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Potential changes in temperature extreme events under global warming at 1.5 °C and 2 °C over Côte d'Ivoire*

E T N'Datchoh[1,**], K Kouadio[1,2], S Silué[3], A Bamba[1], E Naabil[4], K B Djè[5], A Diedhiou[1,6], M B Sylla[7], S Anquetin[6] and C Lennard[8]

[1] LASMES, University Felix Houphouët-Boigny, 22 BP 582 Abidjan 22, Côte d'Ivoire
[2] Geophysical Station of Lamto, BP 31, N'Douci, Côte d'Ivoire
[3] University Peleforo Gon Coulibaly de Korhogo, BP 1328, Korhogo, Côte d'Ivoire
[4] Department of Agricultural Engineering, Bolgatanga Technical University, Bolgatanga, Ghana
[5] SODEXAM/Direction de la Météorologie Nationale, 15 BP 990 Abidjan 15, Côte d'Ivoire
[6] University Grenoble Alpes, IRD, CNRS, Grenoble-INP, IGE, 38000 Grenoble, France
[7] African Institute for Mathematical Sciences (AIMS), AIMS Rwanda Center, KN 3, PO Box 71 50 Kigali, Rwanda
[8] Department of Environmental and Geographical Science, University of Cape Town, Cape Town, South Africa
[*] This paper is dedicated to the memory of our late Prof. Abdourahamane Konaré.
[**] Author to whom any correspondence should be addressed.

E-mail: ndatchoh.toure@univ-fhb.edu.ci

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Abstract

This work investigated the impact of 1.5 °C and 2 °C of global warming levels (GWLs) above pre-industrial levels on annual and seasonal mean changes in temperature extremes over Côte d'Ivoire and its different climatic zones. We used the multi-model Coordinated Regional Climate Downscaling Experiment for Africa of 25 regional climate models under the RCP8.5 scenario. The changes in temperature are quantified relative to the period 1971–2000 based on five Expert Team on Climate Change Detection and Indices indexes namely for warm spells, hot nights, hot days, cold nights and cold days. We show that a global warming of 1.5 °C and 2 °C will lead to an increase in the frequency of warm days and warm nights and a decrease in the occurrence of cold days and cold nights across Côte d'Ivoire in all climatic zones and seasons. More than 80% of the model ensemble members project this change at both GWLs. Moreover, the assessment of differences in GWLs highlights that the difference between the 1.5 °C and 2 °C thresholds may intensify the changes over all the country, climatic zones and seasons. Therefore this 0.5 °C difference in global warming is likely to impact upon energy demand and the agricultural system throughout the country and over all of the seasons. This study provides climate information for decision makers related to sectors such as agriculture, energy in their adaptation strategies.

1. Introduction

Africa, with its high population growth and low adaptive capacity, is one of the most vulnerable continents to climate changes and its impacts. For example, agriculture remains rain-fed in many West African countries and is highly impacted upon by climate change and associated extremes such as droughts and floods (Sultan and Gaetani 2016, Trisos *et al* 2022). Also, over recent decades, frequent high impact events like floods and droughts over West Africa have been responsible for numerous human deaths and structural damage (Tschakert *et al* 2010).

In 2015, during the 21st Conference of the Parties (COP21) held in Paris (hereafter referred to as the Paris Agreement), the decision was made to limit global temperature increases to 1.5 °C above pre-industrial levels, well below the 2 °C of the COP16 Cancun agreement. While this global target is useful for communication, the limitations of the global mean temperature as a measure of climate change impact was apparent during the recent warming 'hiatus' discussion (Trenberth and Fasullo 2013, Steinman *et al* 2015), which addressed changes in global temperature anomalies instead of the discernible regional impact of extreme events in temperature and precipitation in response to the representative concentration pathways (RCPs) emissions scenarios (RCP2.6, RCP4.5, RCP6.0, and RCP8.5). Previous work (Sylla *et al* 2015, Egbebiyi 2016, Abiodun *et al* 2017) has shown that increased greenhouse gases concentration will result in an increase in extreme events intensity and frequency. Investigating the implications of changes in consecutive dry days (CDDs) and consecutive wet days at the regional scale of West Africa at global warming levels (GWLs) of 1.5 °C and 2 °C, Klutse *et al* (2018) found that enhanced warming will lead to a reduction in the mean rainfall across the region, with an increase of CDD over the Guinean region. Moreover, Diedhiou *et al* (2018) applied a scaling approach over various sub-regions within the West African domain, such as Western Sahel, Central Sahel, Eastern Sahel, Guinea Coast, and Central Africa including Congo Basin. They found that the increase in temperature within the region is projected to be higher than the global mean temperature increase (at 1.5 °C and 2 °C) and heatwaves are expected to be more frequent and of longer duration. Over the wetter regions of the Guinea Coast and Central Africa, Diedhiou *et al* (2018) noticed a negligible change in total precipitation, a decrease in the length of wet spells, and the highest increase of heavy rainfall under the 1.5 °C global warming scenario. Though the implications of projected global mean temperature changes tend to be underestimated at the regional and countries level, since the global changes are much smaller than the expected changes in regional temperature mean and extremes over most land areas (Seneviratne *et al* 2016), projected changes in temperature extremes can significantly differ from each other at different warming levels (Nkemelang *et al* 2018).

Over Côte d'Ivoire Yapo *et al* (2019, 2020) investigated future changes in temperature using the warm spell days index (HWFI), very warm days frequency index (TX90P), warm nights frequency index (TN90P), and intra-period extreme temperature range based on 14 of the Coordinated Regional Climate Downscaling Experiment (CORDEX)-Africa simulations ensemble under the RCP4.5 and RCP8.5 scenarios. They found moderate changes in extremes over Côte d'Ivoire and projected changes in the seasonal extreme precipitation intensity and dry spell length under RCP4.5 and RCP8.5 forcing scenarios, which suggested a robust increase in the cumulative intensity of precipitation associated with an amplification of extreme precipitation events during the West African Monsoon (WAM) period (Yapo *et al* 2020). Although these studies provide information about projected changes for the Côte d'Ivoire, they did not assess the regional changes at 1.5 °C and 2 °C of global warming. This study investigates the implications of 1.5 °C and 2 °C of global warming at the country scale, since countries face different challenges (local economy, energy, water resources, social and political situation) and decision-making, with respect to adaptation, usually occurs at the national scale. The aim of this work is to quantify the projected changes in temperature extremes over Côte d'Ivoire under global warming in the context of the Paris Agreement, relative to both pre-industrial and present-day temperatures.

2. Material and method

2.1. Study area

Côte d'Ivoire is a country in West Africa located in the Gulf of Guinea (figure 1). Its economy is based largely on rain-fed agriculture and rainfall is driven by the WAM. The regional climate is characterised by the north–south shift of the inter-tropical convergence zone, which is warm and humid, ranging from equatorial in the southern coasts, to tropical in the central regions and semiarid in the far north. In the southern coastal regions, precipitation patterns are correlated with air–sea interactions in the equatorial Atlantic known as the Atlantic Niño index, rather than the WAM index (Nnamchi and Li 2011). The dry and hot season is from November to May, while the wet and hot season is from June to October. The country is the world's top exporter of Cocoa with almost 70% of the population involved in agriculture. With a total population of 22 million in 2015, the country's population rate is increasing and is expected to reach 48 million inhabitants in 2050.

In this study we consider three climatic regions in the country, the southern equatorial region from the coast 4° N to 6° N (R1), the central tropical region from 6° N to 8° N (R2) and the northern semi-arid climatic region from 8° N to 10.5° N (R3) (figure 1).

2.2. Data

2.2.1. CORDEX-Africa data

An ensemble of 25 simulations from 12 regional climate models (RCMs) driven by ten global climate models (GCM) from the fifth Coupled Model Intercomparison (CMIP5), as described in Nikulin *et al* (2012, 2018) are used in this study. A bilinear interpolation has been conducted to re-grid the CORDEX data from 50 km

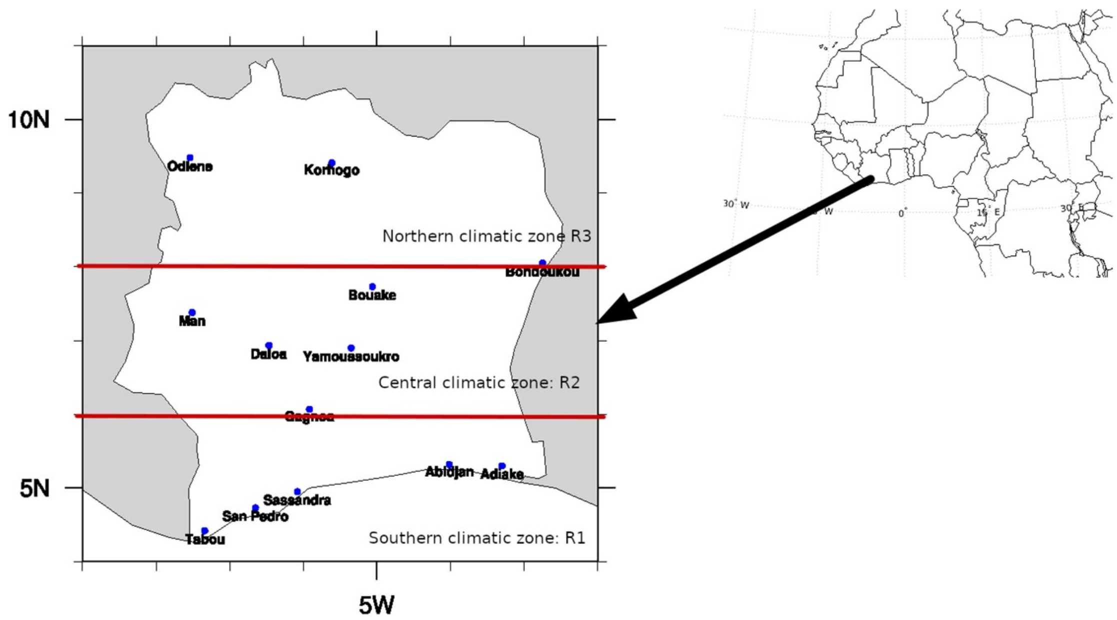

Figure 1. Map of Cote d'Ivoire (in West Africa) with the meteorological station locations and climatic zones considered here, based on the suggestion made by Kouadio *et al* (2007, 2011, 2015).

to 12 km. This enables more grid points for climatic zone analysis since the 50 km resolution was too coarse a resolution. Following Klutse *et al* (2018), the RCP8.5 scenarios.

2.2.2. Meteorological observation data

The spatial distribution of the data from the selected meteorological stations from Société d'Exploitation et de Développement Aéroportuaire, Aéronautique et Météorologique (SODEXAM), presented in figure 1, is used in this study. The three climatic zones (north, centre and south) of Côte d'Ivoire, as suggested by Kouadio *et al* (2007, 2011, 2015), are considered in this work. The southern and central climatic zones are characterised by a bimodal rainfall (peak in June and October), while the northern climatic zone are characterised by a unimodal rainfall during July–August–September (JAS) (Tie *et al* 2007). The selection of the stations is fully motivated by the data availability over the reference period (1971–2000). Since the stations' data were available from 1982 to 2000, CORDEX data is evaluated through this period. Thus, stations in the northern (Odienne and Korhogo), the central (Bondoukou, Bouaké, Yamoussoukro, Daloa, Man and Gagnoa) and the southern (Abidjan, Adiake, San Pedro, Sassandra and Tabou) climatic zones, are used to assess the CORDEX RCMs ability to reproduce the historical climate of the Côte d'Ivoire. However, unlike in Kouadio *et al* (2015), which focused only on the southern and central part of the country, the current work includes available northern stations data. It is worth noting that there is still a need to reinforce the density of the observation network to allow a more complete assessment (see Trisos *et al* 2022).

2.3. Method

This present work focuses on the changes in temperature based on the GWLs (1.5 °C and 2 °C). The term GWLs is defined as the average GWL above some baseline period (of e.g. 1.5°, 2°, 3°, 4°). Various definitions, depending on a pre-industrial baseline with a mean period of 15, 20 or 30 years, have been used to describe the GWLs. In this work, the methods used to determine the GWLs (1.5 °C and 2 °C) and the robustness of a climate change signal follow Nikulin *et al* (2018), who report on the timing (i.e. years) of when these levels are crossed, and an assessment of the robustness of the changes are detailed in Nikulin *et al* (2018).

The timing of each warming level crossing is computed for each downscaled GCM and defined as the centre year of a long enough period (usually 20 or 30 years) when global mean temperature reaches predefined anomalies (1.5 °C or 2 °C) compared to preindustrial levels. Then, for the RCM, the same GWL timing defined by the downscaled GCM is used to extract 30 years for analysis. The corresponding 30 years period is then extracted from the corresponding RCM simulations for analysis using 1971–2000 as a control (CTL) period, as discussed in Nikulin *et al* (2018). The time window 1861–1890 is taken as the preindustrial period, as it is a reasonable approximation for pre-industrial global mean temperature and it is available for all CMIP5 historical simulations, as underlined in Klutse *et al* (2018).

Table 1. Temperature-based climate extreme indices. Reproduced from Nkemelang *et al* (2018).

Abbreviation	Description	Units
	Temperature-based indices	
TX10P	Percentage of days when the daily maximum temperature is below the 10th percentile	%
TX90P	Percentage of days when the daily maximum temperature is above the 90th percentile	%
TN10P	Percentage of days when the daily minimum temperature is below the 10th percentile	%
TN90P	Percentage of days when the daily minimum temperature is above the 90th percentile	%
HWFI	Warm spells duration index (maximum number of consecutive days per year when the daily maximum temperature is above the 90th percentile)	Days

A brief synthesis is provided here, however detailed information can be found in Nikulin *et al* (2018). Information on the changes of the climate will be considered as robust when it fulfils the following two criteria: (a) more than 80% of considered model simulations agree on the sign of the supposed change; (b) the signal to noise ratio, i.e. the ratio of the mean to the standard deviation of the ensemble of climate change signals, is equal to or larger than one. While the first criterion considers only the agreement of the ensemble members, the second criterion is a metric of the strength of the climate change signal. The second criterion is necessary, as even if the first criterion is met, the change signal may be negligible. The responses to the 1.5 °C and 2 °C GWLs of extreme temperature are assessed through five (5) temperature-based indices from the Expert Team on Climate Change Detection and Indices (ETCCDI). These include TX10P, TX90P, TN10P, TN90P and HWDI for temperature (see table 1 for a full description of the indices).

3. Results and discussions

3.1. CORDEX-Africa temperature assessment over Côte d'Ivoire

An assessment of the daily temperature during the historical period (1982–2000) over Côte d'Ivoire was made using ground-based observations from SODEXAM meteorological stations, as shown in figure 2. In the Taylor diagram (Taylor 2001), the individual models interpolated to the nearest grid points around a station considered are represented in black dots, the ensemble mean in red and the meteorological observation in blue dots is used as reference data and labelled 'ref' in the figure 2. Because of differences in the calendars used by individual models (for example the simulations with HadGEM, use a 360 d calendar, while others are using the standard Gregorian calendar) the analysis with the Taylor diagram is made at a monthly scale.

The analysis of the results shows that along the coastal area, in the southern climatic zone (stations of Abidjan, Adiaké, San Pedro, Sassandra and Tabou), most of the single members of the RCMs ensemble show lower standard deviation values close to the reference and relatively low values of RMSE. Also, the correlation values between these RCMs and these stations of the southern zone are between 0.7 and 0.9, except for Tabou where the values are between 0.6 and 0.8. Thus, the ensemble mean of the RCMs is located closer to the reference, suggesting a good replication of the observed temperature by the CORDEX- Africa RCMs over the southern part of Côte d'Ivoire, especially along the coast.

Over the central part of the country, for the stations of Bondoukou, Bouaké, and Yamoussoukro, the single members of the CORDEX-Africa RCMs display standard deviation values at both sides of the reference one. Thus, the ensemble mean has a standard deviation value mostly identical to the reference value. Also, across the stations of Daloa, Gagnoa, and Man, the values of standard deviation displayed by the single members and the ensemble mean are slightly higher than the reference. The values of the correlation coefficient, in this region, are varying from 0.6 to 0.8 for Yamoussoukro, 0.4–0.9 for Bondoukou, and from 0.4 to 0.8 in Bouaké, Daloa, Gagnoa, and Man. Also, the values of the RMSE displayed are relatively higher between these RCM members and the observation, suggesting an acceptable ability of these RCMs in reproducing the temperature patterns of the central part of Côte d'Ivoire.

In the northern climatic zone (stations of Korhogo and Odienné), the majority of the single ensemble members of the RCMs display standard deviation values close to the reference value. These northern stations also have smaller values of RMSE and a high correlation between these RCMs and the observations. Therefore, the ensemble mean of the CORDEX-Africa RCMs and the single members are located closer to the reference, suggesting a better performance of these RCMs over the northern part of Côte d'Ivoire compared to the other regions. This assessment of the simulated daily temperatures of CORDEX-Africa over the period 1982–2000 highlights an increasing performance of RCMs from the South towards the North of Côte d'Ivoire, in agreement with previous works which underlined that the skills of the RCMS varied from one location to another with higher performance away from the coastal area (Kouadio *et al* 2015).

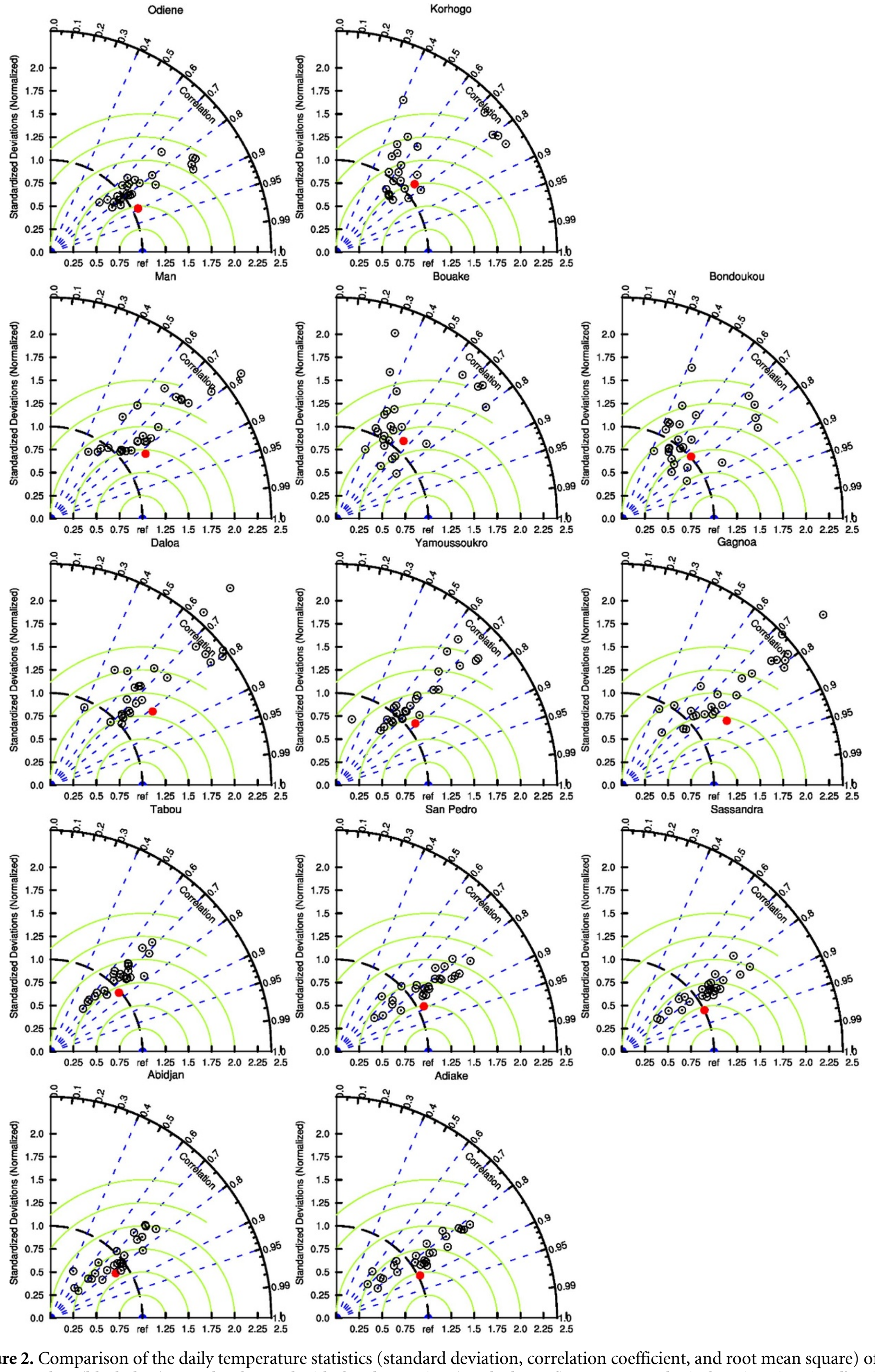

Figure 2. Comparison of the daily temperature statistics (standard deviation, correlation coefficient, and root mean square) of CORDEX data (black dots) to each other and with the observation (marked as ref) over meteorological stations in Côte d'Ivoire. The red dots account for the model's ensemble mean. The first row indicates the northern stations, the second and third row accounts for the central stations, and the fourth and fifth rows for the southern stations.

Moreover, Gbobaniyi *et al* (2014) noticed substantial variable biases in both the magnitude and spatial extent from model to model in the CORDEX-Africa RCMs. These biases in the RCMs were related to several sources, including boundary condition, internal dynamic physical schemes convective parameterization and horizontal resolution (Crétat *et al* 2014, Klutse *et al* 2015).

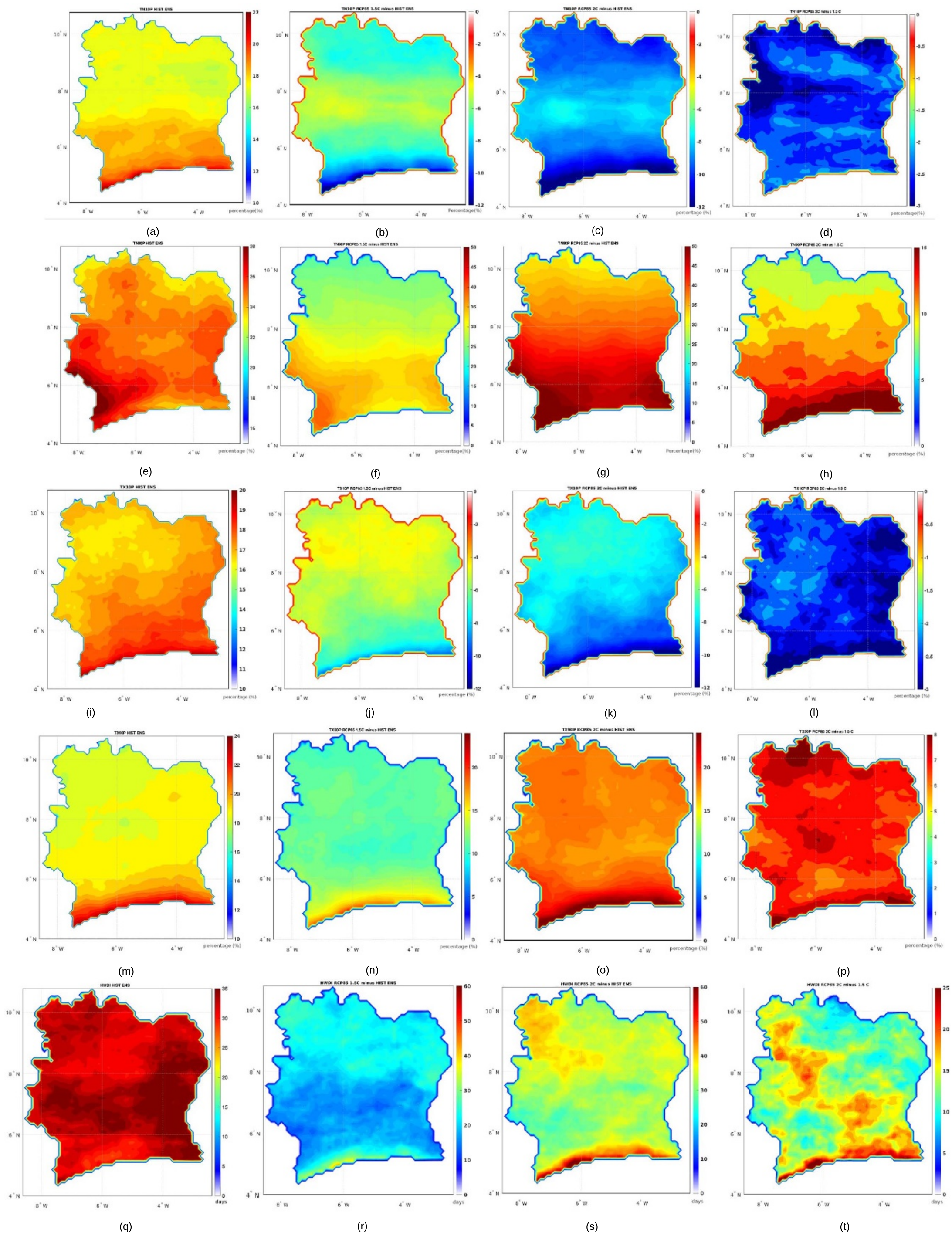

Figure 3. Ensemble mean of TN10P (a)–(d), TN90P (e)–(h), TX10P (i)–(l), TX90P (m)–(p) and HWDI (q)–(t) for the reference period 1971–2001 (a)–(q), (b)–(r) and (c)–(s) respectively for the projected changes at 1.5 °C and 2 °C GWLs with respect to the reference period and (d)–(t) the difference between the changes at 2 °C and 1.5 °C.

3.2. Spatial distribution of the annual mean changes in temperature extremes

Across Côte d'Ivoire, the percentage of days when the daily minimum temperature is below the 10th percentile (TN10P) decreases by up to −12% under GWL 1.5 °C and −15% under GWL 2 °C (figures 3(a)–(d)). These decreases suggest a reduction of the occurrence of cold night events, especially along the coastal region and the northern part of the country of up to 12% (GWL 1.5 °C) and 15% (GWL 2 °C) from about 20% of the time during the reference period (1971–2000). This reduction is at a minimum over the central parts of the country, less than 5% with GWL 1.5 °C and approximately 5% for GWL 2 °C. Compared to GWL 1.5 °C, the extra warming to GWL 2 °C could bring an additional reduction of the occurrence of cold nights by 2% – 4%, with maxima mainly located in the western, the southern and northern part of the country.

An increase in GWL to both 1.5 °C and 2 °C will increase the highest values of the minimum temperature (TN90P), from 23% to 25% during the reference period, to about 36% and 54% respectively (figures 3(e)–(h)). This shows that exceeding the GWL threshold of both 1.5 °C and 2 °C will result in an increase in warm nights compared to the historical period. The projected increase in warm nights shows a north–south gradient with maximum values towards the coast. Exceeding the GWL 1.5 °C and reaching the 2 °C threshold is projected to cause an increase in warm nights, characterised by a north–south gradient, with 5% in the north to 14% towards the coastal part of the country.

The spatial distribution of the annual mean changes in TX10P due to the GWLs at 1.5 °C and 2 °C, over Côte d'Ivoire (figures 3(i)–(l)), suggests a decrease, from about 19% during the historical period, up to 9% and 12% respectively. The spatial distribution pattern of these changes shows a south–north gradient with highest reductions of TX10P in the south (compared to the north) at both GWLs at 1.5 °C and 2 °C. These changes show that the percentage of cold days will reduce across the country as the global temperature rises above the level of 1.5 °C and 2 °C. The occurrence of cold days decreases by approximately 3.2% at GWL 2 °C compared to GWL 1.5 °C, I with a maximum reduction located over the coastal zones and along the eastern border with Ghana.

The projected changes in the spatial distribution of the annual mean of TX90P over Côte d'Ivoire show an increase under GWLs at 1.5 °C and 2 °C (figures 3(m)–(p)). The percentages of occurrence of TX90P increase from 28% during the historical period by about 19% and 27% in the context of GWLs at 1.5 °C and 2 °C respectively compared to the historical period.

Thus, in the context of GWL at 1.5 °C and 2 °C, the warm days events are projected to be 12% – 18% and 15% – 30% respectively more frequent compared to the reference period, which recorded an occurrence of about 20%. The maximum values of these changes are projected in the coastal zone under GWL at 1.5 °C and spread across the country in the context of GWL at 2 °C.

The enhanced GWL at 2 °C (compared to GWL 1.5 °C) will result in an additional increase of up to 8% in the occurrence frequency of warm day events.

An enhancement of the GWL to the 1.5 °C and 2 °C thresholds may lead to changes in the temperature pattern across Côte d'Ivoire similar to the West African region discussed by Kumi and Abiodun (2018) and Klutse *et al* (2018).

The spatial distribution of the annual mean of HWDI indices (figures 3(q)–(t)) revealed increases of these indices for both 1.5 °C and 2 °C of GWLs. These increases in HWDI of up to 25 and 55 d respectively for GWLs 1.5 °C and 2 °C indicate that warm spells are expected to lengthen over Côte d'Ivoire. Also, the spatial distribution shows that the maxima are located over the coastal region in the southern part of Côte d'Ivoire. These warm spells are expected to be more pronounced along the coast and in the northern half of the country. Moving from GWL 1.5 °C to 2 °C lengthens the warm spells by up to 27 d, with maximum values located along the coast, in the middle east, and the north–west of the country.

3.3. Seasonal changes in temperature extremes

The previous section discussed the annual mean and spatial distribution of the changes in temperature extremes over Côte d'Ivoire. It reported an increase in warm days, nights, and spells associated with a decrease in cold days and nights in the context of GWL of both 1.5 °C and 2 °C thresholds. The current section focuses on the seasonal mean changes in TN10P, TN90P, TX10P, TX90P and HWDI under GWLs at 1.5 °C and 2 °C, across Côte d'Ivoire and for each of its climatic zones as defined in figure 1. Following Yapo *et al* (2019), four seasons, namely January–February–March (JFM), April–May–June (AMJ), July–August–September (JAS) and October–November–December (OND) have been used for each of the three climatic zones.

The assessment of the projected changes in temperature extremes over Cote d'Ivoire and its climatic regions projects a decrease in the occurrence frequency of cold nights and days, associated with an increase in the occurrence frequency of warm nights and days. These expected changes may also result in an increase in the length of the maximum warm spell per year at 1.5 °C and 2 °C GWLs. This implies that the expected changes in temperature extremes would affect the diurnal cycle of temperature over the entire country and its climatic regions, during all of the seasons. Thus, these changes in temperature will potentially impact agriculture, crop production, and food security as well as human health and energy.

The maximum seasonal changes in the frequency of warm nights is projected to occur during JAS under GWL at 1.5 °C at the country level and in all of the climatic zones. In the context of GWL at 2 °C, the maximum rise in warm night events occurs during the season OND in the southern and central part of the country and during the season AMJ for the northern zone and at country level (table 2). The minimum changes in warm night occurrence are mainly expected during JFM. The maximum decrease, in cold night events, under GWL at 1.5 °C is expected during JAS in southern and northern Cote d'Ivoire. In the context of GWL at 2 °C, the maximum decrease in the occurrence of cold nights are projected in AMJ across the

Table 2. Summary of maximum and minimum seasonal change in temperature extreme occurrences for Côte d'Ivoire and its climatic regions under GWL at 1.5 °C, 2 °C of RCP8.5 and their differences. The maximum and minimum values are in parenthesis.

	GWL		TN10P	TN90P	TX10P	TX90P	HWDI
Southern climatic region	1.5 °C	Max	JAS (−8.95%)	JAS (12.56%)	JFM (−5.87%)	JFM (9.26%)	JFM (5.65 d)
		Min	JFM (−2.84%)	JFM (10.00%)	AMJ (−3.29%)	OND (5.21%)	JAS (2.16 d)
	2 °C	Max	AMJ (−11.08%)	OND (14.71%)	OND (−7.90%)	JFM (14.14%)	JFM (9.92 d)
		Min	JFM (−5.89%)	AMJ (13.71%)	AMJ (−5.07%)	OND (8.01%)	JAS (2.47 d)
Central climatic region	1.5 °C	Max	AMJ (−22.38%)	JAS (29.20%)	OND (−11.78%)	JFM (14.76%)	OND (14.75 d)
		Min	OND (−6.66%)	JFM (14.72%)	AMJ (−5.40%)	OND (12.32%)	JAS (2.41 d)
	2 °C	Max	AMJ (−11.08%)	OND (14.71%)	OND (−7.90%)	JFM (14.14%)	JFM (9.92 d)
		Min	JFM (−10.27%)	JFM (22.18%)	AMJ (−8.54%)	JAS (17.47%)	JAS (4.26 d)
Northern climatic region	1.5 °C	Max	JAS (−16.23%)	JAS (26.44%)	OND (−10.04%)	OND (14.24%)	OND (14.59 d)
		Min	OND (−7.72%)	JFM (4.24%)	AMJ (−5.70%)	AMJ (12.36%)	JAS (2.61 d)
	2 °C	Max	JAS (−17.49%)	AMJ (28.01%)	JFM (−14.38%)	JFM (21.94%)	OND (19.26 d)
		Min	OND (−13.29%)	JFM (9.61%)	AMJ (−6.95%)	JAS (17.18%)	JAS (4.18 d)
Entire Côte d'Ivoire	1.5 °C	Max	AMJ (−13.91%)	JAS (20.47%)	OND (−7.60%)	JFM (10.77%)	OND (8.82 d)
		Min	OND (−5.53%)	JFM (9.09%)	AMJ (−4.16%)	AMJ (8.67%)	JAS (2.34 d)
	2 °C	Max	JAS (−15.27%)	AMJ (21.66%)	OND (−10.16%)	JFM (18.98%)	JFM (12.59 d)
		Min	OND (−8.80%)	JFM (13.12%)	AMJ (−5.92%)	JAS (13.16%)	JAS (3.74 d)

south and centre and during JAS in the north of Côte d'Ivoire (table 2). The minimum decrease in cold night events varies between seasons and regions at GWL 1.5 °C and mainly in OND under GWL 2 °C. The maximum increase in warm day occurrences is expected during JFM in all climatic zones, while the rainy seasons are relatively less affected. The maximum decrease in cold days, under GWL at 1.5 °C, is expected in JFM in the south and north and OND in the centre. In the context of GWL at 2 °C, the maximum decrease in cold nights is expected in OND. This suggests more frequent warm nights during the WAM period, when the parts with bimodal rainfall patterns (southern and central) experience the little dry season, meaning that the JAS season will experience more warmer nights. Warm days are projected to increase during JFM in a period that already records frequent warm events. The increase of 0.5 °C from the 1.5 °C threshold to 2 °C may not only impact the amplitude of temperature extreme events such as cold days/nights and warm days/nights, but also induce a slight shift of these amplitudes between seasons.

These general increases in warm day/night and decreases in cold day/night occurrences, associated with the occurrence of longer warm spells expected over Côte d'Ivoire, are in line with Klutse *et al* (2018), who show a rise in temperature across West Africa at both 1.5 °C and 2 °C GWL using CORDEX data under the RCP 8.5. Moreover, Nikulin *et al* (2018) show that the West African region has already experienced a 1.5 °C warming since 2004 and the temperature is expected to continue to increase through 2049. They further noticed that some models indicated that the temperature rise has already crossed the 2 °C GWL since the year 2012 and would continue to rise through 2066. Furthermore, the current results are in agreement with a similar analysis in temperature extreme over Côte d'Ivoire (Yapo *et al* 2019) that projected an increase, during the periods 2031–2060 and 2071–2100, in the frequency of warm spell days, very warm days, and the warm nights across the country, under both RCP4.5 and RCP8.5. Using the low-warming projections of NCAR-CESM to assess the differences in extreme temperature events under the GWLs at 1.5 °C and 2.0 °C, relative to the recent climate taken from 1976 to 2005 over Africa, Iyakaremye *et al* (2021) found that the frequency of occurrence of hot days (TX90P) is projected to increase with global warming across the African continent, while the frequency of cold day events (TN10P) is expected to decrease, especially across West Africa. Moreover, Mba *et al* (2018) using CORDEX projection under RCP8.5 indicated that despite large uncertainties associated with projections at 1.5 °C and 2 °C, the 0.5 °C increase in global temperature is associated with a larger regional warming response in Africa. The intercomparisons between the changes due to GWL at 1.5 °C and 2 °C reveal generally marginal differences, in agreement with Klutse *et al* (2018). Most of the CORDEX-Africa models (generally more than 90%) used in the present work, across Côte d'Ivoire and the respective climatic zones, agree on the signs of the changes in temperature extreme. This indicates robust results for the increase in warm days/nights and the decreases in cold days/nights, associated with the occurrence of longer warm spells. Our results clearly indicate that these changes in temperature extremes, which would occur over all the climatic regions and during all of the seasons in Côte d'Ivoire, may certainly influence heatwave intensity and occurrence and may also contribute to increased disaster risks. Additionally, previous works showed that across Africa, an increase in hot nights, long and persistent heatwaves, and disaster risks are expected to increase under GWL at 1.5 °C and will be amplified in the 2 °C level (Dosio *et al* 2018, Weber *et al* 2018, Djalante 2019).

3.4. Potential impacts on food and energy security

Several areas of the country are projected to experience warmer hot extremes which will necessarily impact agriculture, crop production, and food security in a country like Côte d'Ivoire, whose economy is mainly based on rain-fed agriculture, since surface temperature may affect plant growth, development and crop yield. The current agricultural system will need to be restructured in light of the present results, by developing and integrating species more tolerant to this temperature increase, to ensure food security. Concerning the energy sector, these longer warm spells, at the country level will probably increase temperature discomfort, which will induce more energy demand and consumption for cooling systems in both households and offices (Akara *et al* 2021). It will also affect solar energy production (Danso *et al* 2022) which remains one of the major sources of low carbon energy. Moreover, since our results highlighted that a difference of 0.5 °C may not only impact extreme temperature amplitudes but may induce some seasonal shifts, changes will also be expected in the current pattern of energy demand. In a country where electricity production and access is still climate-dependent, as seen recently (in 2021) with widespread power shortage due to climatic hazards (low precipitations, high temperatures), it will be necessary and useful for decision-makers to put in place more sustainable energy systems, such as renewable energy, integrating the findings of this work in the infrastructure designs. These projected changes in temperature in Africa, can be an opportunity for African countries to put in place common policies, to better develop tools and use the continent solar energy reserves which are estimated to be about 60 000 000 TWh yr^{-1} (representing 40% of the global total solar energy potential), making Africa the most sun-rich continent in the world (Liu 2015).

As underlined by Nikulin *et al* (2018), the change in temperature over Cote d'Ivoire shown in the present results may be biased by some specific RCMs of the ensemble considered. Similar to their finding, the CORDEX ensemble used in this study is at least biased towards ten members of one RCM. Although in such a case, it is advisable to carefully analyse and understand the individual models considered, though this has not been analysed here. Therefore, our results only provide an overview of temperature expectations under GWLs at 1.5 °C and 2 °C over Côte d'Ivoire and its sub-climatic zones.

4. Summary and conclusion

This work investigates the annual and seasonal mean changes in temperature extreme under GWLs of 1.5 °C and 2 °C in Côte d'Ivoire and its climatic zones using 25 simulations of the CORDEX-Africa ensemble under the RCP8.5 scenario. It uses daily temperatures from 13 meteorological stations to assess the CORDEX data across Côte d'Ivoire during the period 1982–2000. The results show that the CORDEX reasonably reproduces daily mean temperatures across the country with a correlation varying between 0.4 and 0.9 from south to north.

The analysis of the changes in selected ETCCDI extreme temperature metrics show longer warm spells (HWDI) under GWLs at 1.5 °C (25 d) and 2 °C (55 d) compared to the historical period. Also, the results show an increase in the occurrence of hot nights (TN90P between 19% and 56%) compared to the historical period under both GWL at 1.5 °C and 2 °C. An additional 0.5 °C temperature rise from 1.5 °C GWL may lead to an increase in daytime warm event occurrence frequencies by 8%, with maximums over the coastal, central and widespread northern regions. This is associated with an increase in warm night occurrences of about 4%–12% with a maximum over the coastal region well south of 6° N. Moreover, a decrease in the occurrence of cold nights (TN10P) and cold days (TX10P) is expected from 14% to 12% and 9% to 12% under respectively GWLs at 1.5 °C and 2 °C. Thus, crossing the 2 °C GWL threshold may induce a decrease, of about 3%, in cold night occurrences over the western part and mountainous region of the country (from 7° N to 10° N). This projected decrease in cold night events may extend toward the centre of Côte d'Ivoire and reach the northern borders. Additionally, this decrease in cold night events is also associated with a decrease in cold days (about 3%) with the maximum reduction located over the coastal region and along the eastern border.

The seasonal analysis revealed that at the country level, the warm spell lengths (HWDI) are expected to increase over all of the seasons.

The seasonal analysis of the changes in temperature extremes over the climatic zones of Côte d'Ivoire reveals an increase in the warm spell duration across all of the regions and over all seasons, in the context of a global warming at both the 1.5 °C and 2 °C threshold. An increase in warm night/day occurrences (TN90P/TX90P) is also expected over all seasons and climatic zones at both GWLs 1.5 °C and 2 °C. This increase in warm night/day occurrences (TN10P/TX10P) is associated with a decrease in cold night/day events across all regions and seasons. The seasonal means over the climatic zones suggest that the difference of 0.5 °C may not only impact the amplitudes of changes in temperature extremes, but may induce some shifts in the seasons. There is generally a good agreement (∼85% – 95%) in the projection of increases of warm night/day events, warm spell duration and the decrease in cold night/day events by the model ensemble members in the context of both GWL at 1.5 °C and 2 °C. The combination of the projected increases in warm day/night occurrences and the decreases in cold day/night occurrences will contribute to a temperature rise across the country and its climatic zones and over all of the seasons. This will likely affect many sectors, such as energy demand for home cooling as heatwave intensity and occurrences increase. In addition, these warmer conditions all over the country and the seasons will impact the agriculture sector, crop production and food security. It is therefore necessary and urgent for decision-makers and the scientific community to investigate the development of new crop systems and crop variants that are more tolerant to this temperature increase. Further studies should investigate the impact of these changes in temperature extreme on specific crops such as cocoa, cashew or/and food security as well as energy, for example.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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Conflict of interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

ORCID iDs

E T N'Datchoh https://orcid.org/0000-0003-3139-6581
K Kouadio https://orcid.org/0000-0003-0255-1757
S Silué https://orcid.org/0000-0002-3213-8501
A Bamba https://orcid.org/0000-0002-0677-2381
E Naabil https://orcid.org/0000-0002-3055-8887
K B Djè https://orcid.org/0000-0003-4730-4602
A Diedhiou https://orcid.org/0000-0003-3841-1027
M B Sylla https://orcid.org/0000-0002-5566-0538
S Anquetin https://orcid.org/0000-0001-5127-1650
C Lennard https://orcid.org/0000-0001-6085-0320

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