Hindawi
International Journal of Geophysics
Volume 2019, Article ID 5610328, 19 pages
https://doi.org/10.1155/2019/5610328

Research Article

Twenty-First Century Projected Changes in Extreme Temperature over Côte d'Ivoire (West Africa)

Assi L. M. Yapo[1] **Adama Diawara,**[1] **Fidèle Yoroba**[1] **Benjamin K. Kouassi**[1] **Mouhamadou B. Sylla,**[2] **Kouakou Kouadio**[1] **Romaric C. Odoulami**[3] **and Dro Touré Tiémoko**[1]

[1]*Laboratory of Atmosphere Physics and Fluid Mechanics, University F.H.B. of Cocody-Abidjan, 22 BP 582 Abidjan 22, Côte d'Ivoire*
[2]*West African Science Service Center on Climate Change and Adapted Land Use (WASCAL), WASCAL Competence Center, Ouagadougou, Burkina Faso*
[3]*African Climate and Development Initiative, University of Cape Town, Cape Town, South Africa*

Correspondence should be addressed to Assi L. M. Yapo; martialdeyapo@yahoo.fr

Received 3 June 2019; Revised 7 October 2019; Accepted 15 October 2019; Published 23 December 2019

Academic Editor: Salvatore Gambino

The projection of the future climate changes is of paramount importance inasmuch as it contributes to provide useful information for adaptation planning worldwide to local scales. This study investigated the future changes using four temperature related indices based on an ensemble of 14 CORDEX-Africa simulations at $0.44° \times 0.44°$ of resolution under the RCP4.5 and RCP8.5 scenarios. These indices indicate moderate extremes over Côte d'Ivoire. The results show an increase in the warm extreme indices such as the warm spell days index (HWFI), very warm days frequency index (TX90P), and the warm nights frequency index (TN90P) over the entire country under both emission scenarios. The increase in these indices was higher under RCP8.5 and reached 85, 72, and 90% for HWFI, TX90P, and TN90P respectively. In addition, the magnitude of the changes is relevant along the coastal areas in the 2031–2060 and 2071–2100 periods. Moreover, the intra period extreme temperature range (ETR) shows future decrease following a south-north gradient with values in the range [−0.5; 1.5°C] over the country during January–March (JFM) and October–December (OND) seasons whereas an increase (~0.5°C) is projected for April–June (AMJ) and July–September (JAS) seasons, particularly in the central and northern parts. The minimum temperature increases faster than the maximum, except in AMJ and JAS in the central and northern regions. On the other hand, the changes in the indices based on the mean values of the reference period (1976–2005) are in concordance to the expected warming at the end of the twenty-first century with important trends. The projected changes are, however, subject to uncertainties, which are higher under RCP8.5 than under RCP4.5 scenarios. Overall, these changes are meaningful as all the 14 CORDEX-Africa simulations agree to an increase of warm extreme temperature.

1. Introduction

The most severe effects of global warming result from the frequency and severity of extreme events such as floods [1, 2], droughts [3, 4] and heat waves [5–8]. Severe, extreme and exceptional heat waves occurred worldwide, for example in 2003 in France [9–11], in 2010 in Russia [12, 13] and recently in west Africa (i.e., Niger) in 2010 [14, 15] with many drawbacks implying increased mortality, reduced labor productivity and human discomfort [16–18]. Because of its high vulnerability to climate change [19], Africa underwent many heatwaves events that are not often noticed or documented [20, 21]. However, some extremely hot events that occurred in West Africa have been highlighted as: the abnormally high temperature (up to 50.6°C) in the Sahara, during the boreal summer of 2002 [22], the heat wave associated to high temperature rise (about 47°C) recorded in Niamey (Niger), in April 2010 and May 2013 [14], respectively. In addition, Russo et al. [23] underlined that Africa experienced hotter, longer and more extent heat waves during the 1979–2015 period across all seasons than in the last two decades of the 20th century. Africa generally faces the occurrence of such peak temperatures and heat waves during the dry season (JFM), [15]. Particularly, the Sahel faces an important rise of minimum temperatures compared with the maximum temperature during that season (i.e., JFM) since 1980 [14, 24, 25]. This agrees with the warming observed over the continent for the past 50–100 years [26]. In addition, this rise in temperature was statistically significant between 0.5°C and 0.8°C during the 1970–2010 period in Africa [27] and had been projected to increase between 1.5°C and 6.5°C under RCP4.5 and RCP8.5 scenarios in West Africa [28].

Previous studies, on the projection of extreme temperature and heat wave, focused on the exposure and vulnerability of the population at a regional scale. For example, Dosio et al. [29], Sylla et al. [18] under 1.5°C and 2°C reported that heat stress of category Extreme Caution would extend spatially (up to 25%) over most of the West Africa region including Gulf of Guinea, Sahel, and Sahara. In addition, [23] reported a robust and consistent occurrence of unusual heat waves observed under present climate. These heat waves are expected to occur more frequently by 2040 under RCP8.5.

Odoulami et al. [21] used a regional climate change model to assess the future changes in heat wave characteristics based on the change in vegetation cover (with and without reforestation) in West Africa. Their results suggest a general increase in heat waves number and days over the region, reforestation on the average, may increase these numbers and days over Savannah areas, and decrease them over the Sahel and along the Guinea coast.

Ceccherini et al. [20], in an analysis of the extreme temperature regime of heat waves across West Africa during 1981–2015, underline an increase of their frequency and intensity as well as the maxima and minima temperatures in the last decades. For its part, Russo et al. [13] quantified the magnitude of heat waves worldwide and noticed in a warming situation from maximum temperature of CMIP5 global models, whereas Dosio et al. [29] used the results of a high-resolution global atmospheric model to investigate the change in magnitude, frequency, and extension of these heat waves at 1.5°C and 2°C warming levels.

Some authors like Faye et al. [30], focused on the impacts of 1.5°C and 2°C global warming on cereal yields in the West African Sudan Savannah using two crop models. They found that the 2.0°C scenario had more negative impacts on yield compared to the 1.5°C warming scenario. Thus, their results provide meaningful information needed to assess risks to food security of global warming. Schleussner et al. [31] found an increase in the intensity of hot extremes (i.e., annual maximum value of daily maximum temperature) over tropical Africa using the Coupled Model Intercomparison Project Phase 5 (CMIP5) global climate models (GCMs). In addition, James et al. [32] and Nikulin et al. [7] analyzed ensembles of GCMs and regional climate models (RCMs), and found over continental Africa an increase in annual mean temperature characterized by strong regional heterogeneities between the subtropics and the coastal regions.

Most of the studies underlined previously have been carried out either at global scale [13, 29], or regional scale (i.e., West Africa), [18, 20, 21, 30, 33] scales using a single GCM [29] or a RCM [21]. They do not use multi-model ensemble nor assess uncertainties in the model's projection. Nonetheless, Rome et al. [14] evaluated and compared the long term temperature trends and break points (i.e., reversal trend) at local scale in Niamey (Niger) and Abidjan (Côte d'Ivoire) using weather stations in West Africa, and found significant warming trends. However, few works focusing in future changes in temperature have been done at the country level, especially, Côte d'Ivoire. Thus, the current study analyses future changes in extreme temperature over Côte d'Ivoire and assesses the associated uncertainties using an ensemble of fourteen CORDEX-Africa simulations under RCP4.5 and RCP8.5 scenarios.

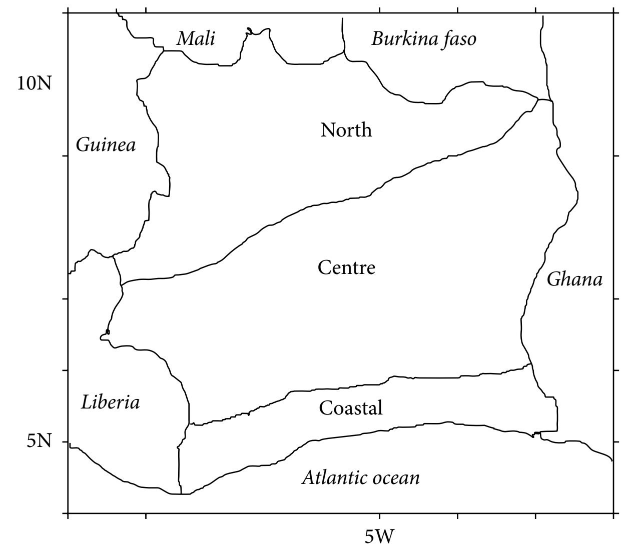


Figure 1: Map of Côte d'Ivoire including the climatic zones (adapted from [34, 41]).

The work 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. Finally, summary and conclusion are given at the end.

2. Study Area, Data, and Method

2.1. Study Area. The study area is Côte d'Ivoire domain which extends from 9°W to 2.5°W longitude and 4°N to 11°N latitude, with a total landmass of about 322,462 km^2 (Figure 1). Located in West Africa, this region is under a humid climate controlled by the West Africa Monsoon (WAM) system [34, 35] during the year. The rainfall regime is related to the local climate type underlined by Kouadio et al. [34] and Diawara et al. [36] which depends largely on large scale atmospheric circulation and continental meteorological conditions [37]. Its seasonal range follows the same variation that the latitudinal displacement of the intertropical convergence zone (ITCZ), itself linked to fluctuations in the trade wind system and the oceanic variables over the tropical Atlantic [38, 39]. Côte d'Ivoire consists of three climatic zones with different seasonal precipitation cycles [34, 40, 41]: (i) the Northern zone (mainly grassy savanna) presents a unique rainy season that occurs during the boreal summer (July–August–September) with a peak of about 270 mm in August, (ii) the Central zone (forested savanna and deteriorated forest) presents two rainy seasons with two maxima in June and September, and (iii) the coastal zone

Table 1: Fourteen RCMs simulations of CORDEX-Africa project phase 2 and their forcing GCMs. ESGF (Earth System Grid Federation), CCCMA (Canadian Centre for Climate Modelling and Analysis), status (Source of the data).

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
		4.5, 8.5	
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

Table 2: The ETR and ETCCDI (HWFI, TX90P and TN90P) temperature indices. The terms T_{Xn90}, T_{Nn90}, T_{Gn90} are the 90th percentile of the maximum, minimum and mean temperature, and the terms T_{Gi}, T_{Ni}, T_{Xi}, indicate the mean, minimum and maximum temperature, respectively. TN_{Ni} is the minimum of the minimum temperature and TX_{Xi} is the maximum of the maximum temperature. All these terms are used to calculate the ETR and ETCCDI (HWFI, TX90P and TN90P) indices that are given in bold.

Index	Definition	Expression	Unit
HWFI	Warm spells duration index	Count when at least six (6) consecutive days with daily maximum temperature is greater than 90th percentile ($T_{Gi} > T_{Gn90}$)	Days
ETR	Intra period extreme temperature range	Difference between the maximum of the maximum temperature and the minimum of the minimum temperature ($ETR = TX_{Xi} - TN_{Ni}$)	°C
TX90P	Warm days	Percentage of days when daily maximum temperature is greater than 90th percentile ($TX_i > T_{Xn90}$)	%
TN90P	Warm nights	Percentage of days when daily minimum temperature is greater than 90th percentile ($TN_i > T_{Nn90}$)	%

(forest and swamp) also presents two rainy seasons with a major peak in June (up to 500 mm) and a second maximum, less pronounced in October (120 mm). The population in Côte d'Ivoire is estimated at more than 22 million [42], of which about 70% live off the income from agricultural activities that were affected by the climate change, particularly extremes in temperature and rainfall conditions [43]. In addition, previous studies [44–46] showed that during the five last decades (i.e., 1962–2012), Côte d'Ivoire faced a significant warming estimated at about 0.5°C (mean value) compared to the 1961–1990 normal period (i.e. reference period), and the 2001–2010 period was particularly hotter (0.8°C), [46]. On the other hand, 2010 was the hottest year of this period with warming around 1.2°C [45].

2.2. Data. We used in this study simulated daily minimum and maximum air surface temperatures from an ensemble of fourteen simulations of the Coordinated Regional Climate Downscaling Experiment (CORDEX) RCMs [47–49] available on the Earth System Grid Federation (ESGF) website (https://esg-dn1.nsc.liu.se/projects/esgf-liu/) at 0.44° resolution. The data span the historical (i.e., 1950–2005) and the future (i.e., 2006–2100) periods under RCP4.5 and RCP8.5 scenarios (Table 1). These simulations are useful to provide climatic analysis for many meteorological parameters (i.e., Temperature, rainfall, etc.) and many extreme events (i.e., heat waves, dry spells, etc.) in a region of Africa, and at many time scales [5, 50–55]. CORDEX data were evaluated in terms of their capability to simulate temperature in Africa [56] with satisfactory results, especially for mean and maximum temperature [57] as well as heat waves over Europe [58].

2.3. Methods. The HWFI (Warm spells duration), TX90P (Warm days) and TN90P (Warm nights) temperature indices from the Expert Team on Climate Change Detection and Indices (ETCCDI) and the ETR (Intra period extreme temperature range) defined by Alexander et al. [59] and used by Tebaldi et al. [60] and then by Russo and Sterl [61] (Table 2) are used. HWFI, TX90P and TN90P are classified as percentile-based threshold indices, which describe the exceedance rates above the 90th percentile derived from the 1976–2005 base period of the daily mean (TGn90), maximum (TXn90) and minimum (TNn90) temperature (Figure 2), respectively [62, 63]. The maxima (~40°C) of TXn90 are located in the northern regions during JFM and AMJ, those of TGn90 (~30°C) extend toward the western areas, while the maxima (~24°C) of TNn90 are located along the coastal zone in JAS and OND seasons (Figure 2). These indices are performed for climate change studies [61] and their trends evaluation [59]. They are calculated for each simulation and then for the multi-model ensemble mean at seasonal time scale.

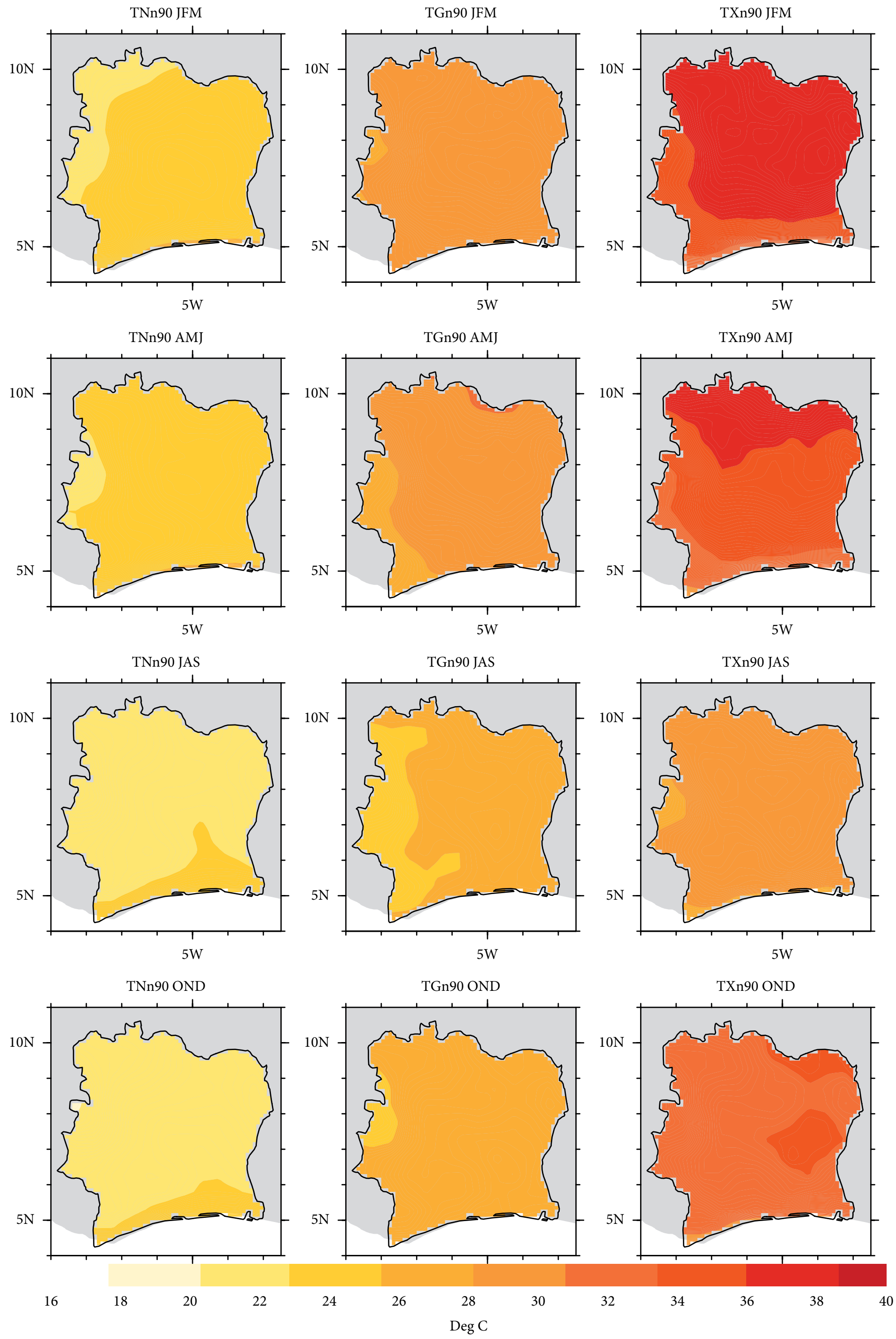


FIGURE 2: Seasonal distribution of the 90th percentile of the daily minimum (TNn90), mean (TGn90) and maximum (TXn90) temperature in Côte d'Ivoire during the 1976–2005 period used to calculate the extreme temperature indices (TN90P, HWFI, TX90P).

This approach was proposed in many studies [51, 55, 64, 65], and the results revealed that the multi-model ensemble (MME) mean approach outperforms the individual RCM at different temporal and spatial scales providing thus a more robust assessment.

In addition, future mean changes in the extremes are calculated for each tropical climatic seasons: JFM (January–March), AMJ (April–June), JAS (July–September) and OND (October–December) for two 30-years periods: 2031–2060 (near-future) and 2071–2100 (far-future), both under RCP4.5 and RCP8.5 scenarios. We assessed the projected changes with respect to the mean climatology of the 1976–2005 period (reference period).

On the other hand, and to have an idea about the trends, the analysis of anomalies is performed for each mentioned season over the entire country. Trends are also estimated using

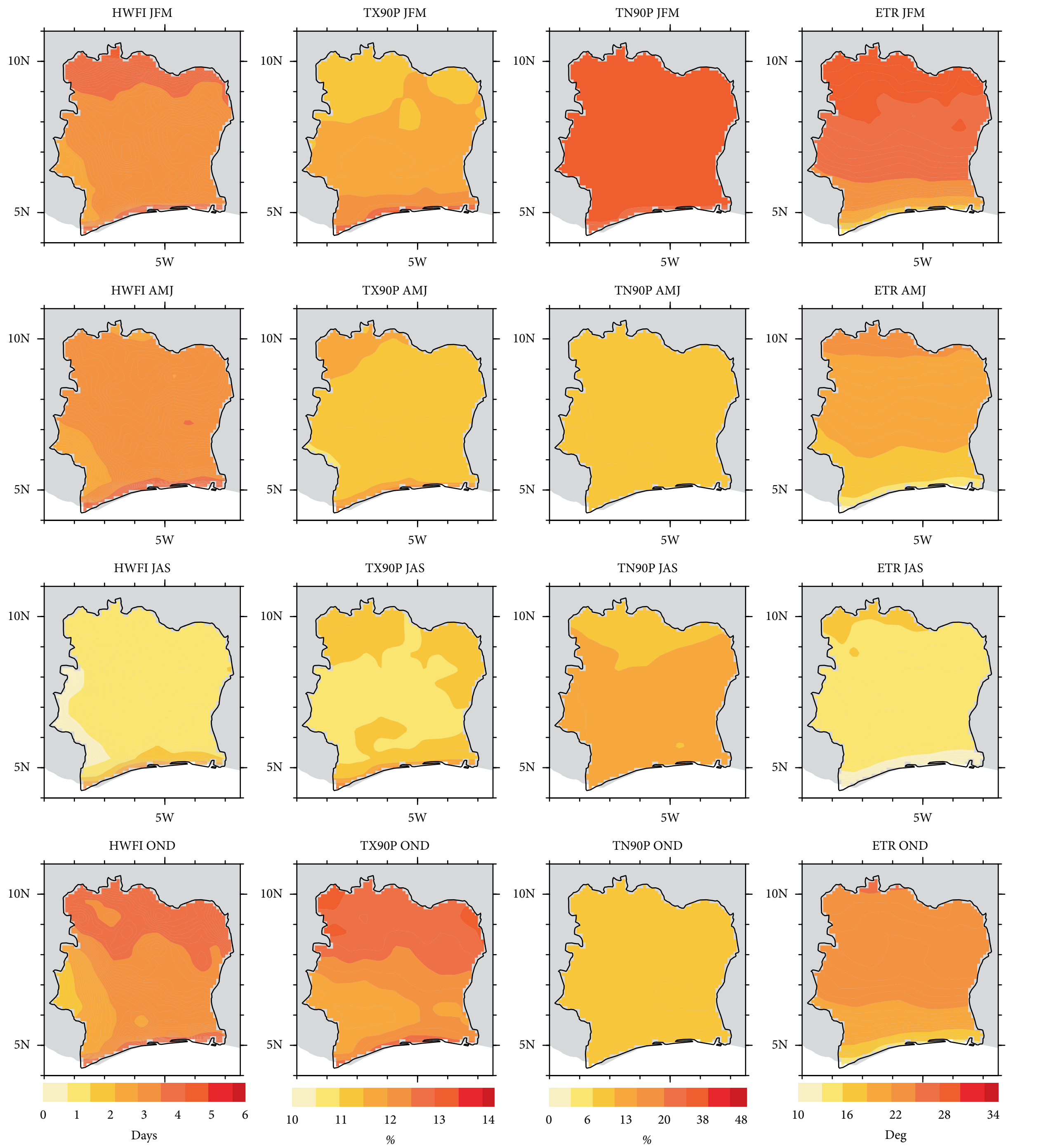


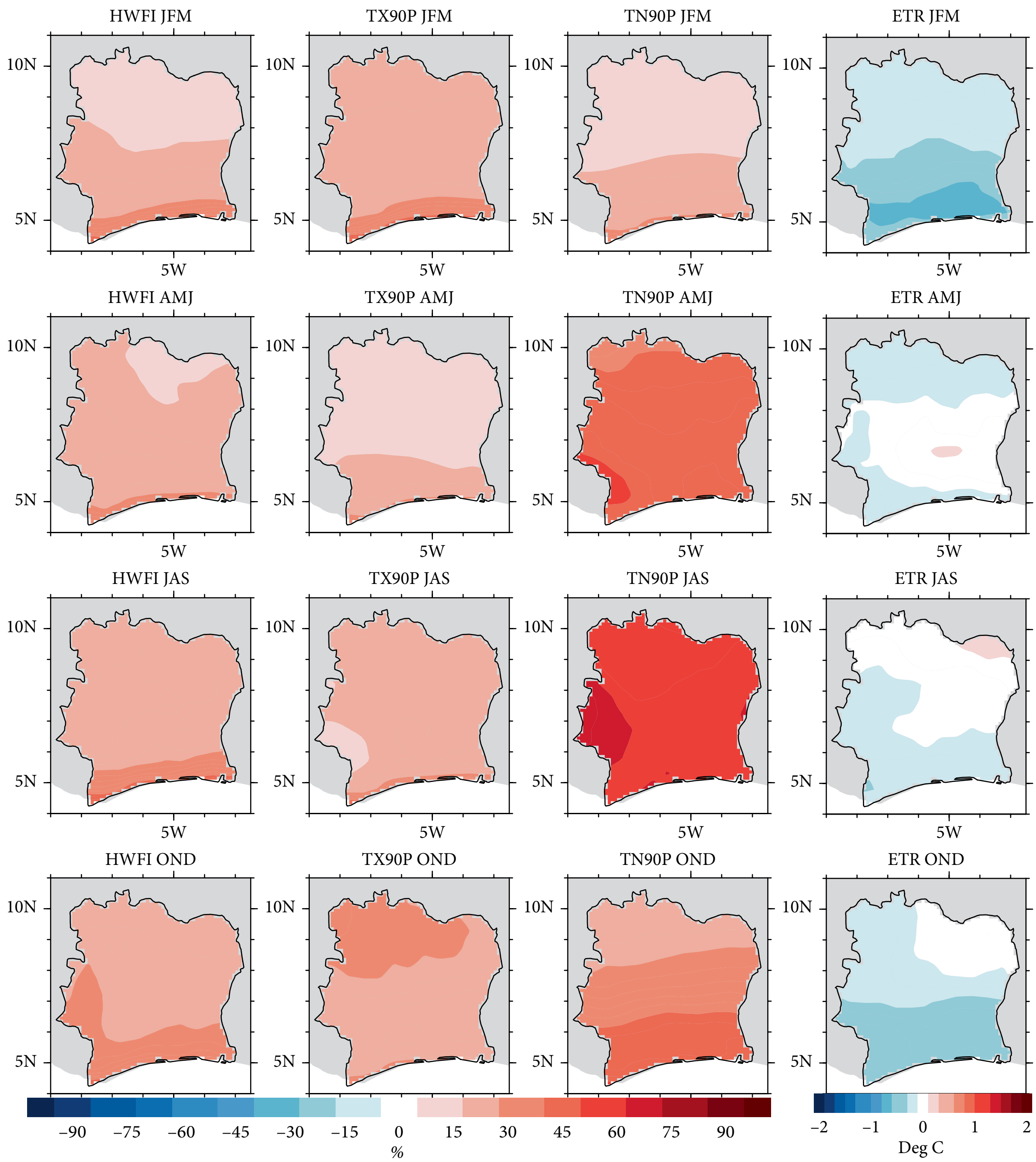
FIGURE 3: Seasonal distribution of the different extreme temperature indices (HWFI, TX90P, TN90P, ETR) in Côte d'Ivoire during the 1976–2005 period.

Mann-Kendall [66, 67] test for 1976–2005 and 2006–2100 periods. These trends are then compared across JFM, AMJ, JAS, and OND seasons.

Furthermore, box-and-whiskers plots are also developed to gain some insights about the associated uncertainties and their ranges. This considers helping quantify the inter-model spread of the changes and the models' consensus to the sign of the changes. This methodological approach is based on the assumption that the projected changes can be considered robust if at least 75% of the models (referred to as the majority of the models) agree to the sign of the changes as underlined by Sillmann et al. [63].

3. Results and Discussion

3.1. Extreme Temperature Indices in the Present Climate Conditions. Figure 3 presents the seasonal variability of



(a)

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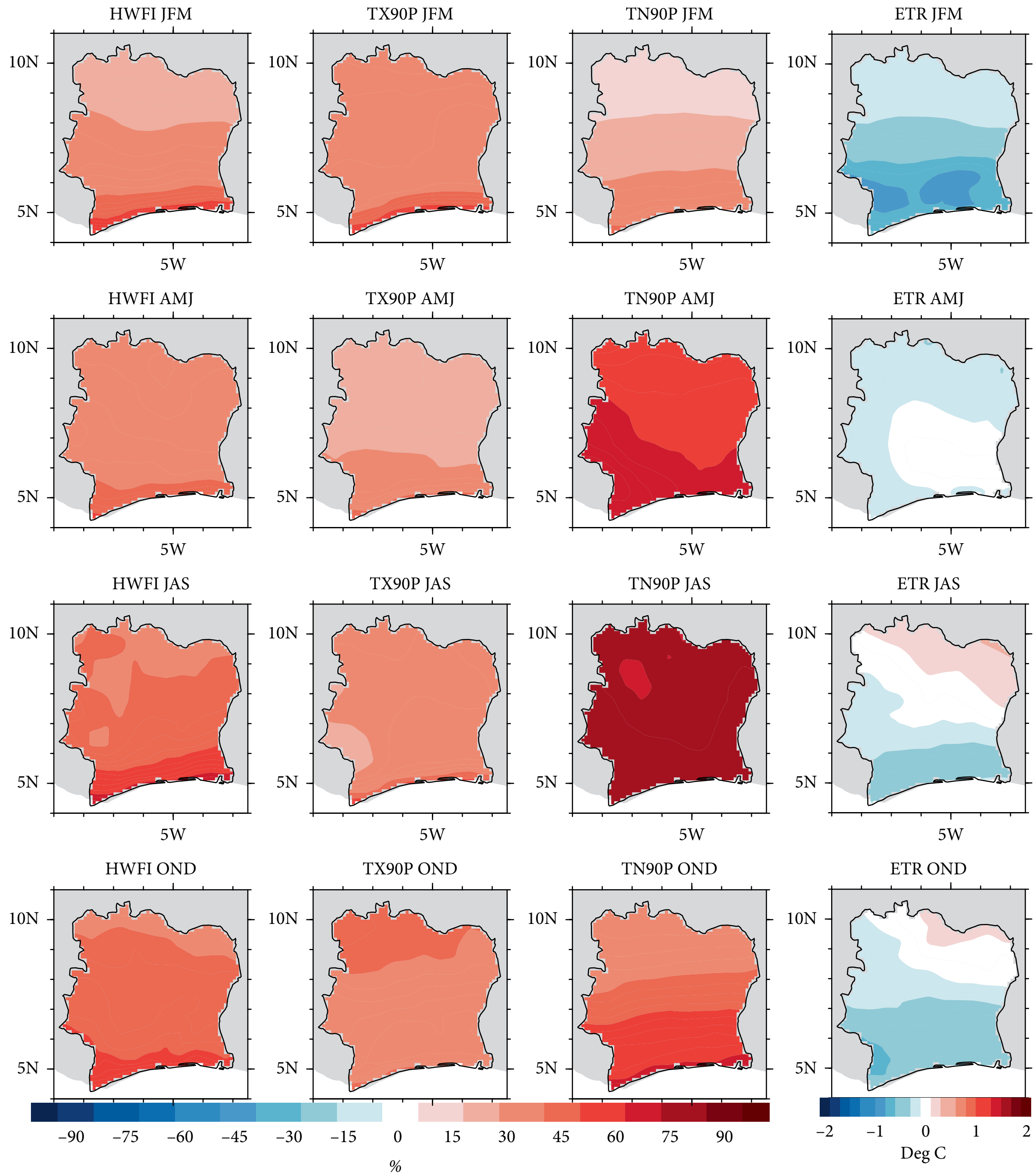
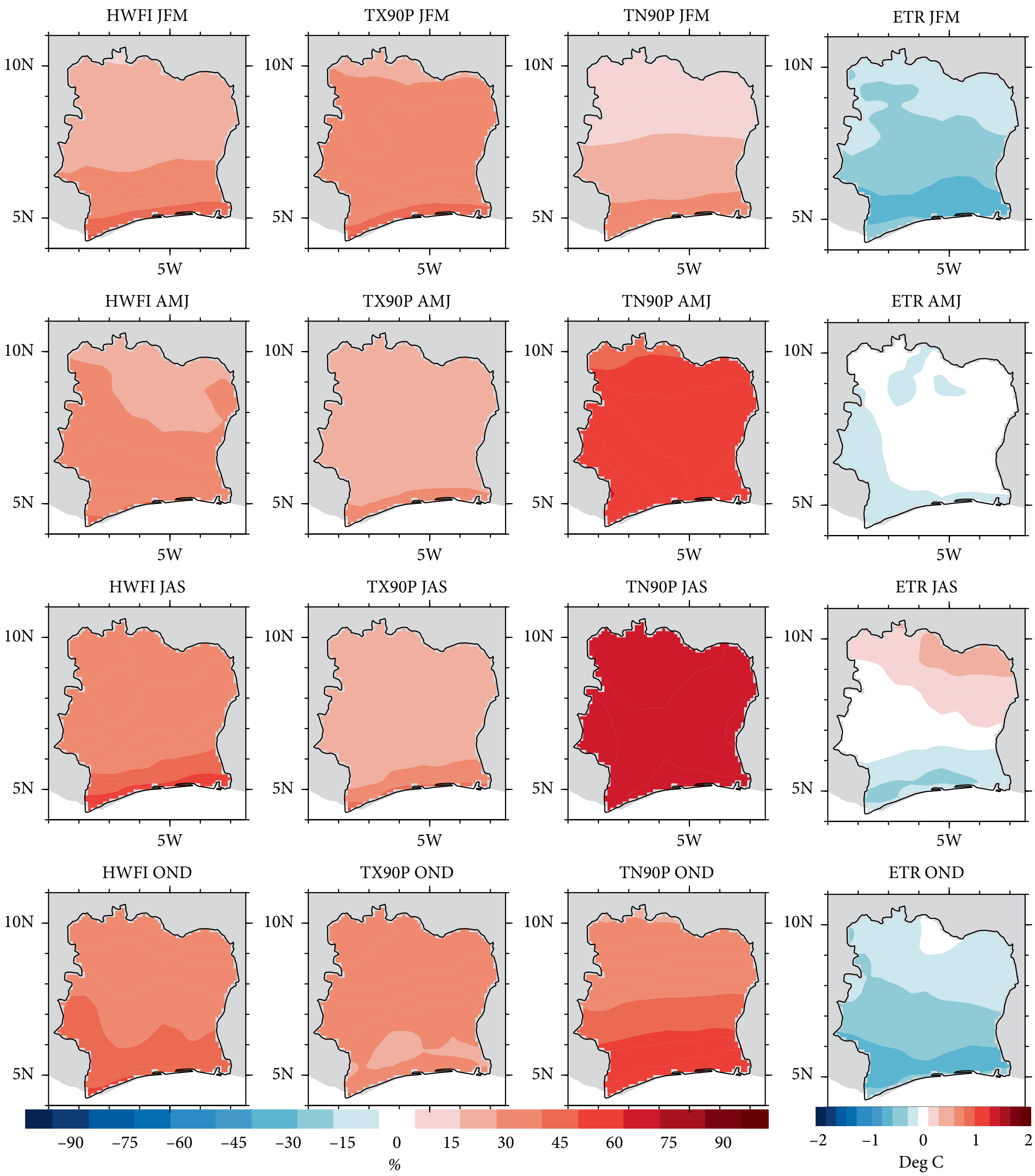


(b)

FIGURE 4: Seasonal mean changes of the HWFI, TX90P, TN90P, and ETR indices, (RCP4.5 minus Historical) from the multi-model ensemble mean of the CORDEX-Africa simulations over 2031–2060 (a) and 2071–2100 (b) periods.

the extreme temperature indices (HWFI, TX90P, TN90P and ETR) during the reference period (1976–2005). HWFI presents a southward gradient during JFM and OND with maxima reaching 5 days; whereas, during AMJ and JAS, the maxima were located in the coastal region and were up to 4 and 2 days, respectively. Warm days frequency index (TX90P) also presents a southward gradient in OND (~13%) while in JFM a south–north gradient is noticed (~12%). In AMJ and JAS seasons, both coastal and northern areas experience important warm days frequency of 12% and 11%, respectively. In addition, the warm nights frequency (TN90P) is characterized by an important magnitude (~38%) during JFM compared to AMJ (~13%), JAS (~20%), and OND (~10%). The intra period extreme temperature range (ETR) shows a north-south gradient during all the seasons with the maximum (~30°C) in JFM and the minimum (tilde 8°C) in JAS seasons along the coastal regions. This characteristic is similar to that observed by [68] who suggested a northward



(a)

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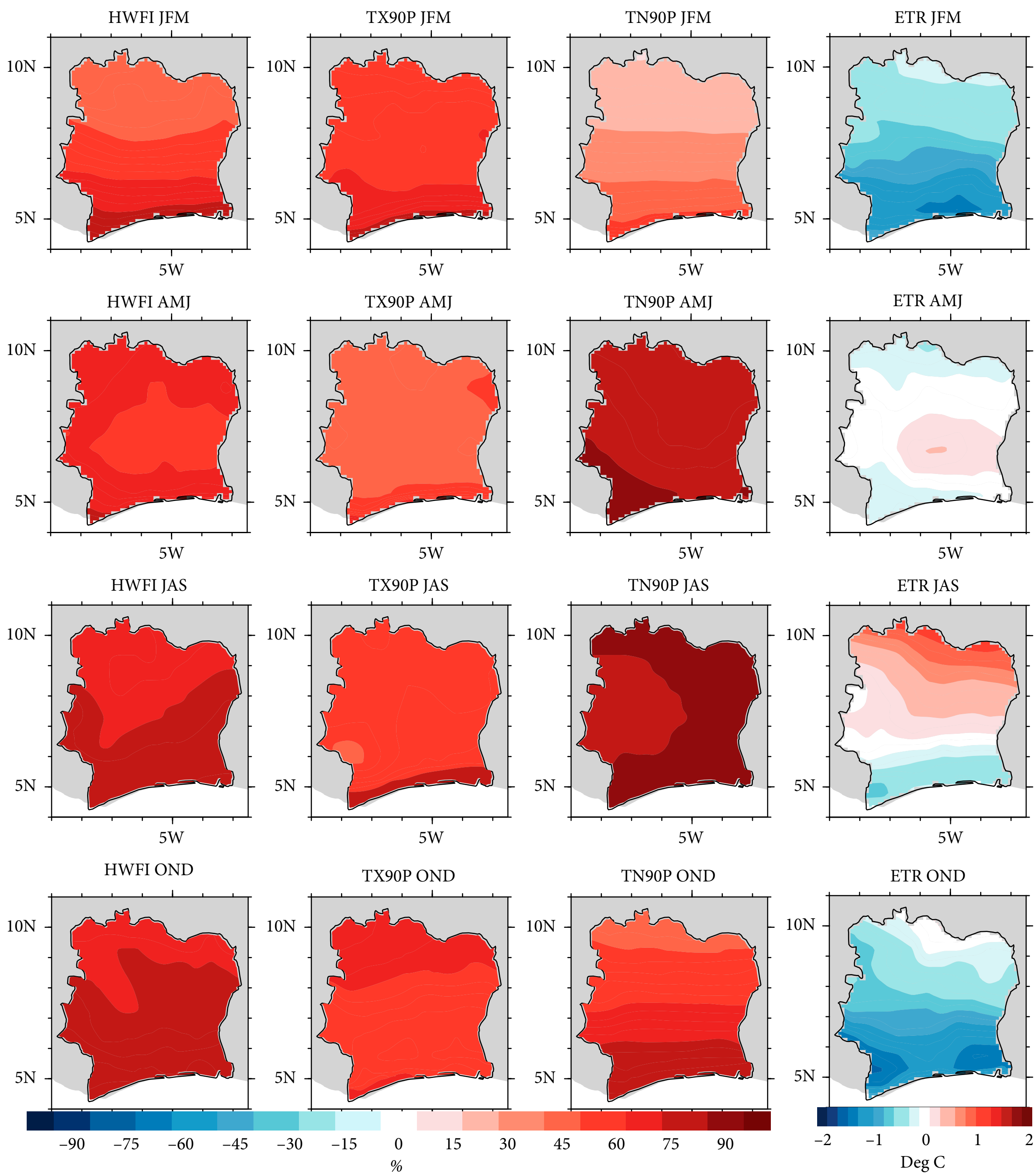
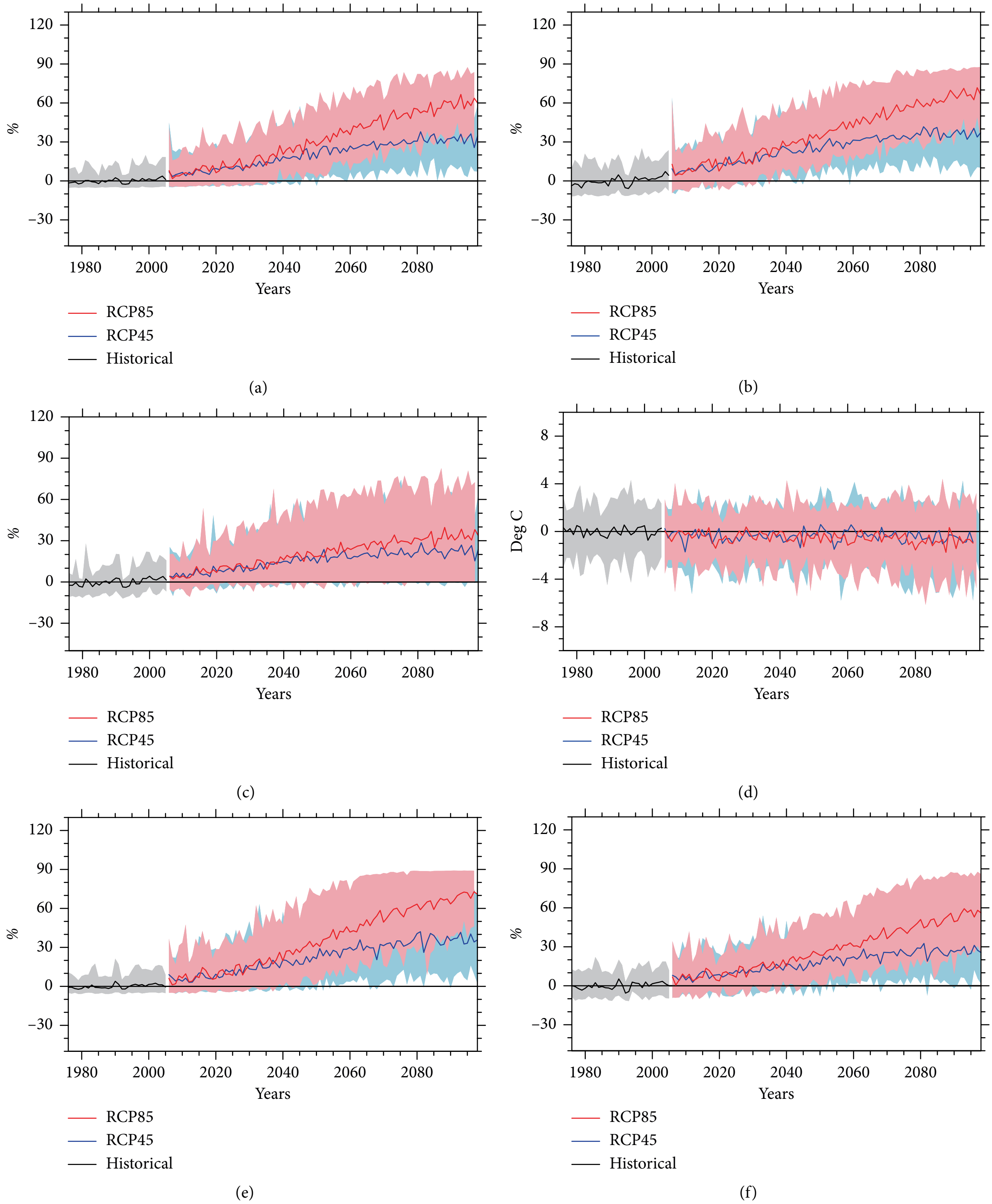


(b)

Figure 5: Seasonal mean changes of the HWFI, TX90P, TN90P, and ETR indices, (RCP8.5 minus Historical) from the multi-model ensemble mean of the CORDEX-Africa simulations over 2031–2060 (a) and 2071–2100 (b) periods.

increase from the equator reaching maxima (~40°C) in northern regions of Africa.

3.2. Mean Spatial Changes. Changes in seasonal mean extreme temperature indices (HWFI, ETR, TX90P, and TN90P) over Côte d'Ivoire show positive tendencies in all seasons (JFM, AMJ, JAS and OND) and for both scenarios RCP4.5 and RCP8.5, except ETR (Figures 4 and 5). Indeed, a general decrease in ETR is projected, especially in the southern part. This decrease highlights a northward gradient associated with maxima intensifying over the coastal climatic zone. Some areas, however, may experience increases in ETR (e.g., the north in JAS and the centre in AMJ). This increase observed during AMJ and JAS seasons in the north and south of Côte d'Ivoire could be related to a reduction of soil moisture favoring high temperatures [61]. In addition, the HWFI, TX90P,



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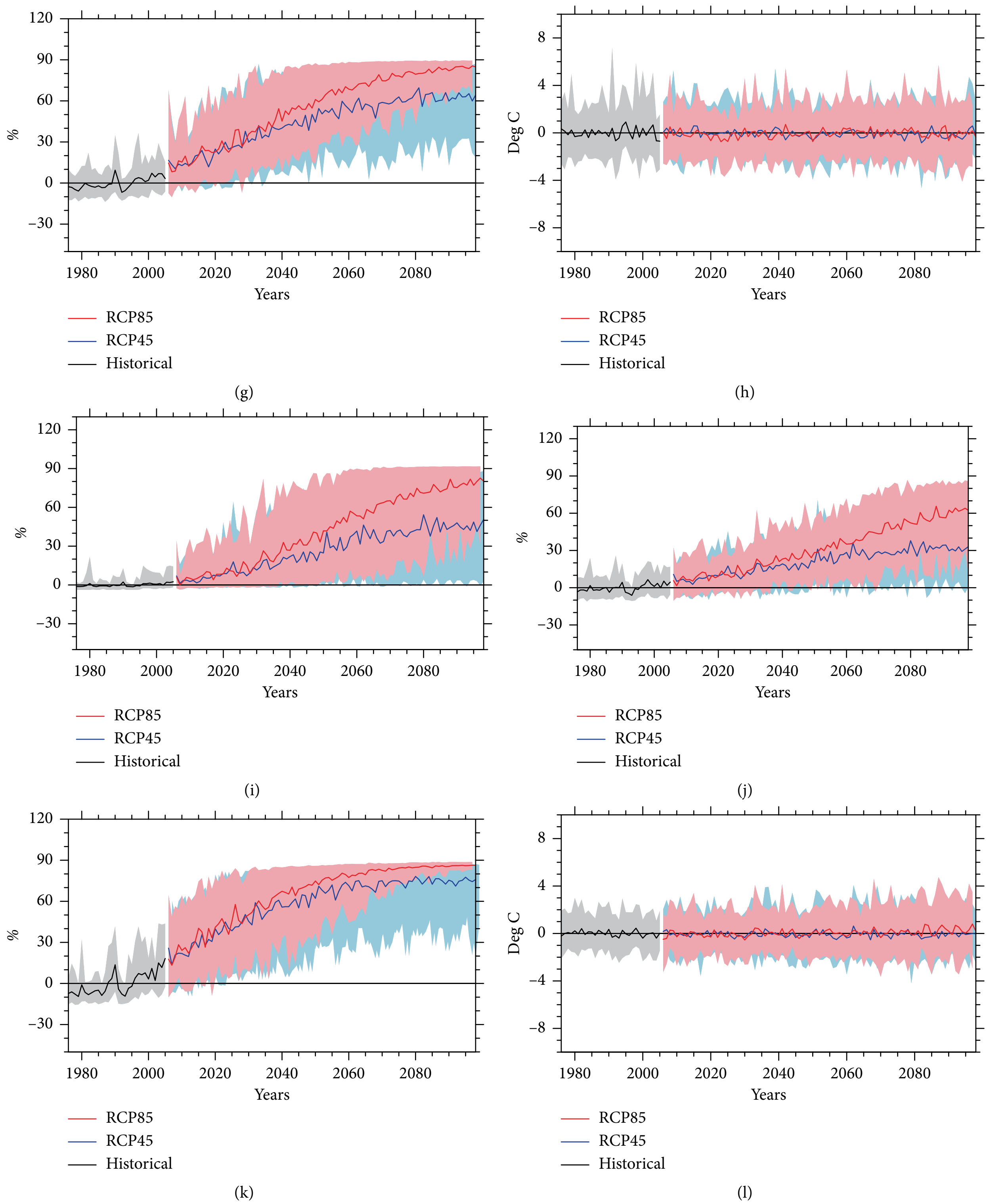

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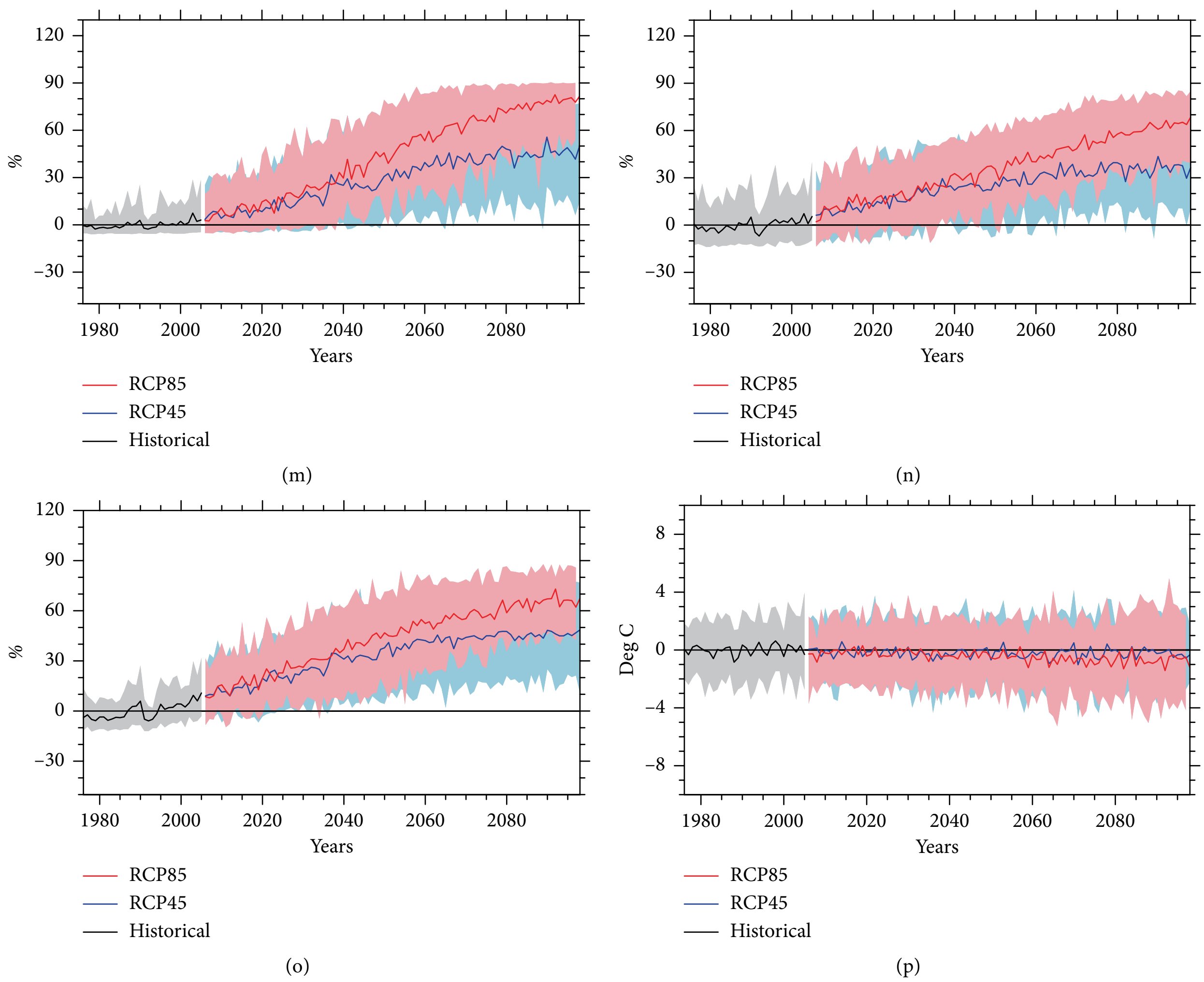
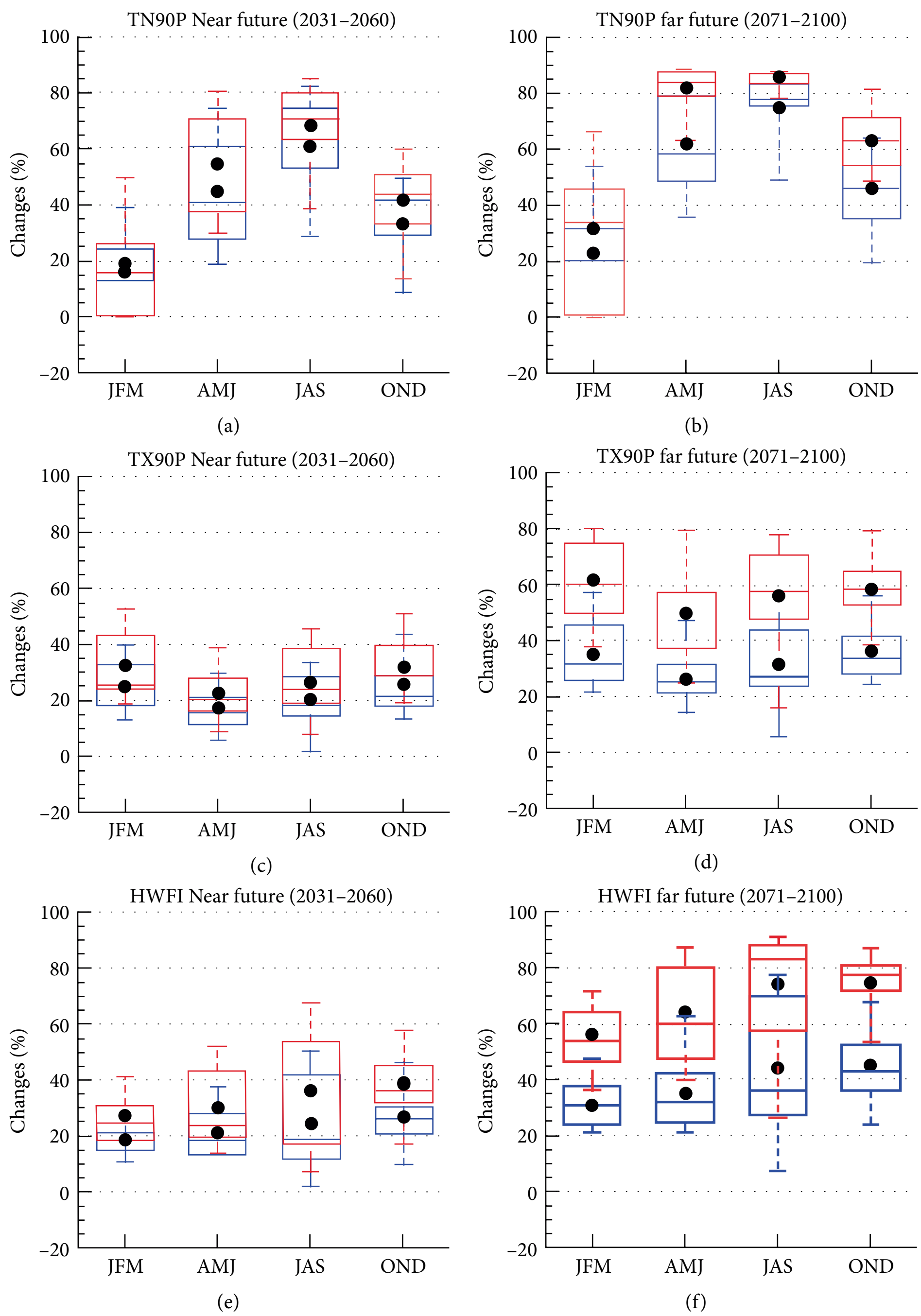


Figure 6: Long-term time series (1976–2100) of seasonal anomalies of HWFI (a, e, i, m), TX90P (b, f, j, n), TN90P (c, g, k, o) and ETR (d, h, l, p) during JFM (a, b, c, d), AMJ (e, f, g, h), JAS (i, j, k, l) and OND (m, n, o, p) seasons in Côte d'Ivoire over 1976–2005 period (grey) and both RCP4.5 (blue) and RCP8.5 (red) scenarios based on multi-model CORDEX-Africa simulations. The anomalies are calculated with respect to the mean value of the 1976–2005 period. The shaded areas denote ensemble 95th and 5th percentiles.

and TN90P indices show in general a south-north gradient indicating that significant changes are mostly projected in the southern part of the country for each scenario and season, except in frequency of very warm days in OND season where maxima are localized in the north. Thus, the littoral climatic zone might become more vulnerable to heat waves episodes over the 2071–2100 period. Indeed, the projected changes in warm extremes (TX90P, TN90P, HWFI) over Côte d'Ivoire are mostly important in the coastal region, especially during the period 2071–2100. This result is in agreement with [5] who reported that the Gulf of Guinea, the Horn of Africa, the Arabian Peninsula, Angola, and the Democratic Republic of Congo are expected to experience long lasting heat waves, of 60–120 days long, every 2-years in the future. The projected increase in the extreme events toward the coastal areas may be related to possible changes in the dynamical features of the West African monsoon and the teleconnection with El Niño/ENSO related to the global warming [69]. The moisture flux from the ocean associated with evapotranspiration over land increases the water vapor content into the atmosphere which could play a major role on heat waves through an enhanced greenhouse effect [69]. Changes in the temperature indices (TX90P, TN90P, and HWFI) are more important and relevant under RCP8.5 forcing scenario and can reach about 85%, 72% and 90% for HWFI, TX90P and TN90P, respectively. As [70] reported the high vulnerability of African coastal cities to extreme precipitation, the present study showed that coastal areas in Côte d'Ivoire may also experience extreme temperature and heat waves events in the future.

3.3. Temporal Evolution and Uncertainties. Figure 6 shows the CORDEX-Africa multi-model ensemble long-term (1976–2100) time series of seasonal HWFI, ETR, TX90P, and TN90P indices anomalies along with the range of possible values during the historical (1976–2005) and the future (2006–2100) periods and for both RCP8.5 (red) and RCP4.5 (blue) scenarios. The anomalies are calculated with respect to the seasonal mean of the reference 1976–2005 period. The time series show significant warming occurred over Côte d'Ivoire during the recent decades (i.e., 1976–2005) and will continue in the future under both scenarios RCP4.5 and RCP8.5. Whatever the emission scenario RCP8.5 or RCP4.5 is, the warming



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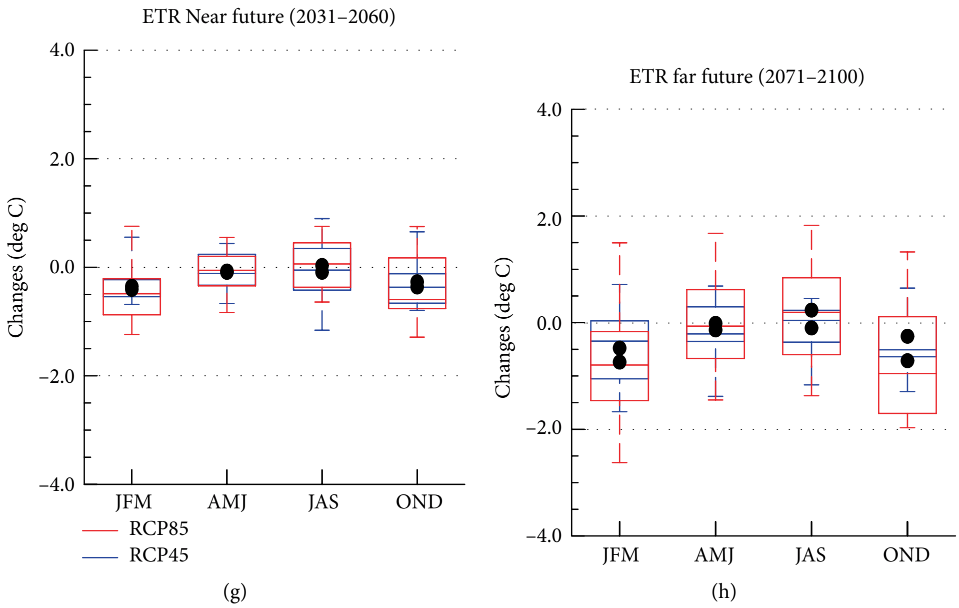

Figure 7: Assessment of CORDEX-Africa models agreement and inter-model spread on the projected changes for the extreme temperature indices during 2031–2060 (left) and 2071–2100 (right) periods under RCP4.5 (blue) and RCP8.5 (red) scenarios. Changes are estimated in (%) for HWFI, TX90P and TN90P and, in (°C) for ETR with respect to the mean value of the 1976–2005 period. Black dots indicate ensemble mean changes.

gradually increases and reaches its maximum value in 2100. We also note that at the end of the Century, under both scenarios, the uncertainty range (i.e., maximum minus minimum) in the projected temperature indices anomalies can reach very high values, up to 30% for HWFI, TX90P, and TN90P and, up to 4°C for ETR. Changes in percentile HWFI, TX90P, and TN90P indices from the two forcing scenarios start to diverge generally around 2040 to reach its maximum in 2100. The divergence year starts earlier in Côte d'Ivoire than over West Africa which is around 2050 [28]. The mid-level GHG forcing scenario RCP4.5 yields to less warming while the high-level forcing RCP8.5 produces greater warming. Therefore, at the end of the century, possible warming over Côte d'Ivoire ranges from 10% to 90%. On the other hand, ETR presents a less evident trend oscillating between positive and negative values (i.e., −4°C and 4°C) indicating that the projected changes in ETR are uncertain over Côte d'Ivoire. Multi-model ensemble, therefore, indicates a decrease of ETR from 2040 to the end of the century during the dry season JFM and the postmonsoon season OND, (Figures 6(d), 6(h), 6(l), and 6(p)). This situation relates the fact that minimum temperature increases faster than the maximum temperature in Côte d'Ivoire. This corroborates the results found by [25] about the faster increase of minimum temperature than the maximum temperature in West Africa in general and particularly in the Sahel. Moreover, we can note that the range of uncertainty gradually increases as the RCPs forcing increases. Also, uncertainty increases as the time frame increases. This implies that the range of possible changes in the future (2006–2100) is larger compared to the historical period (1976–2005), suggesting that the projected climate change over Côte d'Ivoire is associated with large uncertainties. The asymptotic shape observed on Figures 6(e), 6(g), 6(i), and 6(k) could suggest similar projection of TN90P and HWFI by the ensemble members. Hence, the uncertainty may be reduced from the period 2030–2100 in the projection of these indices. This is in agreement with the Figure 7(b) (JAS) and Figure 7(e) (JFM) which indicate robust changes.

3.4. Models Agreement for the Sign of Change. The seasonal mean changes and inter-model spread for each index (i.e. HWFI, TX90P, TN90P and ETR) are shown as box-and-whisker plot for the 2031–2060 and 2071–2100 periods under RCP4.5 (blue) and RCP8.5 (red) scenarios for the whole country (Figure 5). The most remarkable feature is the projected increase in percentile temperature indices (TN90P, TX90P and HWFI) in Côte d'Ivoire under both scenarios RCP4.5 and RCP8.5 and in the JFM, AMJ, JAS, and OND seasons. All the CORDEX-Africa models, therefore, agree to a projected increase with both the lower (25th percentile) and upper (75th percentile) quartiles as well as maxima and minima showing all positive values of changes (above 0%) indicating a robust result for the increase in extreme temperature. However, for ETR, considerable uncertainties predominate for all seasons, except JFM as inter-model spread span both positive and negative values. Furthermore, the inter-quartile range tends to increase under RCP8.5 scenario and for far-future (2071–2100) period compared to RCP4.5 and the near-future (2031–2060) period suggesting that the regional response of the individual RCMs tends to become larger as the greenhouse gas forcing intensifies [71]. The magnitude ranges from 0% during 2031–2060 and under RCP4.5 to 90% during 2071–2100 and under RCP8.5 for TN90P. TX90P magnitude spans from 15% during 2031–2060 and under RCP4.5 to 70% during 2071–2100 and under RCP8.5. For HWFI index, the magnitude stretches from 10% during 2031–2060 and under RCP4.5 to 90% during 2071–2100 and under RCP8.5. However,

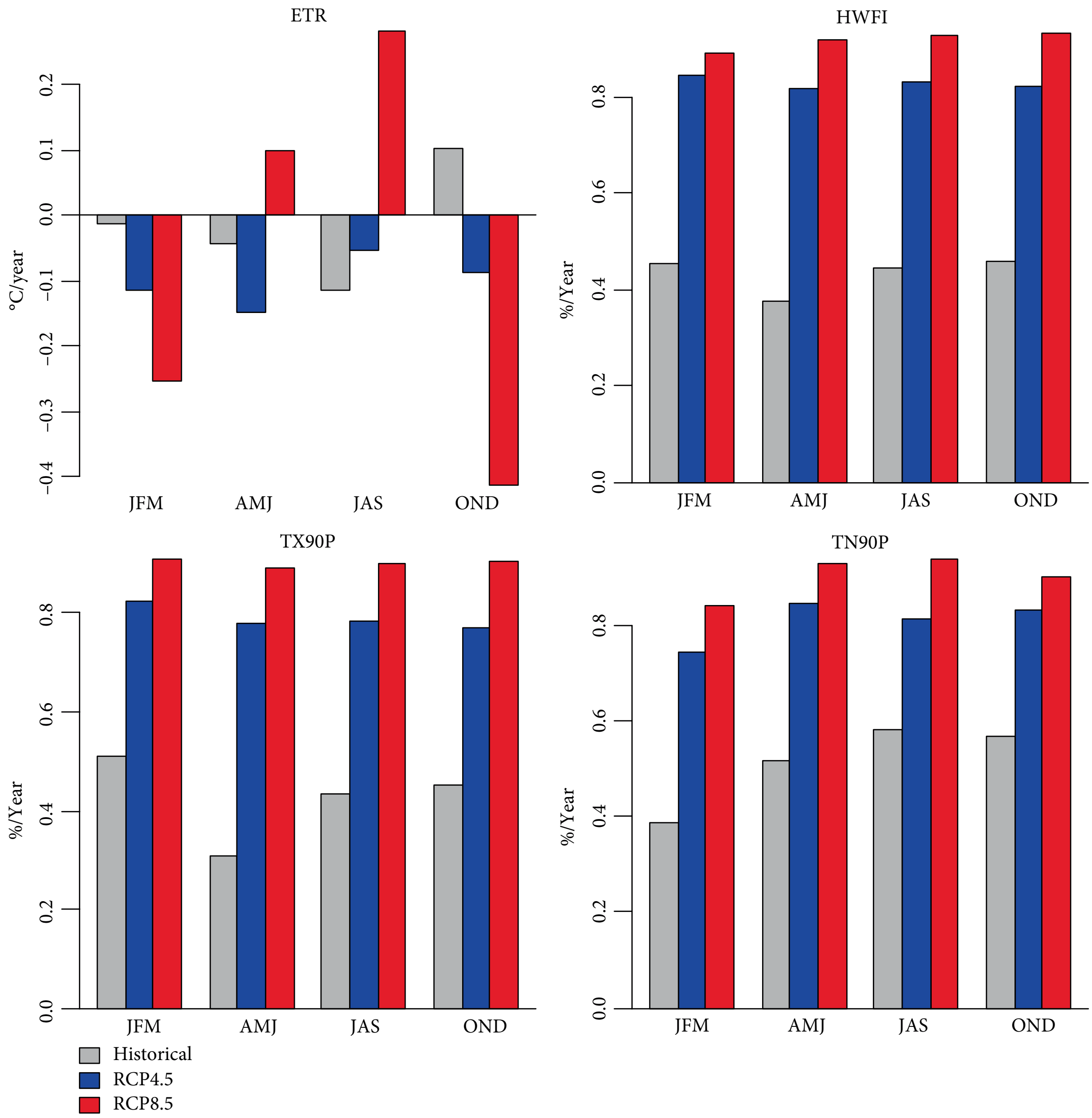

Figure 8: Comparison of the seasonal (JFM, AMJ, JAS, OND) trends of extreme temperature indices (ETR, HWFI, TX90P, TN90P) in Côte d'Ivoire for the historical (1976–2005) and future (2006–2100) periods under RCP4.5 and RCP8.5 scenarios.

the magnitude for ETR spreads from −2°C to 1°C. Thus, it is undeniable that Côte d'Ivoire will face robust changes in hot extreme temperature indicating the occurrence of heatwaves.

3.5. Trends Comparison. A comparative analysis of historical (1976–2005) and future (2006–2100) trends for the different indices discussed above are analyzed in this section. The trends in the future period (2006–2100) under the RCPs forcing scenarios are generally important than those in the 1976–2005 period (Figure 8). Thus, significant modification mostly occurs in future climates under mid-level (RCP4.5) and high-level (RCP8.5) Green House Gas (GHG) forcing scenarios albeit trends under RCP8.5 are higher compared to those under RCP4.5 scenario. The HWFI, TX90P and TN90P trends consistently increase even in the historical and future periods. For example, the increasing trend of HWFI over the entire country can be explained by the projected increase in temperature in comparison with low-temperature variability in the tropics resulting to the strong gradient experienced by the coastal areas of the country [72]. When comparing warm days (TX90P) and warm nights (TN90P) frequencies, trends are generally higher for TN90P than they are for the TX90P. This result is consistent with Russo and Sterl [61] who showed that TX90P and TN90P keeps the increasing trend in the future even if TN90P increases faster than TX90P. For ETR, trends are mostly negative, implying that minimum temperature increases faster than maximum temperature. Apart from the dry season (JFM), the other seasons experience a different sign of trend in ETR. Indeed, during OND season, ETR, under both scenarios, consistently decreases over the reference period, whereas in the future (2006–2100) it increases. In addition, in AMJ and JAS seasons, ETR decreases in the reference and future period under RCP4.5 scenario, while under RCP8.5, the trends remain positive. These observed trends in ETR could be explained by high GHG emission under RCP8.5 which may create favorable conditions to such increase. Under RCP4.5, ETR trends are downward as in the reference period (1976–2005). Overall, the future trend patterns of HWFI, TX90P, and TN90P are similar to those in the reference period, but with larger magnitudes. This may imply that the patterns of climate change appear to be independent to the forcing, supporting previous findings [73].

4. Summary and Conclusion

In this work, we assessed the future changes in temperature indices describing moderate extreme events as they occur several times per season or per year [74]; such as warm spell days index (HWFI), warm days (TX90P), warm nights (TN90P) frequencies and intra-period extreme temperature range (ETR). This country scale assessment focusing on Côte d'Ivoire uses an ensemble of 14 CORDEX Africa simulations to project modifications in the near future (2031–2060) and far future (2071–2100) periods under IPCC's Representative Concentration Pathway scenarios (RCP4.5 and RCP8.5). Our results reveal an increase in warm extreme temperature events in Côte d'Ivoire in the future, leading to a decrease of ETR index, considering both forcing RCP4.5 and RCP8.5 scenarios. These changes in ETR contrast with the works of Russo and Sterl [61] who showed that in the tropics, the faster rise of the warm extreme induces an increase of ETR. They provide a general picture of the tropic whereas, the proposed work provides detailed information about a specific West African country (Côte d'Ivoire) at a finer resolution (0.44°). In addition, their simulations are based on the SRES scenario (A1B) [75]; while the current study utilizes RCP4.5 and RCP8.5 forcing scenarios [76]. Furthermore, the difference in the result may come from the periods analyzed, 2031–2060 and 2071–2100, in this study, while they focused on 2001–2100. Moreover, in the present work, ETR has been computed over specific seasons in contrast to Russo and Sterl [61]. On the other hand, previous studies in tropical Africa [25, 68] and at global scale [77, 78] showed that minimum temperature increases faster than the maximum leading to a decrease in ETR which is in agreement with our findings. Thus, the vulnerability of the coastal areas of Côte d'Ivoire to the occurrence of heat waves is high with projected changes in the different warm extreme indices that present maxima located along the coast. In the other hand, temporal evolutions of extreme temperature anomalies confirm the existence of the warming in the present climate over Côte d'Ivoire due to an increase of anthropogenic GHG emission in the atmosphere. This is consistent with findings in several studies [26, 28, 79] about the warming experienced by West Africa in recent decades and, that will continue till the end of the century [24]. Nonetheless future climate change over Côte d'Ivoire is associated with uncertainties. Despite these uncertainties, projected changes in warm extreme temperature are robust as all the CORDEX-Africa models used in this study agree on the increase of such indices, except ETR. In addition, a complementary analysis of the time series anomalies across the climatic zones (i.e., Coastal, Centre and North) in relation with some dynamic features (e.g., wind, humidity flux, etc.) would improve our understanding and provide more details information on projected changes specific to each climate zone. This is, however, beyond the scope of this study and may require further investigations.

Data Availability

The data used in this study are available online on the website of the Earth System Grid Federation at https://esg-dn1.nsc.liu.se/projects/esgf-liu/.

Conflicts of Interest

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

Acknowledgments

This work is financially supported by the «Programme Stratégique d'Appui à la Recherche Scientifique en Côte d'Ivoire» (PASRES) and the «Centre d'Excellence Africain pour le Changement Climatique, la Biodiversité et l'Agriculture Durable» (CEA-CCBAD). The first authors would also like to thank the Competence Centre of the West African Science Service Center on Climate Change and Adapted Land Use (WASCAL) in Ouagadougou (Burkina Faso) and the Geophysical Station of LAMTO (Côte d'Ivoire) for their technical supports and facilities.

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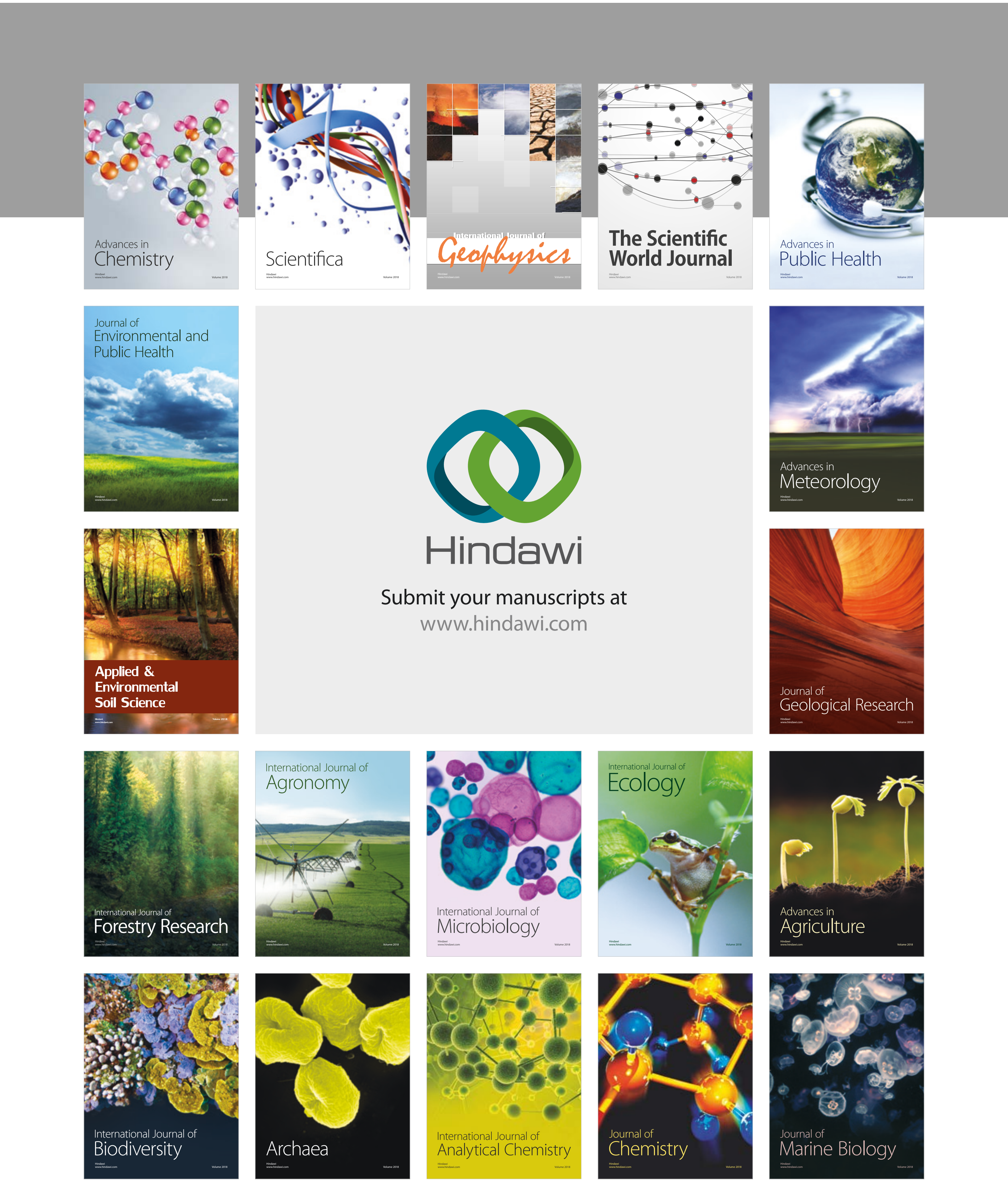
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