 90% confidence level for a time length of segment lower than 10 years. Moreover, the region of Marahoué (**Figures 5(g)-(i)**, third column) distinguishes itself by high values and significant trends in the interannual variation of cocoa production (**Figure 5(g)**). The values of the trends related to the temperature (**Figure 5(h)**) and the rainfall (**Figure 5(i)**) are comparable to the other regions. Negative trends (<-2×10^4 Tons) in cocoa production are observed from 1983 to 1985 and from 2005 to 2010 for a time length of segment less than 15 years with a 90% confidence level. This decrease is followed by an important increase (up to 4.104 Tons) in production from 1987 to 2000. This observation is associated with the alternated positive and negative trends in rainfall variation. For example, negative values of the trend are noticed in cocoa production over the 1983-1985 period with positive trend values up to 400 mm in rainfall variation over a 10-years window till 1985, 1995, and 2005 with a 90% confidence level. However, the trends in temperature show a warm phase between 1983 and 1985 where the values reach 0.4˚C. From 1987 to 2000, the temperature trend values are negative (<−0.2˚C) reflecting the cooling phase for a time length of segments less than 25 years. Consequently, high cocoa production trends are associated with significant cooling phases in temperature trends while warm phases (temperature trend values > +0.2˚C) indicate negative cocoa production trends over the 2000-2010 period also for time segments less than 25 years.

4. Discussion

In Cote d'Ivoire, the seasonal changes in cocoa yields due to the variations in local meteorological conditions, particularly precipitation and temperature, have motivated many studies [15] [16] [27]-[31] to raise awareness of the risks of productivity losses but most of the adoption of different strategies for adapting to new climatic conditions. In addition, the conclusions of the work of [16] highlighted the need to take into account climatic parameters whose variations have more impact on cocoa yields since from one region considered to another, the analyses have shown different impacts. The current study assesses, across the central-western part of Cote d'Ivoire, the variations in cocoa production related to the changes in rainfall and temperature during the period 1979-2010.

The yearly standardized anomaly of cocoa production, rainfall, and temperature (**Figure 5**) indicates strong variability in the regions of Goh, Haut-Sassandra, and Marahoué. If the precipitation and temperature variabilities can be associated to regional [7] [32] [33] and also to local [34] [35] [36] effects, cocoa production variability is significantly governed by climatic factors (e.g., rainfall and temperature) [16] [28] [30] [37]. Furthermore, several studies [38] [39] extend this dependence of cocoa production on climate to all agricultural production based on correlative statistics.

However, rainfall which is one of the key impact factors of agriculture in sub-Saharan Africa seems in some production areas and/or for some crops less determinant in terms of annual rainfall quantity. This is in agreement with [16] who noticed an absence of an important correlation between the cocoa yields and the mean annual rainfall over some production areas. Nevertheless, one can show that these lower values of the correlation coefficient do not necessarily indicate a marginalization of the effects of the changes in rainfall. Also, if considering a part of the rainy season as in the work of [16], or when excluding some exceptional years like in [40], the correlations can be significant. On the other hand, it could be related also to the fact that irrespective of the changes in rainfall, the required amount of rain for a good cocoa yield is constantly satisfied as was the case with the air temperature [16]. This scenario could be possible even more than in the region of Marahoué, where [41] noticed a strong variability in rainfall 1) Starting with a wet period before the year 1975; 2) Followed by a dry period between 1976 and 2000; 3) A recovery after 2001.

The variability in cocoa production could also be due to a change in the dynamics of land use. Indeed, the work of [41] in the Marahoué catchment area showed a significant increase in agricultural area (around 0.84% per year) may be linked to the intensification of perennial crops such as cocoa and coffee trees. This observation has been done by [42] which underlined that the actual Cote d'Ivoire agricultural area is greater than its optimum level.

On another note, in the case of the Goh region, [43] showed that the interannual rainfall variability is related to the variations of the trends in the rainfall indices defined by the Expert Team on Climate Change Detection, Monitoring, and Indices (ETCCDMI). These trends are expressed by a decrease of 3.18 mm/year and 0.003 days/year in total rainfall (PRCPTOT) and a number of rainy days (CWD) index respectively, while the number of dry sequence days (CDD) is up by 0.215 days/year. This rainfall behavior would be on large spatial scale according to [44] and, associated with a trend towards an increase in air temperature of around 0.08˚C every 10 years.

In the case of Haut-Sassandra, the agroclimatological conditions show apparent similarities with those of the Marahoué region, maybe because these two areas are located on the same latitude (see **Figure 1(a)**). On the other hand, too few studies have shown systematic and direct links between meteorological conditions and cocoa production in this area. If climate changes induced largely by Greenhouse Gases (GHGs) are responsible for high variability in rainfall and temperature at global, regional, and local levels, the high year-to-year variability of cocoa production is linked to several factors. However, between social reasons and environmental changes, the causes related to climatic conditions appear to be essential because the humid tropical climate of the Haut-Sassandra region (the first and second production area of the coffee and cocoa in the country respectively) [45] [46] provides rainfall amount ranging between 1200 and 1600 mm/year, high relative humidity with a mean annual homogeneous temperature of 26˚C [47].

Indeed, **Figure 4** shows negative correlations between cocoa production and both rainfall (~−0.32) and temperature (~−0.42) which implies that the relationships between mean annual meteorological conditions and cocoa production yields are low.

In other words, correlations based on the mean annual temperature and total annual rainfalls alone do not determine the low or high agricultural yields. Other factors, such as the spatial and temporal distribution of rainfall, and intra-seasonal temperature and precipitation conditions influence yield trends. Furthermore, many studies [16] [29] [40] [48] showed that the growth period is more sensitive to precipitation and temperature.

Apart from non-climatic factors, [29] [48] have proposed that the rainy season from April to July must record an amount of rain above 700 mm and the little dry season (August to September) must record at least 70 mm to ensure a good cocoa-growing and production. However, although the climatic conditions proposed by these authors are essential, [16] pointed out that no parameter involved in the cocoa production chain (*i.e.*, from the growing cycle to the harvest via the various stages of maturity) could be considered independently. The authors then showed that a linear statistical and conceptual model of correlations between cocoa production, local meteorological conditions, and their associated non-linear terms cannot explain alone all observed variances in yields for a given region. Thus, cocoa cultivation is subject to a combination of stress factors that it could respond to in a non-linear way or shows threshold responses. Taking into account other factors such as planted area, a number of the vegetative cycle, soil moisture, soil types, wind speed, and sunshine is useful to predict the majority change in cocoa production in the context of climate variability and changes.

On the other hand, the intensity of changes and their sensitivity to rainfall and temperature trends in regard to the length of time segments are assessed.

Figure 5 shows that significant and positive trends in cocoa production of Goh (a), Haut-Sassandra (d), and Marahoué (g) regions are observed over the 1987-2000 period and for lengths of segments up to 31 years at 90% confidence level. This means that over this period, excess cocoa production are established on a long-time scale. This situation in the western-center of Côte d'Ivoire emerged because the old cocoa "loop" (*i.e.*, the eastern-center, particularly in the Daoukro region) experienced an unprecedented decline in cocoa production from the 1970-1980 period [13]. According to [13], the main causes of the drop in production were the decrease in rainfall and the ageing of plantations (over 30-years old) associated with the rural exodus to western regions (*i.e.*, new cocoa "loop") in search of new cultivable areas. Furthermore, there are positive and important impacts of the favourable climatic conditions offered by the western-center region for cocoa cultivation as a mean annual total rainfall between 1200 and 1500 mm/year [15] [28] [43] and high relative humidity with a mean annual homogeneous temperature of 26˚C [47]. However, the 1979-1987 and 2000-2010 periods highlight a decrease in cocoa production ($<-2 \times 10^4$ Tons) for a length of segments less than 10-years and 20-years respectively. Indeed, the decrease in the 1979-1987 period is due to that this western-center part was not significantly exploited before the decrease in cocoa production in the Daoukro region. In contrast, the decline in production after 2000 is related in part to climate changes associated to an increase of the dry seasons length [28], but mostly to the same reasons as the old cocoa production "loop" (*i.e.* eastern-centre of Cote d'Ivoire) and, also to a drop in the selling price of cocoa on the world market leading to a disinterest of new producers for cocoa cultivation and the gradual abandonment of it for the benefit of other agricultural products such as rubber trees, palm oil, etc. whose prices on the international markets had until then been satisfactory.

In the same vein, rainfall trends in the three regions (**Figure 5(b)**, **Figure 5(e)** and **Figure 5(h)**) have experienced a succession of positive (>200 mm) and negative (<−200 mm) values for the length of segments less than 10 years with a

90% confidence level in the Student t-test. On the other hand, low trend values [−200; 200] mm are observed at low frequencies (*i.e.* for a length of segments greater than 10 years) indicating high rainfall variability at a small time scale while at large scale variability is low. These observations are also found in the study of [9] in the Lamto region. They seem to be on a regional scale and linked to the internal dynamics of the climate.

In this climate variability, temperature trends (**Figure 5(c)**, **Figure 5(f)**, and **Figure 5(i)**) show a long cooling phase below 1˚C (in absolute value) and quite general over the 1987-2000 period with a warm phase around 1995. This cooling coincided with the high values of cocoa production trends in the Goh, Haut-Sassandra, and Marahoué regions. Therefore, it seems that this climatic condition is linked to the general rainfall deficit that appeared between 1980 and 2009 and observed in many parts of Cote d'Ivoire by several studies [9] [13].

Cooling trends have also been favourable to the increase in cocoa production (see **Figure 3(b)** and **Figure 3(h)**). Indeed, cocoa cultivation seems to favour small temperature variations, and previous works of [16] have shown that in the departments of Abengourou, Agboville, Daloa, Dimbokro, Guiglo, and Soubre, temperature variations in the range 25˚C - 29˚C have not had significant impacts on cocoa production. From 2000 to 2010, trends are high (>0.2˚C) indicating a warm situation. This warm is related to global warming previously discussed by many authors [49] [50] and the Intergovernmental Panel on Climate Change (IPCC) with a high confidence level [51]. According to these authors, global warming is due to human activities through the emission of GHGs into the atmosphere. The impacts are significant and lead to seasonal instability with consequences for agriculture [40] [52] [53] and the economies of West African countries. At local scale, **Figure 3(b)** (not shown) in [16] showed that warming already reached ~1.5˚C over 40-years trends (*i.e.* 1965-2005).

5. Conclusion

This study assessed the trends of cocoa production and both rainfall and temperature established by climate change during the 1979-2010 period in Goh, Haut-Sassandra, and Marahoué regions considered as the new cocoa "loop" area in Cote d'Ivoire. The statistical analysis shows low correlation values between cocoa production and these meteorological conditions because these correlations based on the mean annual temperature and total annual rainfalls alone do not determine the low or high agricultural yields. Indeed, predicting the majority change in cocoa production in the context of climate variability and changes needs to take into account other factors, such as the emblazoned surface (*i.e.* cultivated area), the spatial and temporal distribution of rainfall, and intra-seasonal temperature and precipitation conditions as previously mentioned by [40] and [9] that are not available and accessible for this study. However, results show important positive trends of cocoa production in the Goh, Haut Sassandra, and Marahoué regions over the 1987-2000 period coinciding with a general cooling and succession of wet and dry phases in all regions. The temperature conditions have a stronger impact on cocoa yields than those in the south region described in [16]. This shows that temperature plays a significant role in determining the quality of cocoa production. This influence cannot be neglected in the central western region and the associated cooling trends contribute to an improvement in yields. These results are useful and cocoa production may be improved also by the crop rotation method because monoculture over a long time depletes the soil and leads to low yields even under satisfactory climatic conditions. In addition, results will help to integrate the impacts of climate change and extreme weather events into planning and decision-making tools for improving cocoa production and agricultural yields in general in the climate changes and adaptation context. They will contribute also to improving the quality of climate services dedicated to cocoa cultivation to ensure producers' income.

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Conflicts of Interest

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

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