Projected impact of increased global warming on heat stress and exposed population over Africa

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Abstract

This study investigates the impact of increased global warming on heat stress changes and the potential number of people exposed to heat risks over Africa. For this purpose a heat index has been computed based on an ensemble-mean of high-resolution regional climate model simulations from the Coordinated Output for Regional Evaluations (CORE) embedded in the COordinated Regional Climate Downscaling EXperiment (CORDEX), under two Representative Concentration Pathways (RCPs) scenarios (RCP2.6 and RCP8.5), combined with projections of population growth developed based on the Shared Socioeconomic Pathways (SSPs) scenarios (SSP1 and SSP3). Results show that by the late 21st century, the increased global warming is expected to induce a 12-fold increase in the area extent affected by heat stress of high-risk level. This would result in an increase of about 10-30% in the number of days with high-risk heat conditions, as well as about 6-20% in their magnitude throughout the seasonal cycle over West, Central and North-East Africa. Therefore, and because of the lack of adaptation and mitigation policies, the exacerbation of ambient heat conditions could contribute to the exposure of about 2-10 million person-events to heat stress of high-risk level over Burkina Faso, Ghana, Niger, and Nigeria. Furthermore, it was found that the interaction effect between the climate change and population growth seems to be the most dominant in explaining the total changes in exposure due to moderate and high heat-related risks over all subregions of the African continent.

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Abstract

This study investigates the impact of increased global warming on heat stress changes and the potential number of people exposed to heat risks over Africa. For this purpose a heat index has been computed based on an ensemble-mean of high-resolution regional climate model simulations from the Coordinated Output for Regional Evaluations (CORE) embedded in the COordinated Regional Climate Downscaling EXperiment (CORDEX), under two Representative Concentration Pathways (RCPs) scenarios (RCP2.6 and RCP8.5), combined with projections of population growth developed based on the Shared Socioeconomic Pathways (SSPs) scenarios (SSP1 and SSP3). Results show that by the late 21st century, the increased global warming is expected to induce a 12-fold increase in the area extent affected by heat stress of high-risk level. This would result in an increase of about 10-30% in the number of days with high-risk heat conditions, as well as about 6-20% in their magnitude throughout the seasonal cycle over West, Central and North-East Africa. Therefore, and because of the lack of adaptation and mitigation policies, the exacerbation of ambient heat conditions could contribute to the exposure of about 2-10 million person-events to heat stress of high-risk level over Burkina Faso, Ghana, Niger, and Nigeria. Furthermore, it was found that the interaction effect between the climate change and population growth seems to be the most dominant in explaining the total changes in exposure due to moderate and high heat-related risks over all subregions of the African continent.

Keywords: Africa, Climate change, Heat stress index, global warming

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Key Points:

- Increased global warming induces more widespread, longer and frequent extreme heat events over West, Central and North-East Africa
- Populations of some West African countries are projected to be particularly exposed to moderate and high heat conditions
- Change in population exposure to dangerous heat categories is mainly driven by the interaction effect between climate and population growth

Plain Language Summary

This study investigates the response of increased global warming on heat stress changes and the potential number of persons likely to be exposed to heat risks over Africa. Results show that by the end of the 21st century, the increased global warming is expected to induce a 12-fold increase in the total area affected by dangerous heat conditions over the continent. This would result in an increase of about 10-30% in the number of days with these heat conditions, as well as about 6-20% in their magnitude throughout the seasonal cycle over West, Central and North-East Africa. Therefore, because of the lack of adaptation and mitigation policies, the exacerbation of ambient heat conditions could contribute to the exposure of about 2-10 million person-events to heat stress of high-risk level over Burkina Faso, Ghana, Niger, and Nigeria. Since these heat events would be mainly driven by interactions effects between climate change and population growth, efficient measures allowing not only to mitigate the increased greenhouse gas emissions, but also the effects of high heat on the human body must be urgently implemented on the affected countries' scale, in order to significantly decrease the vulnerability of their populations to potential heat-related health problems.

1 Introduction

During the last decades, most of African countries have experienced a trend of warming, which has been increasing at rates higher than the global average rate of temperature increase (Colin, 2011). According to the Intergovernmental Panel on Climate Change's report (IPCC, 2022), climate change risks will rapidly increase in the mid-to-long term with continued global warming, particularly in areas already exposed to high temperatures. Furthermore, projections also suggest that by 2050, half of the net increase in the world's population is expected to be concentrated in sub-Saharan Africa, leading to high urbanisation rates and extensive land cover changes (Forget et al., 2021). Given the ambient climatic threat, coupled with the high demographic growth as well as the low capacity and resilience partly due to endemic poverty of its population, the African continent is particularly vulnerable to climate hazards through exposure to a wide range of climate risks (Opoku et al., 2021). Among these hazards, those related to extreme heat, which in fact result from the combination of natural and human stressors (e.g., high air temperature, high air humidity, high population density, among others), will continue to significantly increase with additional warming, especially without further adaptation efforts (IPCC, 2022). This would contribute to a substantial worsening of the potential impacts that these extreme events can have on the socio-economic development of nations (Parkes et al., 2019; IPCC, 2022), and therefore will represent one of the main challenges for decision makers of the continent.

It is commonly known that the level of discomfort experienced in warm weather environment, is directly linked to the amount of incident solar radiation as well as the evaporation rate of the considered region (Diffenbaugh et al., 2007; Pal & Eltahir, 2016). This discomfort which is in fact a consequence of heat stress occurs when the human body is exposed to high temperatures and high humidity for a certain time (Lucas et al., 2014). Despite some internal acclimatisation processes which vary according to the metabolism of each individual, human body has an absolute limit of tolerance to heat stress exposure (Medina-Ramon & Schwartz, 2007). Beyond that limit, severe repercussions can be recorded, particularly on health through heat cramps, heat exhaustion and heat stroke, and sometimes even premature death (Rothfusz, 1990; Scovronick et al., 2018). Epidemiological research on temperaturemortality functions has shown that elderly people and children are the most vulnerable to these heat-related health risks (Burkart et al., 2014). In addition to age, factors such as gender, ethnicity, pre-existing health problems, education, income level and population density can also increase vulnerability to the harmful heat-related health effects (Burkart et al., 2014). Therefore, future health-related risks induced by heat stress would be strongly influenced by socio-demographic changes, including population growth, ageing population and urbanization patterns, as well as social vulnerability (Jagarnath et al., 2020).

In the past, the severity of impacts of heat stress events has been largely ignored over the African continent. This is probably the reason for the particular attention they have received in recent years. In this regard, several studies have been conducted to investigate the future impact of heat stress over Africa in response to increasing global warming. For example, the study of Asefi-Najafabady et al. (2018), based on the high-resolution Community Earth System Model simulations and carried out over some countries located over the East African subregion, revealed that the greatest increases in the frequency of occurrence of heat stress days is likely to occur in the future over the northern and western parts of Kenya, Uganda, and Democratic Republic of Congo (DRC). These authors also concluded that this projected increase in the number of hot days would induce an exposure of local populations to extreme heat stress up to 269-fold higher, strongly driven by demographic and urbanization dynamics. The results of Yengoh and Ardö (2020) over the same subregion are consistent with these trends, indicating that the periods of February-March and August-September are those where high heat intensities are likely to occur in the 2050 and 2100 horizons. Although the issue of heat stress is not the main concern over some cities of South Africa, Jagarnath et al. (2020) showed an increase in their severity, which would impact the most disadvantaged social classes, both in rural and urban locations. Furthermore, in their investigations based on an ensemble-mean of 22 Regional Climate Models (RCMs) simulations over the West African subregion, Sylla et al. (2018) showed a trend towards an increase in the spatial extent as well as the frequency of moderate and high hazardous heat stress events. These conditions of high heat felt are likely to severely affect the majority of populations of countries crossed by the Sahelian area of the studied subregion, especially when the global warming level will have reached the threshold of 2 ºC. Recently in their work based on an ensemble-mean of 8 RCMs, Fotso-Nguemo et al. (2021) found that these high heat-related risks for human health were expected to be 3-fold for thresholds ranging from 1.5 to 3 ºC over the northern and central parts of the Central African subregion, with repercussions on the socio-economic development of affected countries through decreased workers' productivity and increased cooling degree days. In a wider perspective based on an ensemble-mean of 5 Global Circulation Models (GCM) simulations, the results of Liu et al. (2017) highlight the fact that out of the increase in the world population's exposure to extreme heat events by the end of the 21st century, Africa alone records a 118-fold increase compared to 4-fold over Europe.

Alongside the above studies, which are focused on extreme heat events, some authors have looked at other extreme wheather events combined with population change, which can also have severe consequences on the socio-economic development of the affected countries (e.g., Bouwer, 2013; Weber et al., 2020; Ayugi et al., 2022; among authers). Although these studies have investigated the combination of climate and population change, most of them focused their attention just on certain subregions or countries of Africa (Sylla et al., 2018; Asefi-Najafabady et al., 2018; Jagarnath et al., 2020; Yengoh & Ardö, 2020; Fotso-Nguemo et al., 2021). Nevertheless, to our knowledge a more comprehensive view of the spatiotemporal variation of heat stress days based on the Regional Climate Models (RCMs), as well as the relative importance of the different drivers of change in the projected population exposure to these heat events at continental scale, has not yet been proposed. Such information could be useful for the implementation of efficient adaptation and mitigation strategies, by helping policy makers to better target countries/areas as well as months of the year that are particularly vulnerable to the adverse effects of heat-related hazards. In addition, identifying areas across the continent that are likely to less changes in dangerous heat-related risks, and therefore can serve as a refuge for populations, could also be revealed.

In this context of lack of continental studies that combines heat stress and population changes, we propose to use the projections of heat index computed based on an ensemble-mean of high-resolution Regional Climate Models (RCMs), performed in the framework of the Coordinated Output for Regional Evaluations (CORE) embedded in the COordinated Regional Climate Downscaling EXperiment (CORDEX; hereafter CORDEX-CORE) initiative (e.g., Remedio et al., 2019; Ciarlò et al., 2021; Teichmann et al., 2021; Giorgi et al., 2022) to explore the response of increased anthropogenic radiative forcing on heat stress changes towards the end of the 21st century in terms of spatial extent, seasonality and frequency of occurrence. Furthermore, the projections of population growth developed based on the new Shared Socioeconomic Pathways (SSPs; Jones and O'Neill, 2016) scenario, will be employed to estimate not only the changes in the potential number of person exposed to these extreme heat events, but also the relative importance of the different drivers of these projected changes. The rest of this document is structured as follows: First, the datasets and methodology used in the work are described in Section 2. Afterwards, the results are presented in Section 3. Finally, the main results will be summarised and discussed in Section 4.

2 Data used and methodology

2.1 Data

For the analyses of the potential changes in heat stress variations, we considered daily data of mean air temperature (T) as well as relative humidity (RH), from an ensemblemean of 9 RCMs simulations members, performed in the framework of the CORDEX-CORE project (Remedio et al., 2019; Ciarlò et al., 2021; Teichmann et al., 2021; Giorgi et al., 2022). In fact, the CORDEX-CORE experiments used in this study have consisted in the use of 3 RCMs named CCLM5, REMO2015 and RegCM4.7, to dynamically downscale 3 same GCMs (HadGEM-ES, MPI-ESM-LR and NorESM1-M; but the RegCM4.7 has used MPI-ESM-MR) involved in the phase 5 of the Coupled Model Intercomparison

Project (CMIP5; Taylor et al., 2012), at horizontal resolution of about 25 km (~0.22º) instead of about 50 km (~0.44º) as done with the previous CORDEX models (Nikulin et al., 2012).

In this work, all downscaling experiments covering the 1970-2100 period were performed over the CORDEX-Africa domain, by considering two Representative Concentration Pathways (RCPs; Moss et al., 2010) scenarios: i) a low scenario RCP2.6, which considers some mitigation measures that could control greenhouse gases (GHGs) emissions; and ii) a high scenario RCP8.5, which describes a situation in which radiative forcing reaches 8.5 W/m^{-2} by 2100, without implementing any GHG-emission mitigation policies. Therefore for each RCM member, three 30-year time slice periods were chosen as follows: one historical (1979-2008) representing the baseline period, and two future (2069-2098) representing the projections under the two chosen scenarios. For brevity, details on the 9 considered RCM outputs members, resulting from the dynamical downscaling of different GCMs can be found in Table S1 of the supplementary material. It is worth noting that all RCMs used in this study have been already validated in numerous studies conducted over the African continent (e.g., Nikulin et al., 2012; Teichmann et al., 2013; Fotso-Nguemo et al., 2016; Diallo et al., 2016; Vondou and Haensler, 2017; Pokam et al., 2018; Diallo et al., 2018; Weber et al., 2018; Tamoffo et al., 2019; Fotso-Nguemo et al., 2019; Remedio et al., 2019; Abiodun et al., 2020; Taguela et al., 2020; Fotso-Kamga et al., 2020; Teichmann et al., 2021; Ciarlò et al., 2021; Dosio et al., 2021; Tamoffo et al., 2022; Giorgi et al., 2022; among others). It was found that the performance of these models varies depending on the considered season and subregion. Moreover, it was shown that the multi-model ensemble-mean performs better than the individual models.

Changes in the population exposure, have been analysed by considering historical data from the protocol 2b of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b; https://www.isimip.org), as well as projection data from the NASA Socioeconomic Data and Applications Center (SEDAC; https://sedac.ciesin.columbia.edu). The ISIMIP2b datasets are annual data covering the 1861–2005 period at horizontal resolution of 5 arc-minutes (~0.083º), whereas the SEDAC datasets are decadal data covering the 2010–2100 period at horizontal resolution of 7.5 arc-minutes (~0.125º) and generated according to the new SSPs scenario, which take into account amongst other: i) the trends in population growth; ii) the educational composition; iii) the urbanization and gross domestic product (Jones & O'Neill, 2016).

2.2 Methodology

The heat stress induced by the combined effects of both high T and RH, has been assessed by considering the heat index (hereafter HI) formulation, based on a multiple regression equation of apparent temperature developed by Steadman (1979) and adapted by the United States National Weather Service (Rothfusz, 1990), as follow:

$$\boldsymbol{HI = -42.379 + 2.04901523 \times T + 10.14333127 \times RH - 0.22475541 \times T \times RH - 6.83783 \times 10^{-3} \times T^2 - 5.481717 \times 10^{-2} \times RH^2 + 1.22874 \times 10^{-3} \times T^2 \times RH + 8.5282 \times 10^{-4} \times T \times RH^2 - 1.99 \times 10^{-6} \times T^2 \times RH^2} \quad (1)$$

where, T and HI are in °F, while RH is in %. Please, see Text S1 in the supplementary material, for more information about the HI formulation. Although there are various methods in the literature for calculating HI values, most of the algorithms implemented in these methods generate values that are strongly correlated (Anderson et al., 2013). Therefore, the formulation of HI shown in Equation (1) has been chosen not only because it is more consistent with the original apparent temperature equation (Anderson et al., 2013), but also because previous studies have shown that it performs well when applied in warm environments of America (Hass et al., 2016; Weinberger et al., 2018), Asia (Sung et al., 2013; Opitz-Stapleton et al., 2016), Europe (Diffenbaugh et al., 2007; Fischer & Schär, 2010) and even Africa (Sylla et al., 2018; Diba et al., 2021; Fotso-Nguemo et al., 2021).

For the analysis, values of HI were computed for each day, then sorted by ranges according to the categories defining the level of heat risk attributed to each range, as well as the health problems that may result as presented in Table 1. In fact, the categories are classified in the increasing scale of impact as follows: Safe, Caution, Extreme Caution (Ex-Caution), Danger and Extreme Danger (Table 1). Hence, as we move from the Caution to the Extreme Danger categories, it is possible for the human body to develop certain health problems such as fatigue, heat cramps, heat exhaustion, and/or heat stroke that can occur with prolonged exposure and/or physical activity (Lucas et al., 2014; Scovronick et al., 2018). Please visit the web-site "https://www.weather.gov/safety/heat-index", for more information about the HI classification and their associated health problems.

In this study, exposure is defined as the size of population be exposed to heat stress, and is computed at each grid point by multiplying the annual number of occurrences of these heat events and population together for both baseline and future periods. Furthermore, the total change in exposure (in person-events) will be investigated based on the approach developed by Jones et al. (2015) and adopted by certain authors (e.g., Liu et al., 2017; Weber et al., 2020; Ayugi et al., 2022), through the following equation:

$$\boldsymbol{\Delta E = P_R \times \Delta C + C_R \times \Delta P + \Delta C \times \Delta P} \quad (2)$$

where $\boldsymbol{P_R}$ and $\boldsymbol{C_R}$ are the population and climate in the reference period, respectively; while $\boldsymbol{\Delta C}$ and $\boldsymbol{\Delta P}$ the climate and population changes, respectively. In the Equation (2), the term $\boldsymbol{P_R \times \Delta C}$ refers to the climate effect, which takes into account the influence of climate exposure; the term $\boldsymbol{C_R \times \Delta P}$

represents the population effect; and the term $\boldsymbol{\Delta C} \times \boldsymbol{\Delta P}$ refers to the interaction effect which measures the simultaneous variations in both climate and population.

All our analysis is done over the whole African domain (Fig. 1a), as well as the different subregions based on the new updated IPCC reference regions for the African continent (Iturbide et al., 2020), represented in Figure 1b as follows: North Africa (NAF), Sahara (SAH), West Africa (WAF), Central Africa (CAF), North-East Africa (NEAF), Central-East Africa (CEAF), South-West Africa (SWAF) and South-East Africa (SEAF). Changes in the area extent of each of the different HI categories are expressed as percent of the total area extent of the study domain, with only land-grid taken into account. With regard to changes on the total exposure, they will be expressed in person-events. Note that, in order to ensure that our results reflect a better analysis of the best and worst scenarios, we consider a scenario of strict emissions mitigation, combined with a low population growth scenario (RCP2.6/SSP1), as well as a scenario of continued global carbon emissions and rapid population growth (RCP8.5/SSP3). For the computation of the absolute values of these metrics during the current climate, we will consider T and RH fields from the ERA5 reanalysis data (Hersbach et al., 2020), available from 1979-present at horizontal resolution of about 28 km (~0.25º). In order to take into account the uncertainties that may exist in the projected changes, the climate change signal from the RCMs ensemble-mean will be considered significant if at least 7 out of 9 members agree on the sign of the change. The conformity between the spatial resolution of the different datasets was ensured by remapping them onto the ERA5's reanalysis grid through the bilinear interpolation method.

3 Results

3.1 Projected spatial extent of heat stress

Figure 2 displays the spatial distribution of HI categories for the baseline period (ERA5 reanalysis and historical), and the different global warming scenarios over Africa. During the baseline period, ERA5 reanalysis shows a predominance of areas with moderate heat risk (Ex-Caution) in the northern part of the domain, as well as some small hotspots more or less isolated with high heat risk (Danger) over certain countries of WAF and SAH subregions. On the other hand, the southern part of the continent is dominated by areas with low (Caution) and extremely low (Safe) heat risks, probably favoured by the presence of several mountain chains which provides it with a rather high elevation and therefore low temperatures (Fig. 1a). The RCM ensemble-mean historical show a similar pattern to that of the ERA5 reanalysis but with lower heat load around mountainous areas of the studied domain. This could be attributed to the fact that because of their finer resolution, the RCM ensemble-mean better capture the topography of Africa compared to the ERA5 reanalysis which have a coarser resolution. Compare to the baseline period, the results from the two RCPs show a progressive extension of areas with dangerous heat risks, which will be more widespread for the high GHG-forcing scenario RCP8.5.

More specifically, in the case of RCP2.6, the total area with Caution and Safe conditions gradually decreases by about 9 and 10% respectively, and leave place to an extension of areas with Ex-Caution conditions, which records an increase of about 15% and the danger areas increase by about 2% (Fig. S1). It is worth to note that by the late 21st century, the implementation of adaptation and mitigation measures in countries such as Ethiopia, Tanzania, Zambia, South Africa and Madagascar could contribute to a slight increase of areas with Safe conditions at the disadvantage of those of Caution. Furthermore, although the lower scenario RCP2.6 is the most optimistic, the majority of countries located in the northern part of the domain, as well as those located along the coastal area of the Indian Ocean, will still be affected by Ex-Caution conditions.

Concerning the case of RCP8.5, which is the most pessimistic, the models project a stronger extension of Ex-Caution areas towards the southern extremity of the continent, with an increase of about 20% compared to the baseline period (Fig. S1). In addition, the intensification of the latter heat conditions under the effect of increased global warming leads to the emergence of Danger conditions over most of West, Central and East African countries, as well as over coastal areas of the Red Sea and Indian Ocean. Consequently, in the absence of mitigation policies, the Danger category is likely to increase by about 23% in surface area by the end of the century compared to the baseline period (Fig. S1). This implies that the increased global warming will lead to an increase in the spatial extent of high heat conditions by about 21% over the continent.

Although sometimes of smaller spatial extent, the RCMs ensemble-mean detect future climate shifts towards warmer conditions in RCP8.5 compared to RCP2.6. For instance, mountainous areas of Cameroon, Ethiopia and Angola and Great Lakes region, which were unexposed under RCP2.6, will be affected by Caution category in RCP8.5 (see, Fig. 2b-c). Moreover, we note that areas with HI of Danger category which were almost absent in RCP2.6 will significantly increase in RCP8.5 (Figs. 2 and S1).

3.2 Projected seasonal cycles of heat stress

The seasonal cycles of both observed and projected HI for each subregion (Fig. 1b) are presented in Figure 3. Generally, the annual evolution of HI shows peaks (with magnitude varying according to the considered GHG-emission scenario), appearing once or twice during the year, indicating the period where populations experience high heat load. During the baseline period, the seasonal cycles of HI shown by ERA5 reanalysis (purple lines) generally present peaks of moderate heat risks (with peaks between 35-41 ºC) over the subregions located around and northern Equator (Fig. 3a-f), except over NEAF where the presence of areas with high risk level along the Red Sea (Fig. 2a) generates a peak of about 43 ºC around September. On the other hand, the seasonal cycles HI generally present peaks of low heat risks (with peaks up to 32 ºC) over the subregions located southern Equator (Fig. 3g-h). Note that despite the high magnitude of HI over NAF during July-September, almost the entire year is dominated by heat conditions similar to that of SWAF and SEAF (i.e., Safe and Caution categories). Similar to the case of the spatial distribution of HI categories, the seasonal cycles of HI presented by the RCMs ensemble-mean historical (green lines) is similar to that of the ERA5 reanalysis but with less intense heat load, more pronounced over NEAF and SWAF. This is probably due to the effect of the of the presence of relatively higher mountain chains located in these sub-regions (see, Fig. 1a), which is better taken into account in the RCMs simulations.

Results from the RCP2.6 scenario show that the RCMs ensemble-mean project heat peaks localised around the same months as those found during the baseline period, but with slightly higher magnitudes (with an increase of about 4-9% compared to the baseline period; see, Fig. S2). This difference is more noticeable in the sub-regions located in the southern part of the continent, where the slight extension of the Caution and Ex-Caution areas would lead to peaks of up to 34 ºC during April-May (DecemberFebruary) over SWAF (SEAF). Nevertheless, this increase could have as main consequence the intensification of heat load towards higher heat magnitudes, coupled with a slight extension of period of discomfort due to heat.

With regard to the high emissions scenario RCP8.5, the RCMs ensemble-mean suggests a substantial increase in HI values, with magnitudes largely exceeding the threshold of high risk (41 ºC) over SAH (with peak of about 49 ºC during SeptemberOctober) and NEAF (with peak of about 47 ºC during June-July and September-October). According to this scenario, the magnitude of HI is projected to increase by about 10-29% with respect to the baseline period, over all subregions (Fig. S2). This could be translated by an intensification of heat stress towards heat conditions of high risk level, and lengthening of periods of Ex-Caution over all subregions.

It is important to note that with the increased global warming towards the high emission scenarios, areas such as NAF, SAH, WAF, CAF and NEAF are likely to experience the emergence of HI of Danger category, with relatively high magnitudes compared to the case of low emission scenarios Therefore, an increase of about 6-20% is recorded over these subregions when going from RCP2.6 to RCP8.5. Furthermore, the duration of these dangerous heat periods will differ according to the subregions, ranging from 2 consecutive months (July-September) over NAF, to 7 consecutive months (March-October) over WAF.

3.3 Projected frequency of occurrence of heat stress

Figure 4 shows the projected changes in the frequency of occurrence of days with each HI categories, for the different global warming scenarios over Africa. Changes in the frequency of days with Safe conditions presents a generalised decrease over the entire domain, with peaks more pronounced for RCP8.5 (up to 350 day/year) over countries located around the Equator (between 15ºS-15ºN; see, Fig. 4a-b). In fact, areas such as Sierra Leone, Liberia, southern Cameroon, Central African Republic (CAR), Gabon, Congo, northern Angola, DRC and Uganda, which present a strong decreases in Safe conditions, are those likely to experience more intense Caution heat conditions. Furthermore, areas where there is almost no change in this heat condition (northern Morocco, northern Algeria, western Cameroon, Burundi, central Ethiopia, western Kenya, central Angola, eastern South Africa including Lesotho), correspond to countries experiencing almost no heat stress throughout the year, with a number of days with Safe conditions reaching 350 day/year (see, Fig. S3a-c).

Regarding the future evolution of HI of Caution category, we note an increase in its number of days of occurrence, with peaks of up to 200 and 300 day/year for RCP2.6 and RCP8.5 respectively, over countries located between the 30ºS-10ºN band (Fig. 4c-d). Furthermore, we note a significant decrease in the frequency of days with this category over countries located between 5ºN-20ºN, which persists and becomes more pronounced with increasing global warming (with decrease of up to 100 and 200 day/year for RCP2.6 and RCP8.5 respectively).

The number of days with Ex-Caution conditions shows a generalized increase over most of the northern part of the continent, with peaks located around the Equator (between 10ºS-20ºN; see, Fig. 4e-f). For this category, which may represent a moderate risk level to local populations, their frequency of occurrence is almost 5-fold compared to the baseline period, with a projected peak of about 50 and 250 % for RCP2.6 and RCP8.5 respectively over WAF, CAF and NEAF.

Although with a small spatial extent, the RCMs ensemble-mean project an extension of the number of days with Danger heat conditions over some countries included in WAF and NEAF, only for high emission scenarios. Therefore, populations of countries located in these subregions are likely to experience about 20-50 days/year with high heat-risk level (Fig. S3i).

3.4 Projected population exposure to heat stress

Exposure to future heat stress generally depends on future population changes occurring in a given country, including adopted urbanisation planning, population growth, as well as their vulnerability. For the African continent in particular, the SSP1 scenario projects strong population growth, which is expected to intensify in the SSP3 scenario, along the coastal regions of the NAF countries, as well as in WAF, CEAF and SEAF countries including Madagascar (Fig. S4). The spatial distribution of the total exposure change including population projections for each HI category and for the different considered global warming scenarios over Africa, is presented in Figure 5.

The spatial variation of total exposure to Safe category is generally high over the entire domain, except over SAH, SWAF and some parts of CAF where less than 100 thousand person-events will experience extremely low heat conditions under both considered scenarios. Note that in this case the spatial extent of the exposure distribution is larger for RCP2.6/SSP1 than for RCP8.5/SSP3. This suggests that the climate change has the effect of reducing the spatial extent of thermal comfort areas, for which peaks of about 60 million person-events are localized over the mountainous regions of Nigeria, Rwanda, Burundi and Ethiopia (see, Fig. 5a-b). The highest value of the regional change in total exposure is thus recorded over CEAF, where about 7 and 9 million person-events are likely to experience extremely low heat conditions under RCP2.6/SSP1 and RCP8.5/SSP3, respectively (Fig. 6a-b).

Concerning the HI with Caution conditions, pattern of the total exposure is similar to that of Safe, but with a wider spatial extent as the GHG-forcing scenario increases. Here, the highest value of the regional change in the total exposure is observed over WAF, where about 7 and 6 million person-events are likely to experience extremely low heat conditions under RCP2.6/SSP1 and RCP8.5/SSP3 respectively (Fig. 6c-d). For this heat category, the population effect seems to be the main driver of the total change over all subregions, except for SWAF and SEAF where the interaction effect contributes for about 89 and 74%, respectively to the total exposure change under RCP8.5/SSP3 (Fig. 6 and Table S2; Caution).

The total change in exposure to heat with Ex-Caution conditions is smaller than that of the two previous HI categories and is generally confined in the subregions located around the Equator (between 15ºS-15ºN; Fig. 5e-f). Furthermore, the RCMs ensemble-mean project peak of exposures more pronounced for RCP8.5/SSP3 compared to RCP2.6/SSP1, with about 40-60 million person-events at risk over Côte d'Ivoire (with hotspot in Abidjan), Nigeria (with hotspots in Lagos, Port-Harcourt and Kano) and Egypt (with hotspot in Cairo). Overall, the highest increase in regional change in exposure is projected over WAF, where about 2 and 16 million person-events are likely to experience moderate heat conditions under RCP2.6/SSP1 and RCP8.5/SSP3 respectively (Fig. 6e-f). In this case, the interaction effect is found to be the main driver of this change, with contributions of about 70 and 89% under RCP2.6/SSP1 and RCP8.5/SSP3 respectively (see, Fig. 6 and Table S2; Ex-Caution).

Concerning the risk category Danger, the RCMs ensemble-mean project a moderate spatial pattern, with about 2-10 million person-events at risk over Burkina Fao (with hotspot in Ouagadougou), Ghana (with hotspot in Abidjan), southern Niger (with hotspot in Bolgatanga) and Nigeria (with hotspots in Bimming Kebbi, Port-Harcourt and Kano). In this case, the highest increase in regional change in total exposure is found over WAF, where about 560 thousand person-events are likely to experience high heat conditions under RCP8.5/SSP3, with the interaction effect as the main driver of change with a contribution of about 95% (Fig. 6 and Table S2; Danger).

4 Discussion

Our results suggest that for both RCP2.6 and RCP8.5 scenarios, countries located around the Equator (between 15ºS-15ºN) are likely to experience substantial increases in heat stress by the end of this century, probably partly due to the fact that this part of the continent is the most affected by incident solar radiation (Coffel et al., 2018) which would increase the total heat flux (Pal & Eltahir, 2016).

Particularly, analysis of the future evolution of the spatial extent of heat stress categories revealed that the RCMs ensemble-mean project a predominance of Safe and Caution heat conditions in the southern part of the domain, for which spatial extent gradually decreases as global warming increases (with a decrease of up to 25% under RCP8.5). We further noted a strong extension of Ex-Caution (Danger) conditions, which would increase by 20% (23%) under RCP8.5 against an increase of 15% (2%) under RCP2.6 over the continent, and will affected most countries of SAH, WAF, CAF and NEAF subregions. This implies that in the case of Ex-Caution (Danger) heat category, the increase in global warming would induce a 4-fold (12-fold) increase in the area affected by dangerous heat conditions. Although restricted to a subregional scale, the future evolution of the spatial extent of high heat stress conditions has been investigated by other authors (e.g., Sylla et al., 2018; Fotso-Nguemo et al., 2021), who have also concluded to an increase under the effects of increased global warming levels. Accordingly, the study conducted over WAF by Sylla et al. (2018) showed an almost 1.5-fold increase in the spatial extent of Ex-Caution heat category, for the global warming levels ranging from 1.5 to 2 ºC under RCP8.5. Similarly, the study Fotso-Nguemo et al. (2021) realized over CAF, showed a 3-fold increase in the spatial extent of Ex-Caution heat category, for global warming levels ranging from 1.5 to 3 ºC under RCP8.5.

The projected seasonality of heat stress showed that populations from certain subregions of Africa, especially those located around the Equator (SAH, WAF, CAF and NEAF) could experience a tendency towards longer and more intense periods of high heatrelated risk under RCP8.5 compared to RCP2.6. This result is consistent with the studies of Asefi-Najafabady et al. (2018) and Jagarnath et al. (2020), where in their study areas (CEAF and SEAF, respectively) have shown a trend towards not only a lengthening of the periods of high heat felt by population, but also an intensification of their magnitude. Our results show that the subregion with the longest duration of high heatrelated risk is WAF, with up to 7 consecutive months (March-October) of Danger heat category under RCP8.5. Similarly, the subregion with the most intense heat events is SAH, with a HI of 49 ºC around September under RCP8.5, representing an increase of about 8 ºC when moving from RCP2.6 to RCP8.5. Overall, an increased magnitude of about 6-20% is recorded over the above subregions when moving from RCP2.6 to RCP8.5.

Concerning changes in the frequency of occurrence of heat stress, we noted an almost 4-fold increase in the number of days with Ex-Caution conditions, with a projected peak of about 60 and 15% of the length of the year for RCP8.5 and RCP2.6 respectively, over WAF, CAF and NEAF. The intensification of heat due to increased radiative forcing will contribute to the emergence of dangerous heat stress conditions, for which the number of days will increase by about 10-30% at the end of the century. These events mostly concern countries such as Senegal, Mali, Burkina Faso, Ghana, Benin, Niger, Nigeria, Cameroon and Chad, Sudan, Ethiopia, Somalia, Eritrea and Egypt. Substantial increase in the frequency of occurrence of extreme heat events over Africa has also been recently reported by certain authors (e.g., Diedhiou et al., 2018; Sylla et al., 2018; Asefi-Najafabady et al., 2018; Jagarnath et al., 2020; Yengoh and Ardö, 2020; Fotso-Nguemo et al., 2021), indicating that future heat hazard conditions will worsen in the future if no mitigation efforts are implemented. However, the projections of the frequency of occurrence of Extremely Low heat conditions for late 21st century could allow to anticipate on the locations where demographic transitions are most likely to occur. For instance, the mountainous areas of Morocco, western Cameroon, Ethiopia, Angola, South Africa, eastern Madagascar and the Great Lakes region are likely to be unaffected by heat-related risks whatever the considered radiative forcing scenario.

The analysis of change in population exposure to heat stresses showed that the subregion in which populations will be most exposed to high heat-related risk levels is WAF. This was found for both the RCP2.6/SSP1 and RCP8.5/SSP3 scenarios, for which the RCMs ensemble-mean project a regional change of about 2 and 16 million person-events respectively, likely to be exposed to Ex-Caution heat conditions. This means that in this subregion, the increase of radiative forcing would lead to a 8-fold increase in exposure to moderate heat stress, which exacerbation could potentially induce the exposure of about 580 thousand person-events to high heat-related risks. Currently, it is difficult to explain with precision the driven mechanisms responsible for these changes. However, some important factors such as i) large-scale variability through atmospheric parameters (insulation, temperature, precipitation, humidity, cloud cover); ii) changes in anthropogenic GHG concentrations; and iii) changes in land use/cover could play a key role (Pal & Eltahir, 2016; Coffel et al., 2018). Nevertheless, in order to understand the relative importance of the potential drivers of projected changes in population exposure to high heat stress, results of the total change in exposure were divided into three components (climate, population, and interaction effects). It thus appears that for both considered scenarios, the population effect appears to be dominant in explaining the total changes in exposure due to extremely low (Safe) and low (Caution) heat-related risks over all subregions of the African continent. Concerning the total changes in exposure to moderate (Ex-Caution) and high (Danger) heat-related risks, the interaction effect between climate change and population growth appears to be the most important driver. This result is in agreement with the findings of Liu et al. (2017), who in their study conducted with 5 GCMs showed that the total changes in exposure to extreme heat over several regions of the world including Africa, was mainly caused by the synergistic interaction between the large increases in the number of high-heat days during the year and rapidly increasing population. It is worth pointing out that apart from the interaction effect, although of small proportion, the population (climate) effect also plays a role in the case of scenario RCP2.6/SSP1 (RCP8.5/SSP3).

Note that, although the heat stress category of extreme danger conditions does not appear in the considered HI climatology, it cannot be excluded that it may occur on certain days, both during the baseline period and in future GHG-forcing scenarios. Moreover, whilst we used the high-resolution CORDEX-CORE projections dataset, their ensemble-mean size is not sufficiently robust (only 9 members derived from 3 RCMs). This is likely to provide a limited quantification of the uncertainty associated with the projected HI. Therefore, different results would be expected by considering, for example: i) other algorithms for computing heat index; ii) the type of model used to estimate the heat index as well as the population growth; iii) a larger RCMs ensemble-mean; iv) aerosol variation as well as deforestation/afforestation scenarios.

5 Conclusion

The aim of this research was to explore the response of increased anthropogenic radiative forcing on heat stress changes over the African continent towards the late 21st century, not only in terms of its spatial extent, seasonality and frequency of occurrence, but also in terms of the number of person likely to be exposed to these extreme heat events. For this purpose, we have considered the projections of HI computed based the United States National Weather Service's algorithm (Rothfusz, 1990) applied to an ensemblemean of high-resolution RCMs, performed in the framework of the CORDEX-CORE initiative; combined with projections of population growth from ISIMIP2b (only for the baseline period) and SEDAC datasets.

Our results suggest that for all heat stress categories susceptible to create discomfort to populations, their projected changes would be stronger in the high-emission scenario than in that of low-emission. It was shown that in the future, heat conditions of high-risk category will be more severe for populations living over subregions such as SAH, WAF, CAF and NEAF, especially if no adaptation and mitigation policies are implemented. The simultaneous effects of population growth and increasing global warming would be the main driver of this trend toward more widespread, longer, intense and frequent extreme heat events. Recent studies have shown that prolonged exposure to such heat conditions could lead to certain health problems such as heat cramps, heat exhaustion and even heat stroke following a prolonged physical activity (Lucas et al., 2014; Scovronick et al., 2018). Besides the direct negative health impacts, socio-economic sectors that are essential for the development of countries of these subregions could also be affected, through reduced availability and productivity of outdoor workers (e.g., agro-pastoral, fishing, construction, transport, industries, firefighter, services, etc), or disruptions in the electrical network due to high demand for electrical energy to cool down (Sylla et al., 2018; Parkes et al., 2019; Yengoh & Ardö, 2020). Therefore, the projected high heat stress, coupled with the existing problems in most developing countries (e.g., poverty, weak institutions, political unrest, etc.), will further increase the vulnerability of affected countries. These potential threats could justify the need to urgently implement practices that will allow not only to strongly mitigate the effects of increased radiative forcing, but also to sustainably adapt populations living in affected countries for dealing with a warming world, even in regions considered not to be at risk during the baseline period.

For instance, there is still a need for further research to accurately specify the most appropriate measures for populations of the affected areas, nevertheless some actions can be envisaged by public authorities and/or even when possible by the concerned individuals:

- The establishment of a heat index-based health prevention plan for populations, with a particular focus on outdoor workers. The purpose of such a plan would be to prevent heat-related illnesses and even deaths by, for example, raising awareness among workers and decision-makers about health problems associated with working in hot environments (Yengoh & Ardö, 2020);

- Develop and disseminate protective strategies for workers who often work outdoors in adverse weather conditions. These measures could help to reduce heat-related mortality by providing recommendations on: the setting of work and rest schedules, choosing appropriate clothes for different heat stress circumstances, the choice of foods to avoid (e.g., proteins, alcohol, etc) and to prioritise (e.g., fruits, vegetables, etc) in order to keep metabolic heat at a reasonable level, adopting cooling strategies according to social level, the importance of hydration during working hours and how to deal with heat-related emergencies, among others (Yengoh & Ardö, 2020);

- Encouraging and disseminating good practices in order to reduce anthropogenic GHG-forcing and thus temperature. Having the lower temperatures would reduce the number of high heat stress events which can result in lower costs of adapting the energy system to climate change and thus provide enough electricity to prevent heat stress through the cooling of the local environment (Parkes et al., 2019; Akara et al., 2021).

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Table 1: Heat index classification, along with their corresponding risks levels, and the health problems they can trigger

HI (°F)	**HI (°C)**	**Risk levels**	**Classification**	**Associated health problems**
< 80	< 27	Extremely low	Safe	No significant stress
[80;90[	[27;32[	Low	Caution	Fatigue possible with prolonged exposure and/or physical activity
[90;105[	[32;41[	Moderate	Extreme caution	Heat cramps, heat exhaustion, and heat stroke possible with prolonged exposure and/or physical activity
[105;130[	[41;54[	High	Danger	Heat cramps and heat exhaustion are likely. Heat stroke probable with prolonged exposure and/or physical activity
≥ 130	≥ 54	Very high	Extreme danger	Heat stroke is highly likely and imminent

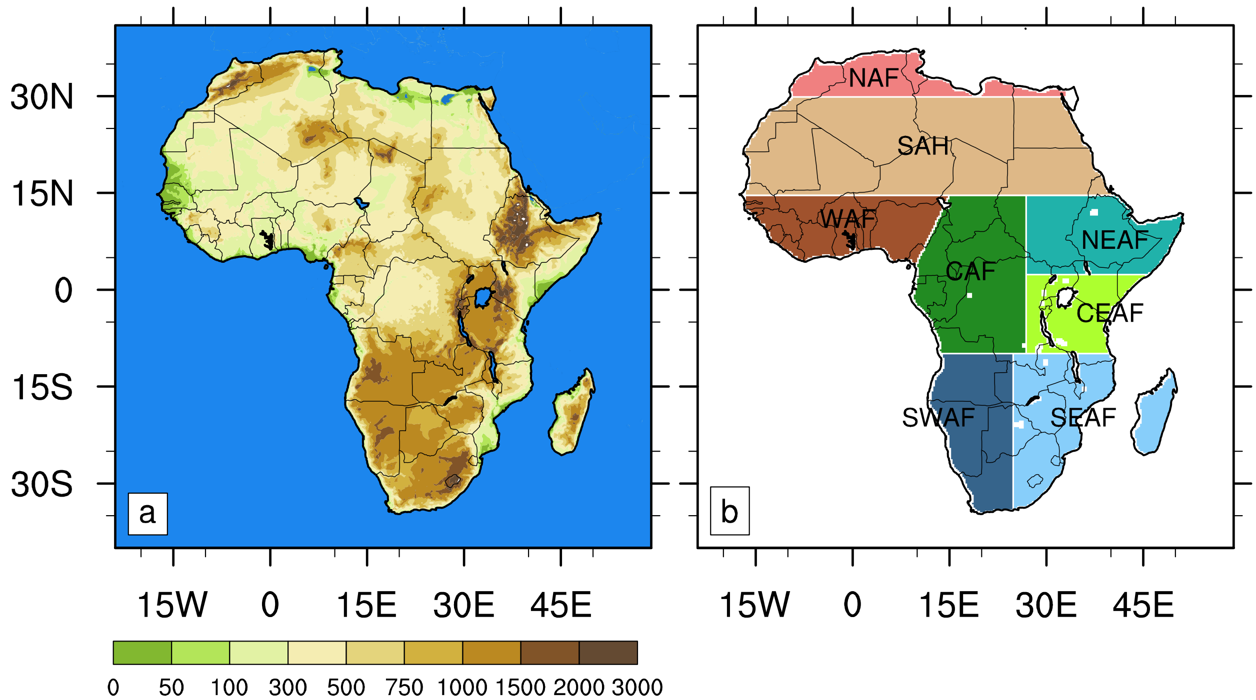

Figure 1:a African domain and its topography (shaded, in meters). **b** Analysis subregions, denoted as North Africa (NAF), Sahara (SAH), West Africa (WAF), Central Africa (CAF), North-East Africa (NEAF), Central-East Africa (CEAF), South-West Africa (SWAF) and SouthEast Africa (SEAF)

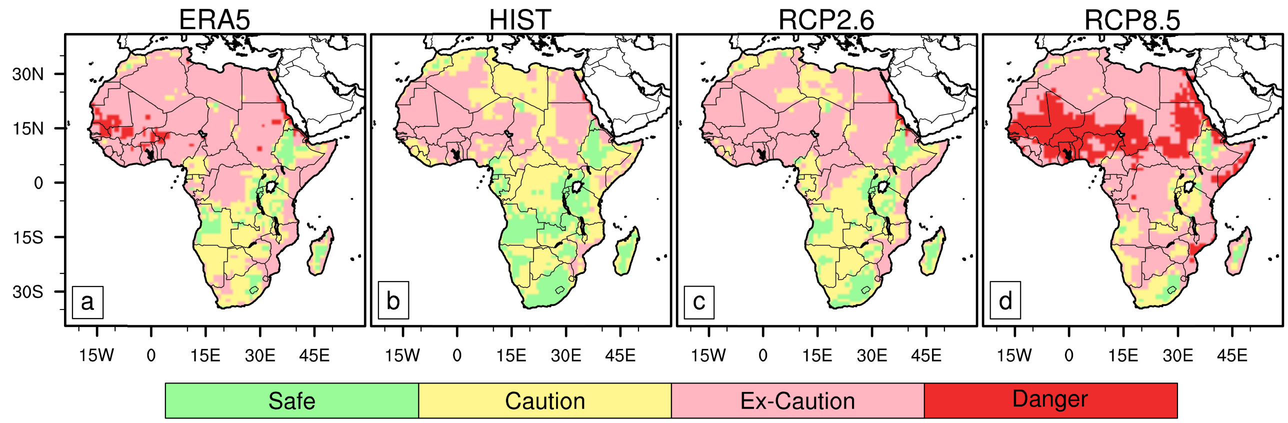

Figure 2: Spatial distribution of heat stress categories, during the baseline period (1979-2008) from ERA5 (first column) and historical (second column); and the late 21st century (2069–2098), under the radiative forcing scenarios RCP2.6 (third column) and RCP8.5 (fourth column)

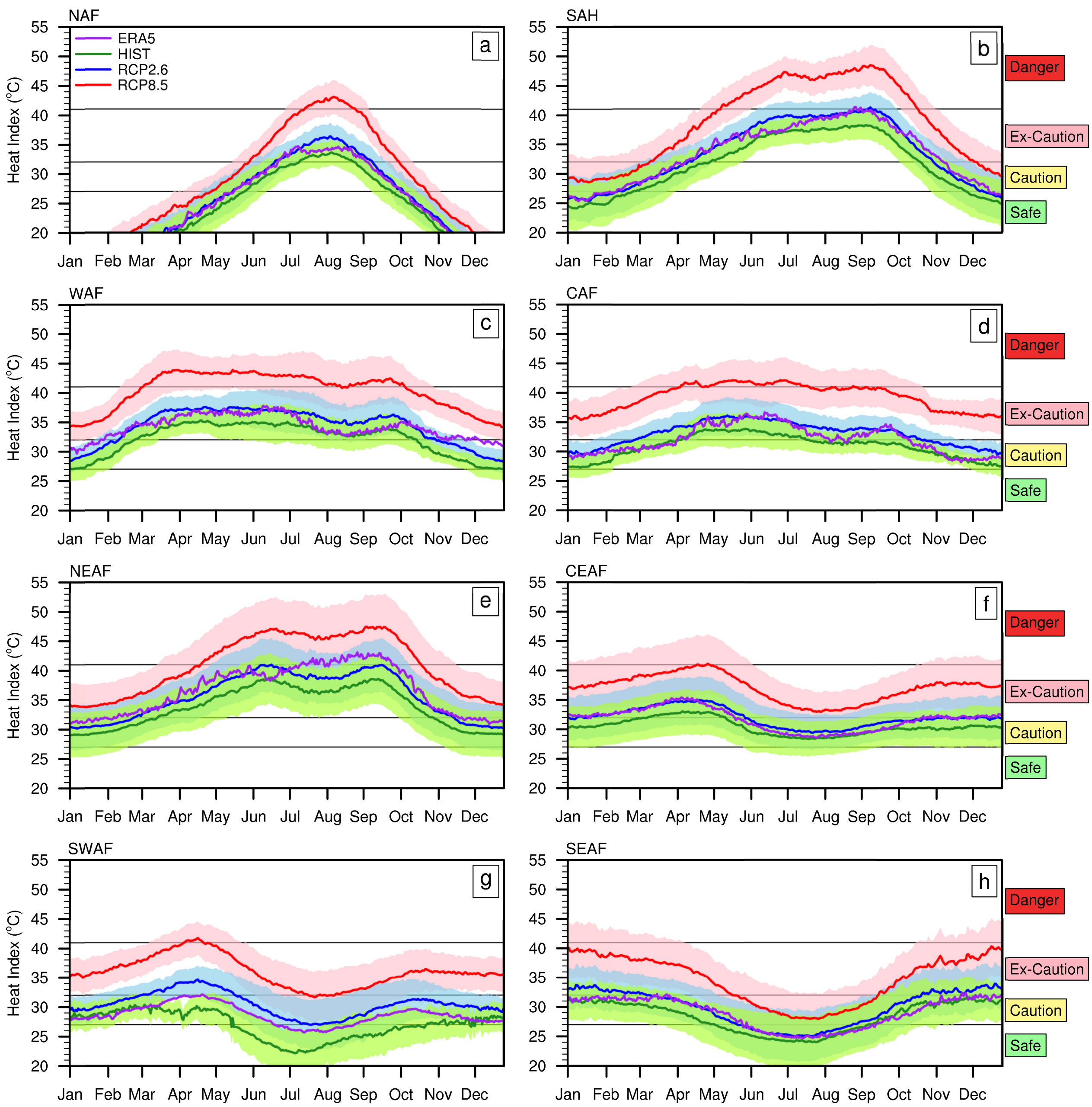

Figure 3: Seasonal cycle of regional heat index (in ºC), during the baseline period (1979-2008) from ERA5 (purple) and historical (green); and the late 21st century (2069–2098), under the radiative forcing scenarios RCP2.6 (blue) and RCP8.5 (red). Green, blue and red shadings correspond to the full range of individual RCM members for the historical, RCP2.6 and RCP8.5, respectively

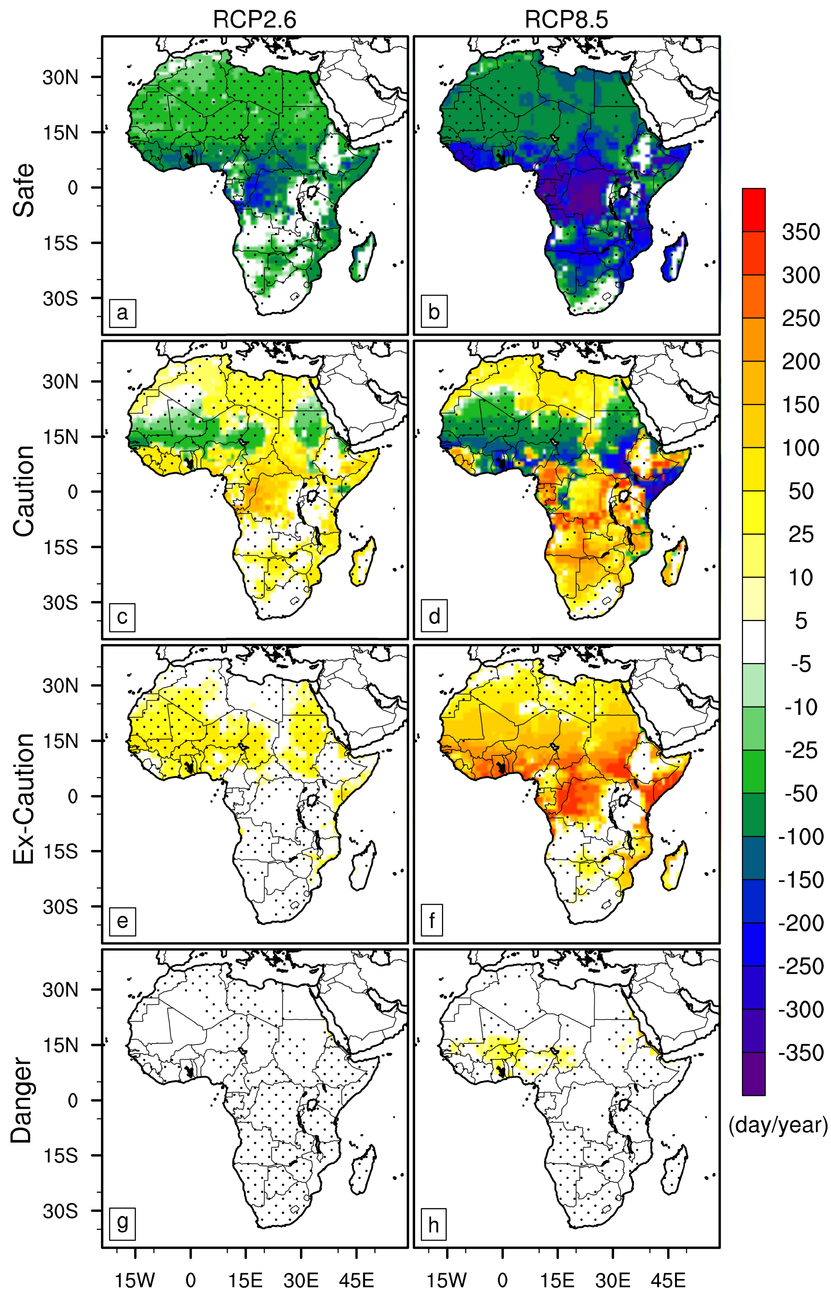

Figure 4: Spatial distribution of change in frequency (with respect to the 1979-2008 historical data; in day per year) of each heat stress categories, during the late 21st century (2069–2098), under the radiative forcing scenarios RCP2.6 (first column) and RCP8.5(second column). Dots indicate areas where the change is significant (i.e., where at least 7 out of 9 RCM members agree on the sign of the change)

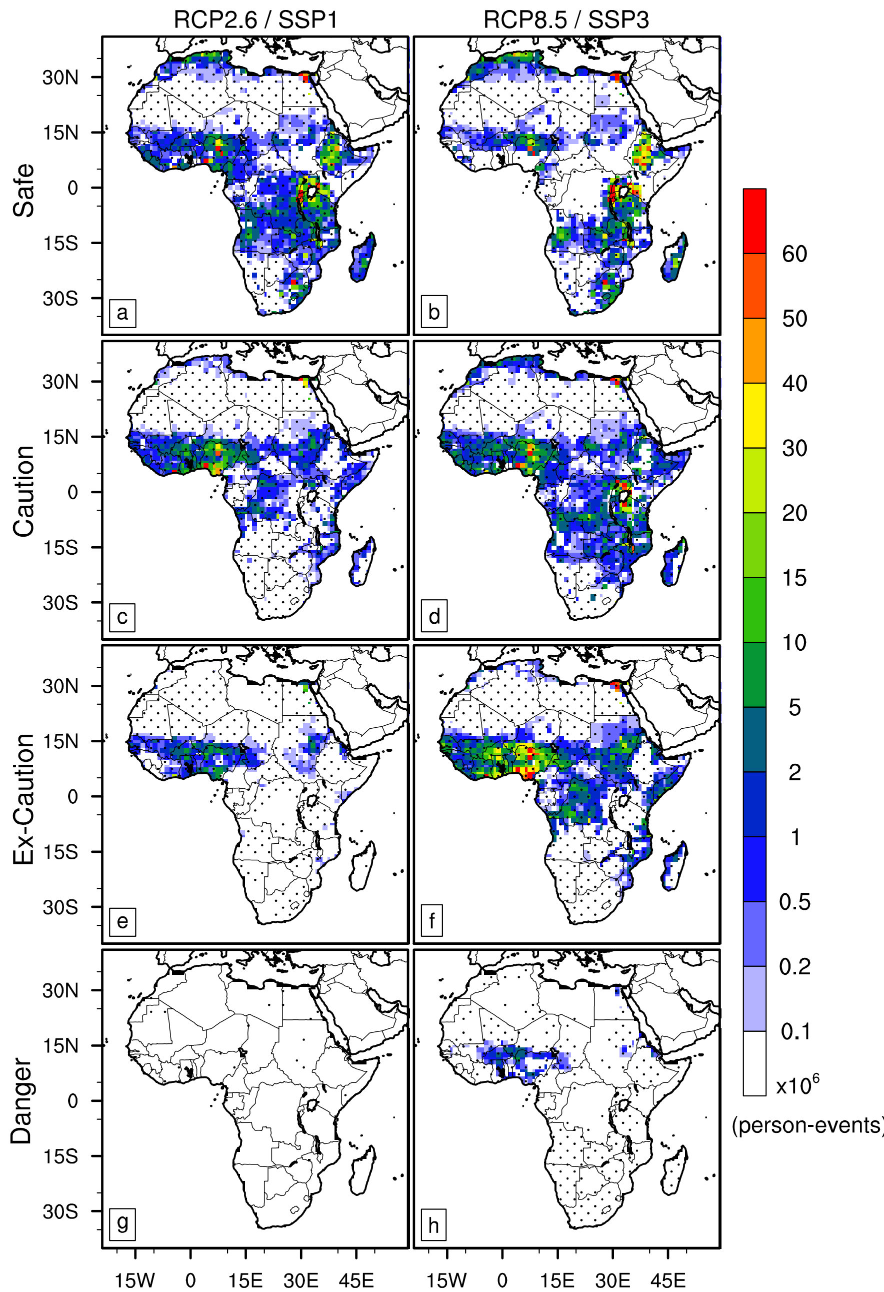

Figure 5: Spatial distribution of total change in exposure (with respect to the 1979-2008 historical data; in 10^6 person-events) to each heat stress categories, during the late 21st century (2069–2098), under the radiative forcing scenarios RCP2.6/SSP1 (first column) and RCP8.5/SSP3 (second column). Dots indicate areas where the change is significant (i.e., where at least 7 out of 9 RCM members agree on the sign of the change)

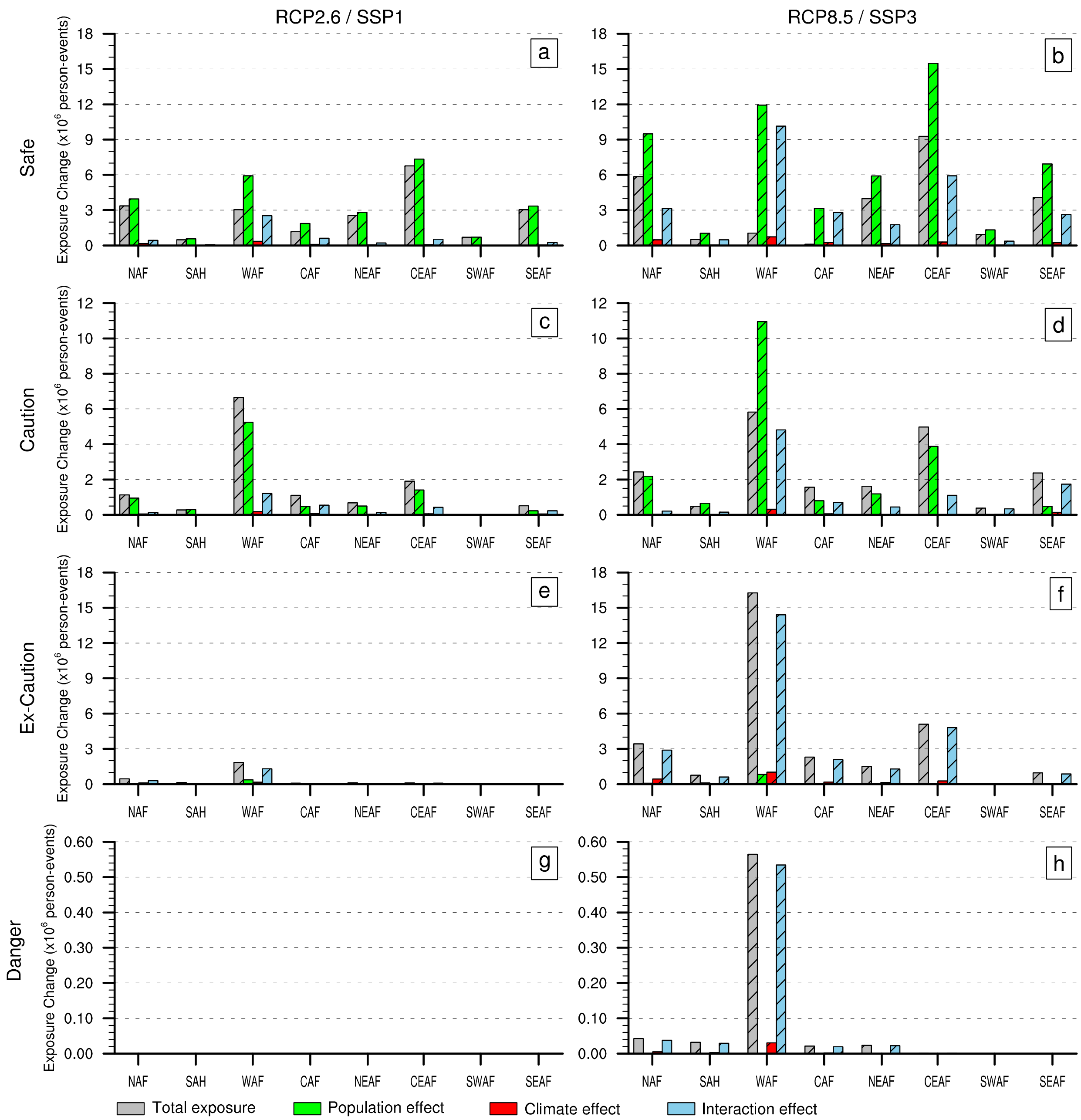

Figure 6: Regional mean of total change in exposure (with respect to the 1979-2008 historical data; in 10^6 person-events) to each heat stress categories and the contribution of different drivers (population, climate, and population-climate interaction), during the late 21st century (2069–2098), under the radiative forcing scenarios RCP2.6/SSP1 (first column) and RCP8.5/SSP3 (second column). Diagonal lines indicate significant change (i.e., where at least 7 out of 9 members agree on the sign of the change)