RESEARCH ARTICLE

Impact of 1.5 ºC and 2 ºC global warming scenarios on malaria transmission in East Africa [version 1; peer review: 1 approved with reservations]

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Abstract

Background: Malaria remains a global challenge with approximately 228 million cases and 405,000 malaria-related deaths reported in 2018 alone; 93% of which were in sub-Saharan Africa. Aware of the critical role than environmental factors play in malaria transmission, this study aimed at assessing the relationship between precipitation, temperature, and clinical malaria cases in E. Africa and how the relationship may change under 1.5 ºC and 2.0 ºC global warming levels (hereinafter GWL1.5 and GWL2.0, respectively).
Methods: A correlation analysis was done to establish the current relationship between annual precipitation, mean temperature, and clinical malaria cases. Differences between annual precipitation and mean temperature value projections for periods 2008-2037 and 2023-2052 (corresponding to GWL1.5 and GWL2.0, respectively), relative to the control period (1977-2005), were computed to determine how malaria transmission may change under the two global warming scenarios.
Results: A predominantly positive/negative correlation between clinical malaria cases and temperature/precipitation was observed. Relative to the control period, no major significant changes in precipitation were shown in both warming scenarios. However, an increase in temperature of between 0.5 ºC and 1.5 ºC and 1.0 ºC to 2.0 ºC under GWL1.5 and GWL2.0, respectively, was recorded. Hence, more areas in E. Africa are likely to be exposed to temperature thresholds favourable for increased malaria vector abundance and, hence, potentially intensify malaria transmission in the region.
Conclusions: GWL1.5 and GWL2.0 scenarios are likely to intensify malaria transmission in E. Africa. Ongoing interventions should, therefore, be intensified to sustain the gains made towards malaria elimination in E. Africa in a warming climate.

Keywords

SR1.5, CORDEX, malaria, RCP 8.5, global warming, mosquito vectors

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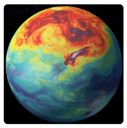

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Introduction

Malaria is an illness caused by *Plasmodium* parasites that are spread to humans through bites of infected female *Anopheles* mosquitoes, commonly referred to as "malaria vectors". Of the five parasite species that cause malaria in humans, *P. falciparum and P. vivax* pose the highest threat (WHO, 2020). According to the World Health Organization (WHO), an estimated 228 million malaria cases and 405,000 malaria-related deaths were reported in 2018, globally. About 93% of the malaria cases and 94% of the malaria-related deaths occurred in sub-Saharan Africa. Uganda, for instance, tops East Africa (hereinafter E. Africa) with the highest number of malaria cases; accounting for 5% of global totals in 2018.

Malaria transmission is affected by, among other things, climatic factors such as temperature, rainfall, and humidity that influence the abundance and survival of mosquitoes (Metelmann *et al*., 2019; Nsoesie *et al*., 2016). While efforts are underway towards elimination, malaria remains a big challenge in E. Africa (Bashir *et al*., 2019; Nkumama *et al*., 2017; WHO, 2020). In a special report on global warming of 1.5 °C (hereinafter SR1.5), the Intergovernmental Panel on Climate Change (IPCC; Hoegh-Guldberg *et al*., 2018) highlighted sector-specific risks posed by a global temperature rise of 1.5 °C and beyond. The SR1.5 identifies a knowledge gap in the impacts of global and regional climate change at 1.5 °C on, *inter alia*, public health and infectious diseases, particularly for developing nations. Some work has been done towards understanding the potential impact of global warming in E. Africa (e.g. Gudoshava *et al*., 2020; Osima *et al*., 2018). However, no conclusive literature exists on the potential impacts of 1.5 °C and 2 °C global warming levels (hereinafter GWL1.5 and GWL2.0) in E. Africa. This study, therefore, aimed at assessing the relationship between precipitation, temperature, and clinical malaria cases in E. Africa and how the relationship may change under the GWL1.5 and GWL2.0 scenarios.

Methodology

Study area

The study focuses on the E. Africa sub-region (marked EA on Figure 1) of the COordinated regional Downscaling Experiment (CORDEX) Africa domain (Kim *et al*., 2014). A slight extension of the CORDEX-EA sub-region was done to cover five countries part of the East African Community (EAC) namely Kenya, Uganda, Tanzania, Rwanda, and Burundi (Figure 1).

Climate model data

Daily precipitation data (in its native form) from two regional climate models (RCMs) participating in CORDEX-Africa were used. Specifically, the study used four RCM realizations (Table 1) driven by general circulation models (GCMs) from the 5th phase of the Coupled Model Intercomparison Project (CMIP5, Meehl *et al*., 2014), under the representative concentration pathway (RCP) 8.5 (Moss *et al*., 2010). The four CORDEX-Africa RCM runs have been identified to be among the best in simulating precipitation characteristics over E. Africa (Ogega *et al*., 2020). The RCMs are described in detail in Nikulin *et al*. (2012).

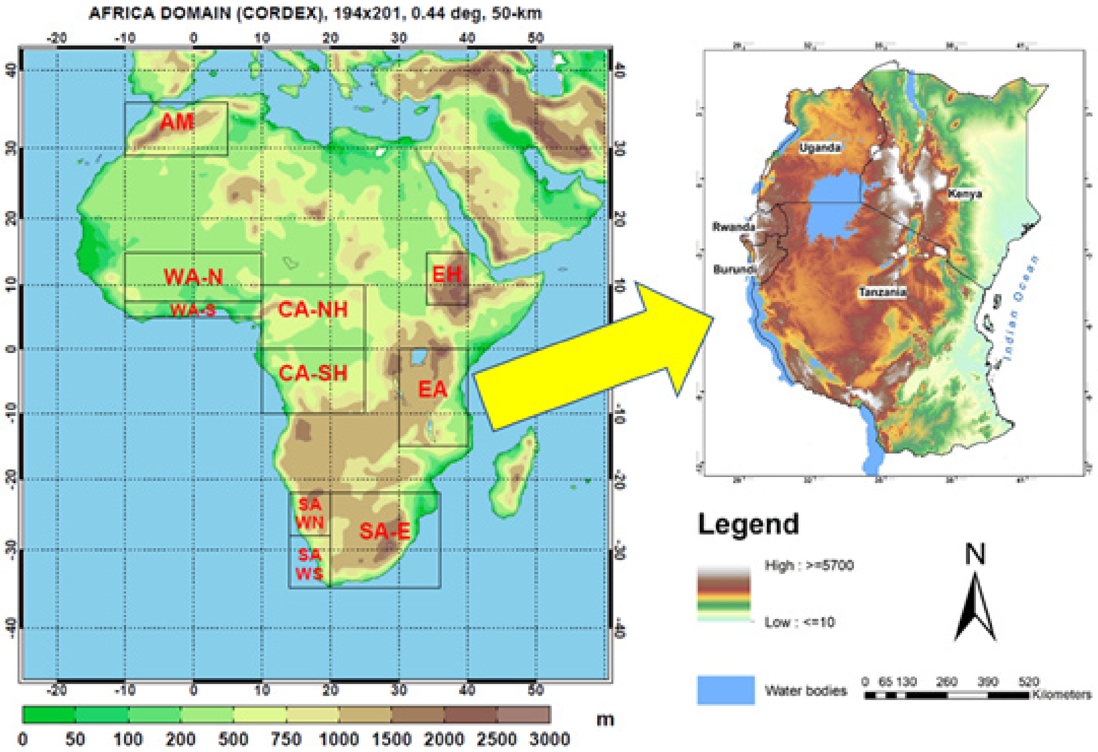

Figure 1. Map of the study domain. Figure is reproduced from Ogega *et al.* (2020) under the terms of the Creative Commons Attribution 4.0 International license (CC-BY 4.0).

Table 1. CORDEX-Africa RCM runs used in the current study, downloaded in April 2020 from the Deutsches Klimarechenzentrum (DKRZ[1]), for the period 1977–2005 (historical) and 2071–2100 (RCP 8.5).

Institute	RCM	Herein-after	Ensemble	Driving Model
Max Planck Institute (MPI), Germany	REMO2009	REMO2009	r1i1p1	MPI-M-MPI-ESM-LR
Sveriges Meteorologiska och Hydrologiska Institut (SMHI), Sweden	SMHI Rossby Center Regional Atmospheric Model (RCA4)	RCA4	r1i1p1	MPI-M-MPI-ESM-LR
				CNRM-CERFACS-CNRM-CM5
			r2i1p1	MPI-M-MPI-ESM-LR

The terms in the table can be used to search for the required data files

Observational climate data

The daily Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) version 2.0 was used as observational precipitation data. CHIRPS data, which have been validated for E. Africa (Dinku *et al*., 2018), incorporate satellite imagery (at 0.05° resolution) with *in-situ* station data resulting in a gridded rainfall time series available from 1981 to near-present (Funk *et al*., 2015). For mean temperature, the Climatic Research Unit time-series (CRU) dataset were used. CRU data are computed on high-resolution (0.5 by 0.5 degree) grids based on a database of monthly mean temperatures from at least 4,000 weather stations from around the world (Harris *et al*., 2020).

Clinical malaria cases data

Data on clinical malaria cases for E. Africa were obtained from the *Malaria Atlas Project* (Hay & Snow, 2006; Weiss *et al*., 2019). The Malaria Atlas Project (MAP) obtains, curates, and shares a variety of malariometric data including malaria cases reported by surveillance systems, nationally representative cross-sectional surveys of parasite rate, and satellite imagery capturing global environmental conditions that influence malaria transmission. The dataset has been validated (e.g. Nakakana *et al*., 2020) and used widely across the world (e.g. Battle *et al*., 2019; Bhatt *et al*., 2015; Weiss *et al*., 2019).

Data analysis

Precipitation and temperature have been identified as the most important climatic factors for malaria vectors (e.g. Arab *et al*., 2014; Mohammadkhani *et al*., 2016). In the current study, a review of literature was done to identify precipitation and temperature thresholds within which malaria vectors thrive. The search was done in Scopus and Google Scholar using the following terms: temperature threshold for *Anopheles* mosquitos, precipitation threshold for *Anopheles* mosquitos, and malaria transmission in East Africa. Results of the review were used to analyse historical (2000–2017, due to limited availability of data on clinical malaria cases from MAP) trends in temperature, precipitation, and clinical malaria cases in E. Africa. Specifically, standardized anomalies, which remove influences of location and distribution from the data (as in Dabernig *et al*., 2016), were computed to determine the year-to-year variability of incidences. Linearly de-trended precipitation and temperature data were used for correlation analysis with reference to reported clinical malaria cases in the study domain.

With reference to the pre-industrial period (1861–1890), 2022 and 2037 have been identified as mid-years for 30-year windows when GWL1.5 and GWL2.0, respectively, are likely to be first experienced (Nikulin *et al*., 2018). Hence, with the period 1977–2005 as the control (CTL), differences between periods 2008–2037 and 2023–2052 (corresponding to GWL1.5 and GWL2.0, respectively) were computed for precipitation and temperature over E. Africa. A comparison of precipitation and temperature values in the current (CTL), GWL1.5 and GWL2.0 (relative to established thresholds within which malaria vectors thrive) was used to determine the potential impact of 1.5 °C and 2.0 °C GWLs on malaria transmission in E. Africa.

Statistical computations and data visualization

Processing (conversion to common calendar, units, grid, and resolution) and statistical computations (e.g. means, anomalies, standard deviation, summations, and data detrending) of climate (precipitation and temperature) data in NetCDF format was done using the Climate Data Operators (CDO), version 1.9.8 – a command line suite for manipulating and analysing climate data. A description of CDO operators is available from the CDO user guide. Additional computations were done using the R Project for Statistical Computing (R, version 3.6.3). Specifically, the *fields, graphics, and ncdf4* R packages were used to process and compute future changes in precipitation and temperature under the 95% confidence level. Data detrending and correlation analysis were done in R using the *pracma* package and the *cor.test* function, respectively. Spatial data visualization was done using the Grid Analysis and Display System (GrADS, version 2.2.1.oga.1). Line plots were done in R using the *ggplot2* (*version 3.3.0*) package.

Due to resolution differences between model and observations data, the data were processed in their native grids before bi-linearly interpolating them to the RCM grid to facilitate comparison (as in Diaconescu *et al*., 2015). Here, final products (after all the statistical computations) for both observational and model data were remapped into the same grid to facilitate comparison. Remapping was done using the '*remapbil*' function in the CDO software.

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[1] http://bit.ly/2RoIist

Results and discussion

An overview of the relationship between temperature, precipitation, and malaria vectors

An. gambiae s.s., An. funestus, and *An. arabiensis* have been identified as the top three potent malaria vectors in sub-Saharan Africa (Wiebe *et al*., 2017) and, in particular, E. Africa (e.g. Dida *et al*., 2018; Karungu *et al*., 2019). A study by (Charlwood, 2017) established that *An. funestus* seemed to be adversely affected by temperatures above 28 °C. Additionally, the wing size of *An. funestus* is said to be highly correlated with temperature and elevation (Spearman test, $p<0.001$) and minimally affected by rainfall and wind speed (Ayala *et al*., 2011). Christiansen-Jucht *et al*., (2014) inferred that temperature during larval development and adult maintenance influences the survival of *An. gambiae* s.s. Their study established that temperatures beyond 27 °C significantly influenced the survival of adult *An. gambiae* s.s. by increasing their mortality.

In areas where malaria transmission by *An. funestus* is high, transmissions by *An. gambiae* s.s. and *An. arabiensis* seemed to be higher/lower with precipitation/temperature (Kelly-Hope *et al*., 2009). Further, a temperature-dependent and stage-structured delayed differential equation developed by Beck-Johnson *et al*. (2013) showed that mosquito population abundance is strongly influenced by the dynamics of juvenile mosquito stages which are temperature-dependent. The model predicts a peak in abundance of mosquitoes old enough to transmit malaria (Figure 2).

This study, therefore, adapts the 20–25 °C temperature range as the threshold within which maximum suitability for survival for *Anopheles* mosquitoes is achieved and 13 °C and 30 °C as thresholds below/above which the suitability drops to zero. While no distinct annual precipitation thresholds have been established for Anopheles mosquitoes, the precipitation suitability for *Aedes* species has been put at a minimum of 400 mm/year while the maximum suitability is said to be achieved in areas receiving annual precipitation of more than 800 mm (e.g. Caminade *et al*., 2012; Metelmann *et al*., 2019). Therefore, the current study adapted 400/800 as the annual precipitation (mm) thresholds below/above which minimum/maximum suitability for *Anopheles* mosquitoes is achieved.

Trends in temperature, precipitation, and clinical malaria cases in E. Africa

The climatology for precipitation (Figure 3f) shows that most of the study domain (except northern Kenya) meets the precipitation threshold for malaria vector abundance and survival of at least 400 mm/year. Mean temperature for all the domain falls within the malaria vector survival threshold of 15–30 °C (Figure 3g). Many areas in the domain, such as the Lake Victoria (hereinafter L. Victoria) region (3°S 1°N, 32°E 35°E), mainland Tanzania and most of Uganda record average annual temperatures between 20–25 °C; the temperature threshold within which maximum suitability for malaria vector abundance occurs. Indeed, five administrative areas recording the highest number of clinical malaria cases per country (marked with

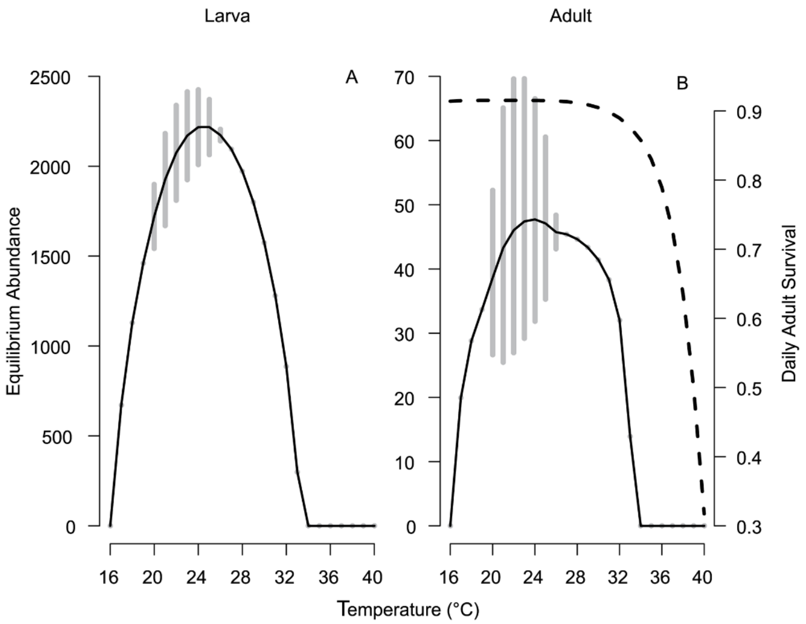

Figure 2. Larval and adult equilibrium abundances for *Anopheles* mosquitoes (Beck-Johnson *et al*., 2013). (A) represents the larval equilibrium abundances across temperatures with exponential density-dependence while (B) the adult equilibrium abundances (solid line, left axis) and daily survival (dashed line, right axis) across temperatures. The grey points and bars in both panels are the stable and cyclic abundances, respectively. The solid line connecting the points is the average abundance across temperature. Figure is reproduced from Beck-Johnson *et al*., (2013) under the terms of the Creative Commons Attribution 4.0 International license (CC-BY 4.0).

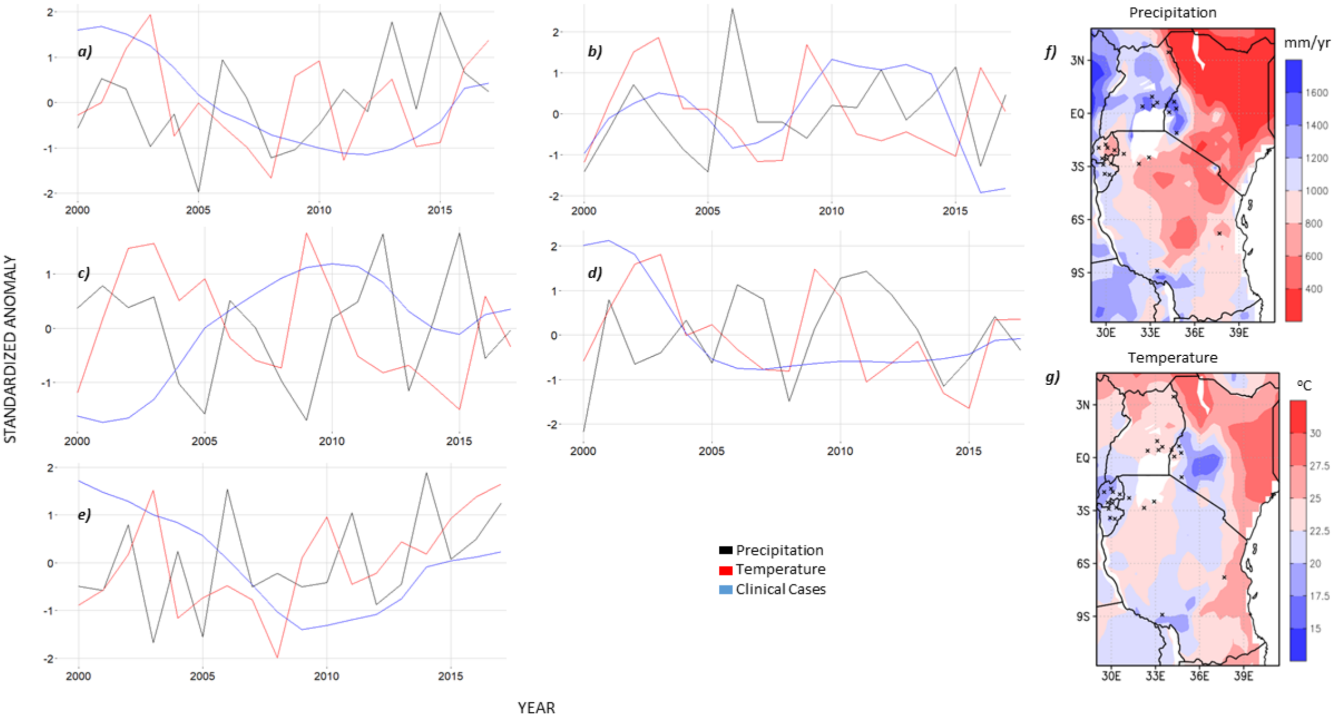

Figure 3. **Climatology of E. Africa and select year-to-year annual precipitation (black), mean temperature (red), and clinical malaria cases (blue) for Gitega, Burundi (a), Siaya, Kenya (b), Jinja, Uganda (c), Kigali, Rwanda (d), and Morogoro, Tanzania (e), averaged for the period 2000–2017. Water bodies on the spatial plots are presented in white while areas with the highest clinical malaria cases per country are marked with 'x'.**

an 'x' on the climatology maps (Figure 3) are located in areas where the suitability thresholds for mean temperature and annual precipitation are met.

Despite heavy investments (Head *et al.*, 2017) made to combat and eliminate malaria in the study domain, clinical malaria cases tend to show some correlation with precipitation and temperature. Siaya and Kigali (b and d, respectively, in Figure 3) are good examples where clinical malaria cases correspond to trends in climate variables, especially mean temperature. Pearson correlation coefficients (PCCs) for five administrative areas recording the highest number of clinical malaria cases per country (Table 2) show a positive relationship between temperature and clinical cases, in 22 out of 25 areas under consideration. Burundi records the highest positive PCCs (up-to 0.6) between temperature and clinical cases while Uganda records the highest negative PCCs (up-to -0.4).

Most areas (16 out of 25) record a negative correlation between precipitation and clinical malaria cases, with the highest negative correlation being -0.4. The rest show a marginal positive correlation with the highest being 0.3. Given that precipitation regimes over the study domain are well-defined (e.g. Nicholson, 2017; Schreck & Semazzi, 2004), the observed negative correlation between precipitation and clinical malaria cases could be as a result of deliberate intensification efforts to combat malaria during the rainy seasons. Nonetheless, areas that record a positive correlation between rainfall and malaria cases (9 out of 25) imply that more interventions are needed to minimize malaria transmission in the region.

Future changes in precipitation and temperature under 1.5 °C and 2.0 °C GWLs

Most of the study domain (except northern Kenya) receives at least 400 mm/year of precipitation – the minimum annual precipitation threshold for mosquito vector survival (Figure 4). Many areas such as the L. Victoria region, most of Tanzania and Uganda, and coastal Kenya receive more than 800 mm/year of precipitation - the threshold for maximum survival suitability for malaria vectors. Under 1.5 °C and 2.0 °C GWLs, the study domain does not record (except for a few places over Tanzania) any significant changes in precipitation (at 95% confidence interval). While a global warming of up-to 2.0 °C may not necessarily significantly change E. Africa's mean annual precipitation, the region already receives enough precipitation for malaria vector abundance.

In terms of temperature, all areas in the study domain record temperatures within the suitability threshold (13–30 °C) for malaria vectors. Areas in red (Figure 4, bottom row) record

Table 2. **Pearson correlation coefficients for de-trended precipitation (pr) and mean temperature (tmp) values relative to clinical malaria cases. Values marked with * are significant at 95% significance interval.**

	Kenya					**Rwanda**				
	Busia	**Kisumu**	**Siaya**	**Kakamega**	**Bungoma**	**Kigali**	**North**	**South**	**East**	**West**
pr	-0.01	0.1	0.14	0.19	-0.13	-0.31	-0.3	-0.1	-0.2	-0.1
tmp	0.19	0.23	0.07	0.23	0.4	0.2	0.3	0.4	0.4	0.23
	Tanzania					**Burundi**				
	Geita	**Kagera**	**Mwanza**	**Mbeya**	**Morogoro**	**Gitega**	**Kirundo**	**Muyinga**	**Ngozi**	**Ruyigi**
pr	0.03	-0.35	-0.18	0.29	0.24	0.24	-0.09	-0.13	0.07	0.07
tmp	0	0.55*	0.25	0.4	0.44	0.5*	0.5*	0.6*	0.5*	0.36
	Uganda									
	Iganga	**Jinja**	**Kaabong**	**Kamuli**	**Wakiso**					
pr	-0.21	-0.33	-0.35	-0.23	-0.21					
tmp	-0.11	0.1	-0.39	-0.03	0.3					

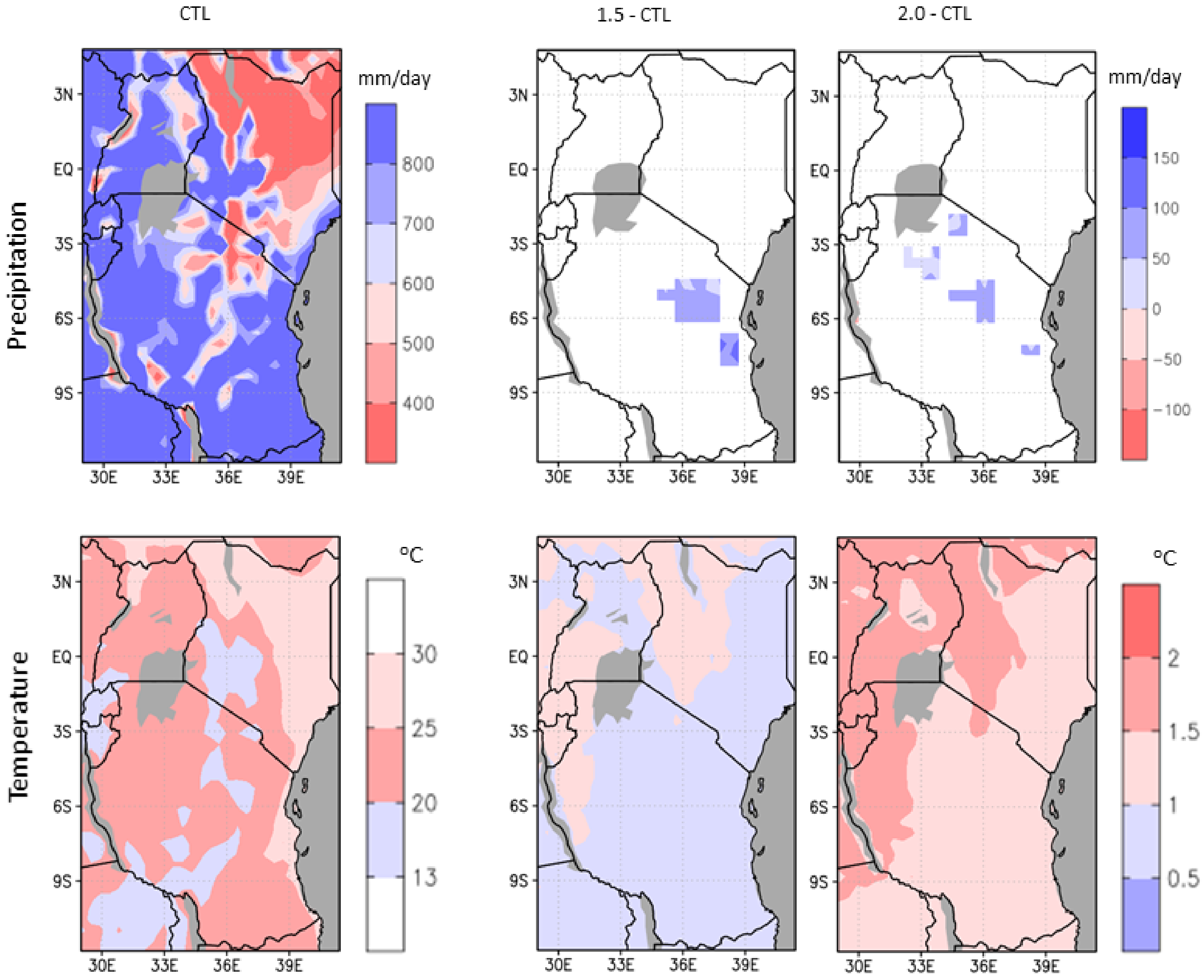

Figure 4. **Climatology and future changes (at 95% confidence interval) in precipitation (top row) and temperature (bottom row) thresholds under GWL1.5 and GWL2.0 scenarios relative to the control period (1977–2005). Water bodies are shown in grey.**

a temperature range within which maximum suitability (20–25 °C) for malaria vectors occurs. Below/above the 20–25 °C threshold (shown in white), the suitability for malaria vector abundance decreases towards none. Under GWL1.5, the study domain records a temperature change ranging from 0.5 to 1.5 °C potentially increasing the portion of E. Africa recording the maximum suitability threshold for malaria vector abundance. This is particularly true for many areas in Burundi, Rwanda, and central Kenya (Central and Nairobi provinces) where clinical malaria cases are currently relatively low. A mean temperature increase of between 1–2 °C is expected over the study domain under the GWL2.0. The temperature increase is likely to affect many parts of western Kenya and Tanzania, most of Rwanda, Burundi, and Uganda hence potentially increasing the area recording the maximum suitability threshold (20–25 °C) for malaria vectors in E. Africa. Our results are consistent with findings from similar studies done over the study domain (e.g. Gudoshava *et al*., 2020; Osima *et al*., 2018; Ogega *et al*. 2020).

Global warming is likely to increase the seasons and geographical extents for malaria transmission resulting in more cases and newer malaria hotspots (e.g. Ebi *et al*., 2018; Himeidan & Kweka, 2012; Karungu *et al*., 2019; Peterson, 2009). While big investments have been made towards eliminating malaria in E. Africa, sustaining the gains made so far remains a big challenge (Bashir *et al*., 2019; Nkumama *et al*., 2017). The current study establishes that, despite the ongoing interventions in E. Africa, climatic factors still influence the number of clinical malaria cases. A warming globe is likely to make it difficult to sustain gains made and slow down the match towards malaria elimination in E. Africa.

Conclusions

Global warming scenarios of 1.5 °C and 2 °C are likely to increase malaria transmission seasons and geographical extents of malaria transmission in E. Africa. Unless interventions are sufficiently intensified, sustaining the gains made towards malaria elimination is likely to be more difficult in a warming climate. Hence, the global community should intensify its collective efforts towards minimizing global warming. Meanwhile, more investment should be made to sustain the gains made and hasten the match towards malaria elimination in E. Africa. More research (considering other variables such as altitude, humidity, and vulnerability of communities) is also required to enhance the understanding of spatial and temporal impacts of global warming on malaria transmission in E. Africa. Specifically, disease modelling is required to project the new exposed population which will inform future malaria eradication efforts.

Data availability

Source data

CORDEX-Africa RCM simulations (files listed in Table 1) were downloaded free of charge from the Deutsches Klimarechenzentrum (DKRZ) accessible at http://bit.ly/2RoIist. To download the data, one needs to create a user account after which data can be downloaded freely for non-commercial use. Gridded mean surface air temperature data (CRU TS v. 4.04) were obtained from the Climatic Research Unit, University of East Anglia and accessed free of charge at https://crudata.uea.ac.uk/cru/data/hrg/. Gridded daily precipitation data (CHIRPS Daily v. 2.0) were obtained from the Climate Hazards Center, University of California, Santa Barbra. The data were freely downloaded from https://bit.ly/3buFCj8. Data on clinical malaria cases for Uganda, Kenya, Burundi, Rwanda, and Tanzania were downloaded (in .csv format) free of charge from the Malaria Atlas Project accessible at https://malariaatlas.org/data-directory/.

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? **Masilin Gudoshava**
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- In the introduction section paragraph 2, the authors discuss that there have been some studies done towards understanding the impact of climate over the region at the different GWL and state that there are no conclusive literature on the impact. Did this statement mean to say no conclusive literature on impacts in sectors such as health, agriculture water etc?
- Methods Climate Modelling paragraph 1: A statement explaining why the authors only chose RCP85 scenario is required in this case as the different scenarios can have differing impacts.
- Table 1 indicates that data was downloaded from 2071-2100 however this is not the same time period that was analyzed. This is a typo that needs to be corrected.
- In paragraph 2 of the data analysis section the authors state that 2022 and 2037 have been identified as mid-years for 30-year windows when GWL1.5 and GWL2.0, respectively, are likely to be first experienced. However different GCMs hit these levels at different times, is it the assumption in this manuscript that both these GCMs will reach the GWL at the same time? I would suggest that the authors rework on this and use the GWL for the different GCMS.
- The malaria temperature survival has two different threshold values (13-30 ^{o} C) in one section and in another section it is written as 15-30 ^{o} C. Double check this.
- Trends in temperature, precipitation, and clinical malaria cases in E. Africa paragraph graph two: an explanation on why malaria clinical cases and temperature are negatively correlated over Uganda is needed here, since in all the other countries the correlation is positive.
- Trends in temperature, precipitation, and clinical malaria cases in E. Africa paragraph three: could the negative correlations be caused by the washing away of the eggs due to high

rainfall rather than intensification of efforts to combat malaria?

- Figure 3: The line plots do not show any obvious relationships between the malaria clinical cases and the temperature/rainfall - could this be because people are taking preventive measures? Is it possible to obtain the actual vector data and do the analysis using this rather than the clinical cases?
- Figure 4: The caption seems incorrect, I would not expect rainfall of up to 700mm/day in any season over East Africa, also in the write-up it is written mm/year.
- A discussion on the large scale drivers and malaria cases could be helpful in explaining any likely changes in the future of the reported clinical cases.

Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and is the work technically sound?
Partly

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Yes

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: climate science

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.