Impact of 1.5 °C and 2 °C global warming scenarios on malaria transmission in East Africa [version 1; peer review: 2 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 °C and 2.0 °C 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 °C and 1.5 °C and 1.0 °C to 2.0 °C 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.
**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 (Mettelmann 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).

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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).
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 (MAP) obtains, curates, and shares a variety of maliometric 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; Mohammadkian 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 mosquitoes, precipitation threshold for Anopheles mosquitoes, 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 °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 2.2.1.0.1). 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.

Table 1. CORDEX-Africa RCM runs used in the current study, downloaded in April 2020 from the Deutsches Klimarechenzentrum (DKRZ), 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 |
| | | | r1i1p1 | CNRM-CERFACS-CNRM-CM5 |

The terms in the table can be used to search for the required data files.
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 1).

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).
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                  | Tanzania              | Burundi             | Uganda         |
|---------|------------------------|------------------------|-----------------------|--------------------|----------------|
|         | pr  | Busia | 0.01 | Kisumu | 0.14 | Siaya | 0.19 | Kakamega | -0.13 | Bungoma | -0.31 | Kigali | -0.3 | North | -0.1 | South | -0.2 | East | -0.1 | West |
|         | tmp | 0.19 | 0.23 | 0.07 | 0.23 | 0.23 | 0.23 | 0.4 | 0.2 | 0.3 | 0.4 | 0.4 | 0.23 |
|         |      |      |      |      |      |      |      |      |      |      |      |      |      |
|         | pr  | Geita | 0.03 | Kagera | -0.35 | Mwanza | -0.18 | Mbeya | 0.29 | Morogoro | 0.24 | Gitega | 0.24 | Kirundo | -0.09 | Muyinga | -0.13 | Ngozi | 0.07 | Ruyigi | 0.07 |
|         | tmp | 0.05 | 0.55 | 0.25 | 0.4 | 0.4 | 0.44 | 0.5 | 0.5 | 0.6 | 0.5 | 0.36 |
|         | pr  | Iganga | -0.21 | Jinja | -0.33 | Kaabong | -0.35 | Kamuli | -0.23 | Wakiso | -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.
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/2R0tli. 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/brg/. Gridded daily precipitation data (CHIRPS Daily v. 2.0) were obtained from the Climate Hazards Center, University of California, Santa Barbara. The data were freely downloaded from https://bit.ly/3b1FCC8. 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/.

Acknowledgements

Both authors are employees of the African Academy of Sciences.

The authors wish to thank colleagues at the African Academy of Sciences (AAS) for their insights that helped shape this paper. Contribution of various modelling groups participating in CORDEX as outlined in Table 1 (as well CHIRPS, CRU, and MAP data) are acknowledged for making the data publicly available. Further, the lead author thanks his Ph.D research supervisors and collaborators (Prof. James Kung’u, Dr. James Koske, Dr. Benjamin Gyampoh, and Dr. Malcolm M. Mistry) for their guidance and support towards the realization of this publication. Statements made and errors, if any, are those of the authors and not the institutions they represent.

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Reference Source
Open Peer Review

Current Peer Review Status:  

**Version 1**

Reviewer Report 23 September 2020

https://doi.org/10.21956/aasopenres.14170.r27822

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- The study has used 20-25°C as thresholds of temperature within which maximum suitability for survival of Anopheles mosquitoes is achieved. What is the basis of selecting this range? This requires clarification. Further, instead of selecting the range for survival of mosquitoes, the threshold for transmission of malaria (sporogony) would have been ideal as the present communication deals with future scenario of malaria and not the anopheles vector. Mosquitoes are known to survive even at lower than 13°C temperature also (IPCC, 2001). The temperature between 18-32°C is considered suitable for transmission of malaria (Craig *et al.*, 1999). Further Mordecai *et al.* (2013) found that the upper threshold is 28°C, bit lower than 32°C.

- In the study, the threshold of rainfall has been taken of Aedes mosquitoes. Anopheles and Aedes mosquitoes are quite different in their ecology, biology and climatic requirements. Therefore, using the thresholds of rainfall meant for Aedes, does not seem appropriate for Anopheles.

- The authors are advised to consult Craig *et al.* (1999) on a climate-based distribution model of malaria in SS Africa where 80 mm rainfall has been considered as the threshold of rainfall causing outbreaks of malaria.

- Using only RCP 8.5 of climate model does not seem appropriate; RCP 4.5 being moderate, would have been ideal.

- Relevance of Fig 2 is not clear.

- Fig 3: Analysis with annual precipitation data is not desirable for a climate-sensitive disease like malaria. The significance of depicting water bodies is not clear.

- Page 6, last paragraph: ‘In terms of temperature, all areas in the study domain record temperatures within suitability threshold (13-30°C) for malaria vectors’ is not appropriate as
at lower than 18°C temperature, transmission is not possible as the mosquitoes would require 56 days to complete sporogony (Craig et al., 1999).

- The authors have undertaken painstaking efforts in analyzing the projected scenario of malaria in view of projected rise in temperature. The objective of the study is also very pertinent. But owing to methodological issues stated above, reanalysis of data is required.

**References**

1. Craig M, Snow R, le Sueur D: A Climate-based Distribution Model of Malaria Transmission in Sub-Saharan Africa. *Parasitology Today*. 1999; 15 (3): 105-111 Publisher Full Text
2. Mordecai EA, Paaijmans KP, Johnson LR, Balzer C, et al.: Optimal temperature for malaria transmission is dramatically lower than previously predicted. *Ecol Lett.* 2013; 16 (1): 22-30 PubMed Abstract | Publisher Full Text

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

Yes

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

No

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

Yes

**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?**

No

**Competing Interests:** No competing interests were disclosed.

**Reviewer Expertise:** Epidemiology and vector control of vector borne diseases. Climate change impacts on VBDs. Early warning of outbreaks of malaria and dengue using climate and satellite data.

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.

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**Author Response 17 Oct 2020**

**Obed Matundura Ogega**, The African Academy of Sciences, Nairobi, Kenya
The authors are very grateful for the Reviewers’ comments. The comments and suggestions have been very useful during the revision process and have been incorporated into the revised manuscript. We believe the quality of the revised manuscript has been improved significantly. The specific actions in response to the reviewers’ comments are outlined as follows.

**Reviewer #2:**

Comment: The study has used 20-250°C as thresholds of temperature within which maximum suitability for survival of Anopheles mosquitoes is achieved. What is the basis of selecting this range? This requires clarification. Further, instead of selecting the range for survival of mosquitoes, the threshold for transmission of malaria (sporogony) would have been ideal as the present communication deals with future scenario of malaria and not the anopheles vector. Mosquitoes are known to survive even at lower than 130°C temperature also (IPCC, 2001). The temperature between 18-320°C is considered suitable for transmission of malaria (Craig et al., 1999). Further Mordecai et al. (2013) found that the upper threshold is 280°C, bit lower than 320°C.

*Response:* This is well-noted. The 20-25°C is the range within which the mosquito abundance increases to maximum. However, we have revised our manuscript to focus on malaria transmission and not mosquito survival (see lines 143 – 146).

Comment: In the study, the threshold of rainfall has been taken of Aedes mosquitoes. Anopheles and Aedes mosquitoes are quite different in their ecology, biology and climatic requirements. Therefore, using the thresholds of rainfall meant for Aedes, does not seem appropriate for Anopheles.

*Response:* We have revised the section on rainfall to focus on malaria transmission rather than Aedes mosquitoes (see lines 136-146).

Comment: The authors are advised to consult Craig et al. (1999) on a climate-based distribution model of malaria in SS Africa where 80 mm rainfall has been considered as the threshold of rainfall causing outbreaks of malaria.

*Response:* This has been revised. We now discuss precipitation patterns in general without referring to specific thresholds (e.g. lines 136-143).

Comment: Using only RCP 8.5 of climate model does not seem appropriate; RCP 4.5 being moderate, would have been ideal.

*Response:* Considering the current global greenhouse emission scenarios, RCP 8.5 gives a more realistic representation of global warming scenario compared to the RCP 4.5. Additionally, more simulations are available for RCP 8.5 compared to RCP 4.5. This explanation has now been given in lines 40-44.

Comment: Relevance of Fig 2 is not clear.
Response: Fig. 2 has been discarded and its details included in the narrative (see lines 127-131).

Comment: Fig 3: Analysis with annual precipitation data is not desirable for a climate-sensitive disease like malaria. The significance of depicting water bodies is not clear.

Response: Fig. 3 has been revised to exclude the spatial plots. We computed and compared year-to-year standardized anomalies for precipitation, temperature, and clinical malaria cases to show a general relationship in trend behaviour for the three variables. Standardized anomalies free data from location and distribution influences hence giving a more realistic trend. While malaria prevention efforts are designed to counter the potential effect of weather and climate in malaria transmission, we wanted to show if any discernible relationships still exist between climatic factors (malaria and temperature) and annual clinical cases. We showed major water bodies (Lake Victoria and Indian Ocean) in grey to focus the analysis only on land.

Comment: Page 6, last paragraph: ‘In terms of temperature, all areas in the study domain record temperatures within suitability threshold (13-300C) for malaria vectors’ is not appropriate as at lower than 18 0C temperature, transmission is not possible as the mosquitoes would require 56 days to complete sporogony (Craig et al., 19991).

Response: The manuscript has been revised accordingly (e.g. lines 137-141).

Comment: The authors have undertaken painstaking efforts in analyzing the projected scenario of malaria in view of projected rise in temperature. The objective of the study is also very pertinent. But owing to methodological issues stated above, reanalysis of data is required.

Response: We appreciate your comments and have made the suggested revisions to make the current version of the manuscript more plausible.

Comment: Additional references
1. Craig M, Snow R, le Sueur D: A Climate-based Distribution Model of Malaria Transmission in Sub-Saharan Africa. Parasitology Today. 1999; 15 (3): 105-111 Publisher Full Text
2. Mordecai EA, Paaijmans KP, Johnson LR, Balzer C, et al.: Optimal temperature for malaria transmission is dramatically lower than previously predicted. Ecol Lett. 2013; 16 (1): 22-30 PubMed Abstract | Publisher Full Text

Response: We are grateful for these suggestions – which have now been used to enrich the manuscript.

Competing Interests: No competing interests were disclosed.

Reviewer Report 10 August 2020
https://doi.org/10.21956/aasopenres.14170.r27675
Masilin Gudoshava
National University of Science and Technology, Bulawayo, Zimbabwe

- 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 °C) in one section and in another section it is written as 15-30 °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.

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**Author Response 17 Oct 2020**

**Obed Matundura Ogega,** The African Academy of Sciences, Nairobi, Kenya

The authors are very grateful for the Reviewers’ comments. The comments and suggestions have been very useful during the revision process and have been incorporated into the revised manuscript. We believe the quality of the revised manuscript has been improved significantly. The specific actions in response to the reviewers’ comments are outlined as follows.

**Reviewer #1:**  
Comment: 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.?

Response: Indeed, we meant to say impacts on the health sector. This has been corrected (see line 22).
Comment: 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.

Response: An explanation has now been given in lines 40-44.

Comment: 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.

Response: Now revised to show 2008-2052 (see line 51).

Comment: 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.

Response: It is indeed true that different GCMs hit the said levels at different times. Years 2022 and 2037 represent values for an ensemble mean of the subset of GCM simulations used in CORDEX. Our analysis used an ensemble mean of these CORDEX GCM simulations. The section has been revised for coherence (see lines 86-97).

Comment: 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.

Response: This has been revised (in both cases) to 18 – 28 °C (see e.g. lines 132-134).

Comment: 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.

Response: We have provided more information in lines 172-184.

Comment: 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?

Response: Egg flushing can indeed be a possibility. However, no major rainfall changes have been recorded during the period under study. Rainfall has mostly remained within the normal range (as shown in Figure 2). As detailed in lines 172-184 of the revised manuscript, the relatively low/high correlation between malaria cases and climatic factors in Uganda/Burundi result from case and vector control investment.

Comment: 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?

*Response:* Please refer to our response in 7 above. The use of actual vector data is out of the scope of the current study. We have recommended a further study (see lines 231-235) where such data can be obtained and used.

Comment: 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.

*Response:* This has been corrected (see Figure 3).

Comment: 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.

*Response:* Thank you for this suggestion. We have provided more information in lines 218-233.

**Competing Interests:** No competing interests were disclosed.