Global malaria infection risk from climate change

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Summary

Background:

As a long-standing public health issue, malaria still severely hits many parts of this world, especially Africa. With greenhouse gas emissions, temperatures keep rising. We aim to quantify the impacts of climate change on the malaria infection rate in all epidemic regions and identify the most vulnerable areas.

Methods:

We estimate the coefficients of relationships among variables by geographically weighted panel regression. Four scenarios based on diverse shared socio-economic pathways (SSPs) are employed, including SSP1-2.6, SSP2-4.6, SSP3-7.0, and SSP5-8.5. We estimate the differences between the predicted $PfPR_{2-10}$ globally under different SSP scenarios during several periods and malaria infection case changes due to those differences.

Findings:

The globally malaria infection case changes (IICs) from SSP1-2.6 to SSP2-4.5, to SSP3-7.0, and to SSP5-8.5 are 6.506 (95% uncertainty interal [UI] 6.150 – 6.861) million, 3.655 (3.416 – 3.894) million, and 2.823 (2.635 – 3.012) million during 2021 – 2040, respectively, which are 2.699%, 1.517%, and 1.171% increase, compared with 241 million infection cases in 2020. During 2081 – 2100, the IICs of three scenario shifts are -79.109 (-83.626 - -74.591) million, -238.337 (-251.920 - -0.141) million, and -162.692 (-174.628

- -150.757), which are -32.825%, -98.895%, and -67.507% increase. Moreover, the temperature increase adversely affects malaria the most in Africa during 2021 – 2040.

Interpretation:

Climate change would increase the danger and risk of malaria in the most vulnerable regions in the near term, which aggravates the difficulty of eliminating malaria. GHG emissions reduction is a potential pathway to protect people from malaria.

Funding:

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Keywords:

Malaria; Climate change; SSPs;

Research in context

Evidence before the study

Existing evidence suggests that temperature affects malaria transmission and the relationship between them is non-linear. We searched PubMed and Google Scholar for published literature on malaria-temperature relations and public health impacts of climate change on malaria globally, using the search terms “climate change”, “malaria”, “temperature”, “global”, on March 2nd, 2022. There are many publications on the relationship between climatic factors and malaria in some countries or regions, but there are no studies that have estimated and predicted the global pattern of malaria infection in the future based on diverse greenhouse gas emission scenarios.

Added value of this study

This study provides the global difference in malaria infection rates between different greenhouse gas emission scenarios in three periods. It estimates the relationship between temperature and malaria at the grid level. The findings in this paper underscore that climate change aggravates malaria transmission in the near term, whereas it alleviates the malaria situation in the medium and long terms. However, the cost of this alleviation is the unlivable environment, especially in Africa. The wide variations in temperature impact on malaria infection can be useful to identify the most vulnerable areas.

Implications of all the available evidence

Climate change has more negative effects on malaria infection in the most vulnerable regions, namely Africa, in the near term. These negative impacts could impede the world health organization's plan to eliminate malaria in most epidemic countries by 2030. Furthermore, although temperature plays a positive role in malaria prevention in most other countries, a gradual increase in temperature would further aggravate malaria transmission in some countries in the medium and long terms. Those countries may be hit severely unless their malaria issue is addressed as a priority.

Introduction

In many parts of this world, especially Sub-Sahara Africa, malaria transmission is high during 2000 – 2019 [1,2]. The World Health Organization (WHO) estimates over 241 million infection cases in 85 countries and 627,000 malaria deaths in 2020, despite various successful malaria control interventions in the past 20 years [1,2]. To achieve Sustainable Development Goals, the WHO sets a series of ambitious aims, including reducing at least 90% malaria case incidence globally compared with 2015 and eliminating malaria in at least 35 malaria-epidemic countries in 2015 [2]. In 2019, the *Plasmodium falciparum* parasite rate in 2-10 olds ($PfPR_{2-10}$) is still over 60% in many Sub-Sahara African regions, as shown by estimated data [1]. In this way, even without the interference of other factors, it is difficult for the WHO to complete its assignments.

Climate change is considered to alter the global pattern of malaria infection rates [3-6]. Climate change influences a variety of environmental factors, including temperature, humidity, precipitation, and causes a wide range of extreme weather events and climate change. Climate change affects malaria transmission [7] because malaria is a vector-borne infectious disease, and the environment impacts the vector, such as mosquitos and other insects. Evidence suggests that the relationship between temperature and malaria transmission by mosquitos is non-linear [8,9]. The malaria transmission increases with temperature, peaks at a specific temperature, and then decreases [8]. Therefore, climate change might aggravate malaria transmission in the near term and alleviate it in the long term if the global temperature keeps increasing. The greenhouse gas (GHG) emission is the main factor associated with climate change and the economy. The Intergovernmental Panel on Climate Change (IPCC) relies on the Coupled Model Intercomparison Projects

(CMIP) to predict the future temperature in three periods based on several future emission scenarios [10]. In 2021, the IPCC sixth assessment report (AR6) is released. In the IPCC AR6, updated emission scenarios are derived from different socio-economic assumptions, called the Shared Socioeconomic Pathways (SSPs) [10,11]. Among several SSPs, four scenarios are well-researched, including SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. From SSP1-2.6 to SSP5-8.5, the GHG emission reduction gradually becomes less, and the temperature increases more [10]. The SSP1-2.6 scenario predicts that temperature increase stabilizes about 1.8℃ by the end of the century, whereas in the SSP5-8.5 scenario, the temperatures grow 4.4℃ or higher by 2100. According to different scenarios, in different periods, including the near term (2021 – 2040), the medium term (2041 – 2060), and the long term (2081 – 2100), the effects of temperature on malaria are diverse. This article presents the global difference in malaria infection rates between different temperature scenarios in three periods.

There is a major need to grasp the temperature impacts on shaping the epidemiological pattern. This study aims to quantify the impacts of climate change on malaria infection rate in all epidemic regions, estimate the potential malaria infection case change due to the temperature increase, and identify the most vulnerable areas due to climate change.

Methods

Estimation of Impacts of Temperatures on $PfPR_{2\text{-}10}$

Global $PfPR_{2\text{-}10}$ grid data set with the 5-km resolution from 2000 to 2019 is reported elsewhere [1]. A detailed description of the geographically weighted panel regression (GWPR) model for estimating the impacts of temperatures on $PfPR_{2\text{-}10}$ is provided in the appendix.

Estimates of temperature-related data are derived from the monthly average temperature obtained from the United States National Aeronautics and Space Administration (NASA) Global Land Data Assimilation System Version 2 [12]. Three temperature-related variables are employed in the analysis, including annual average temperature, annual average temperature square, and standard deviation of monthly average temperature in a specific year. We used the annual average temperature and annual average temperature square because the relationship between malaria transmission by insect vectors and temperature is non-linear, and malaria incidence peaks around 25℃ in laboratory environments [3,8,9]. Extreme low and high temperatures are not suitable for transmission vector survival [8,13]. In this way, the standard deviation of monthly average temperature in a specific year also affects the $PfPR_{2\text{-}10}$. Besides, several other climatic factors, such as air pressure, absolute humidity, precipitation and wind speed, are considered. However, the correlations among these climatic variables are strong. To avoid multicollinearity in the regressions, we only keep the climatic variables interested, specifically temperature-related variables.

Our estimates of greenness are derived from the remotely sensed Normalized Difference Vegetation Index (NDVI). Vegetation and greenness affect malaria vector population size, survival, biting, among others [14]. The NDVI is the most widely used index to depict the quantity of local vegetation [15]. It is employed as a critical indicator for exposure to the natural environment in previous epidemiological studies [15,16]. We obtain the satellite data from the moderate-resolution imaging spectroradiomenter from NASA's Aqua and Terra satellites with a 0.05-arc-degree spatial resolution.

WorldPop project includes the global population distribution with a 1-km resolution, as described elsewhere [17,18]. Moreover, the GDP per capita obtained from the World Bank is used to estimate the public health investments, which is highly related to the malaria infection rate.

Estimation of Impacts of Climate Change on $PfPR_{2\text{-}10}$

We estimate the difference between the $PfPR_{2\text{-}10}$ globally under different climate change scenarios projected by IPCC during several periods, assuming all conditions are the same except temperature. Because the relationship between temperature and $PfPR_{2\text{-}10}$ is non-linear [8,9], the same increase in temperature under various situations would disproportionally affect $PfPR_{2\text{-}10}$. Furthermore, since GWPR is a spatially non-stationary model, the coefficients of the association of temperature with $PfPR_{2\text{-}10}$ spatially vary. Hence, our analysis could grasp the impact of climate change more accurately. Detailed information about the GWPR model and effect estimation is listed in the appendix.

The estimation of impacts of climate change on $PfPR_{2-10}$ is calculated as the difference of the $PfPR_{2-10}$ predictions under four well-known GHG emission scenarios, including SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 as described by the IPCC AR6 [10]. However, the $PfPR_{2-10}$ cannot be predicted directly based on our GWPR model since precisely predicting other variables involving NDVI, population, and GDP per capita in several future periods is difficult. The inaccuracy of other variables' predictions adversely affects $PfPR_{2-10}$ estimations under different scenarios. We assume that all conditions are the same except temperature to avert the influence of other variables' predictions. Although this assumption is irrational because the different SSPs lead to diverse population distribution and economic statuses, it is an effective way to probe and extract the impacts of climate change on $PfPR_{2-10}$. We mainly focus on the difference in the predicted $PfPR_{2-10}$ between SSP1-2.6 and another higher-temperature scenario. This difference is the cost of the increase in temperature. Detailed information is recorded in the appendix.

To further demonstrate the impacts of the temperature increase on malaria infection, we convert the potential difference of $PfPR_{2-10}$ caused by scenario shifts into the malaria infection case change. The IPCC predicts the population density based on diverse scenarios during several periods. We use predicted $PfPR_{2-10}$ difference data and population density to estimate the global change pattern of malaria infection cases attributed to GHG emission scenario shifts. Detailed information is reported in the appendix.

Results

During 2021 – 2040, the globally average difference of $PfPR_{2-10}$ between SSP2-4.6 and SSP1-2.6 is 0.164% (95% uncertainty interval [UI] 0.160% – 0.168%). This difference is associated with a 6.506 (6.150 – 6.861) million increase in malaria infection cases. Compared with the estimated infection case number, 241 million, that is a 2.699% increase. Across the continents, the average difference ranges from -0.076% (-0.063% – -0.090%) in Europe to 0.409% (0.400% - 0.418%) in Africa during 2021 – 2040 (**Table 1**). The globally average difference between SSP3-7.0 and SSP1-2.6 is 0.104% (0.101% - 0.107%), related to a 3.655 (3.416 – 3.894) million increase in malaria infection cases. It is a 1.517% increase based on the number of infection cases in 2020. The average difference of $PfPR_{2-10}$ between SSP3-7.0 and SSP1-2.6 becomes larger in Oceania and South America compared with the difference between SSP2-4.6 and SSP1-2.6, while in Africa, Asia, and Europe, the values tend to be smaller. North America has few grids in the analysis, so the impacts of the increase in temperature are marginal. The globally average difference between SSP5-8.5 and SSP1-2.6 is 0.041% (0.038% - 0.044%) in the near term, correlated with a 2.823 (2.635 – 3.012) million increase that equals a 1.171% increase according to the infection case number in 2020. It must be underscored that even though the difference between SSP5-8.5 and SSP1-2.6 in Africa is numerically smaller than the other two changes, the value is still positive. During 2021 – 2040, in Africa, the $PfPR_{2-10}$ would increase 0.139% (0.132% - 0.146%) following SSP5-8.5 compared with the scenario SSP1-2.6, while the values rise 0.409% (0.400% - 0.418%) and 0.258% (0.251% - 0.265%) under SSP2-4.5 and SSP3-7.0, respectively. To sum up, in the near term, the increase in temperature has negative impacts on malaria infection globally, and the most vulnerable region, Africa, might be hit worst by climate change. The places most affected by temperature often do not coincide with areas of high population density. For each continent, the average malaria infection case changes owing to the shift of development scenarios are different from the average difference of $PfPR_{2-10}$ (**Table 2**). During 2021-2040, the temperature increase affects the African epidemic region the most. On average, the malaria infection cases increase by 0.329 (0.312 – 0.347), 0.189 (0.178 – 0.201), and 0.147 (0.137 – 0.156) case/km^2, under the shifts from SSP1-2.6 to SSP2-4.5, to SSP3-7.0, and to SSP5-8.5, respectively.

Figure 1 demonstrates the national average difference between two different scenarios during 2021 – 2040. According to this figure, most African countries are adversely affected by the higher-temperature scenarios, including SSP2-4.5, SSP3-7.0, and SSP5-8.5. For example, the difference between SSP2-4.5 and SSP1-2.6 tops in Togo in the near term, which is 2.041% (1.873% - 2.208%). The situations in Burkina Faso and Ghana are slightly better, which are 2.020% (1.927% - 2.113%) and 1.693% (1.437% - 1.772%), respectively. Evidence shows that these three countries are hit most by malaria from 2000 to 2015 [1]. On the contrary, the relatively higher-temperature scenario in the near term has positive effects on the $PfPR_{2-10}$. Gabon and Equatorial Guinea are cases in point. In Gabon, the difference of $PfPR_{2-10}$ between SSP2-4.5 and SSP1-2.6 is -0.531% (-0.578% - -0.483%), and in Equatorial Guinea, it is -0.276% (-0.389% - -0.483%). As for the difference of $PfPR_{2-10}$ between SSP3-7.0 and SSP1-2.6, the value peaks in Burkina Faso, which is 1.391% (1.359% - 1.423%). The change from SSP3-7.0 to SSP1-2.6 still has the most positive impacts on the malaria in Gabon, -0.411% (-0.450% - -0.372%) and Equatorial Guinea, -0.406% (-0.502% - -0.310%). Additionally, in Togo, the difference of $PfPR_{2-10}$ between

SSP5-8.5 and SSP1-2.6 heads globally, which is 1.604% (1.439% - 1.772%). The situations in Burkina Faso and Ghana are a little better than Togo's, whose values are 1.592% (1.503% - 1.682%) and 1.301% (1.211% - 1.390%), respectively. On the other hand, in high latitude regions, including Mozambique and Zimbabwe, the effects of the change from SSP1-2.6 to SSP5-8.5 on $PfPR_{2\text{-}10}$ are positive. In Mozambique, the difference between SSP5-8.5 and SSP1-2.6 is -0.530% (-0.553% - -0.507%), and in Zimbabwe, the value is -0.379% (-0.403% - -0.354%), respectively.

During 2041 – 2060, the global average differences of $PfPR_{2\text{-}10}$ between SSP2-4.5 and SSP1-2.6, between SSP3-7.0 and SSP1-2.6, and between SSP5-8.5 and SSP1-2.6 are -0.181% (-0.185% - -0.177%), -0.482% (-0.493% - -0.472%), and -0.730% (-0.762% - -0.730%). These differences are associated with -7.541 (-7.968 - -7.115) million, -24.892 (-26.264 - -23.520) million, and -26.164 (-27.761 – -24.568) million infection case changes, which is -3.129%, -10.329%, and -10.857%, compared to infection case number in 2020. In all continents, the change from low-temperature to higher-temperature scenarios positively affects $PfPR_{2\text{-}10}$ (**Tables 1** and **2**). The difference of $PfPR_{2\text{-}10}$ between SSP2-4.5 and SSP1-2.6 in Africa, Asia, Oceania, and South America in the medium term becomes minus, while those values in the near term are positive. This indicates that the effect of temperature on $PfPR_{2\text{-}10}$ has gone beyond the turning point in most areas [8]. The increase in temperature leads to a potential decrease in malaria infection due to unsuitable environments for the malaria vectors [13]. Even though, in most regions, a higher-temperature scenario is associated with a lower $PfPR_{2\text{-}10}$, the increase in temperature adversely affects $PfPR_{2\text{-}10}$ in some countries (**Figure 2**). For example, the difference of $PfPR_{2\text{-}10}$ between SSP2-4.5 and SSP1-2.6 in Gabon is 0.926% (0.837% - 1.014%). In terms of malaria infection reduction, Mozambique still benefits most from the scenario change from SSP1-2.6 to SSP2-4.5, whose value is -1.924% (-1.970% - 1.878%). It must be noted that the increase in temperature positively impacts the countries worst hit by malaria, such as Burkina Faso and Togo, in the medium term.

In the long term, the global average differences of $PfPR_{2-10}$ between SSP2-4.5 and SSP1-2.6, between SSP3-7.0 and SSP1-2.6, and between SSP5-8.5 and SSP1-2.6 are -1.287% (-1.315% - -1.260%), -3.036% (-3.105% - -2.967%), and -4.096% (-4.190% - -4.002%). These differences are related to -79.109 (-83.626 - -74.591) million, -238.337 (-251.920 - -224.754) million, and -162.693 (-174.628 – -150.757) million infection case changes, which is -32.825%, -98.895%, and -67.507%, according to infection case number in 2020. Apparently, because in most areas, the temperature has gone beyond the turning point of the effects of temperature increase on $PfPR_{2-10}$, the positive impacts of the temperature increase would rise (**Table 1** and **2**). In this case, the positive impacts of temperature increase on $PfPR_{2-10}$ peaks under SSP5-8.5 during 2081 – 2100. However, it must be emphasized that even though, on average, the whole world benefits from the high temperature, some countries suffer more. For instance, in Gabon, the difference of $PfPR_{2-10}$ between SSP2-4.5 and SSP1-2.6 arrives at 4.991% (4.346% - 5.636%), the difference between SSP3-7.0 and SSP1-2.6 reaches 9.317% (7.554% - 11.080%), and the difference between SSP5-8.5 and SSP1-2.6 end up to 10.701% (8.092% - 13.309%).

Figure 4 illustrates the grid-level malaria infection case changes of three scenario shifts during three periods. The spatial distribution briefly shows that the epidemics in the Sub-Sahara African countries are the most sensitive to climate change. There are two reasons for this sensitivity. Firstly, the coefficients of the relationship between temperature and $PfPR_{2\text{-}10}$ are numerically larger in Africa. Secondly, with climate change, the temperature in Africa rises the most. In the medium and long terms, seemingly, the reduction of $PfPR_{2\text{-}10}$ in Africa benefits from the higher-temperature scenarios, but this benefit should be treated carefully because of the nothing-else-different assumption.

Discussion

The GWPR model on the 0.25-arc-degree grid-level analysis leads to a robust and accurate estimate of the impacts of climate change on $PfPR_{2\text{-}10}$. The accuracy of the GWPR model is 94.75%. In the 10-fold cross validation, the goodness of fit of every single fold is over 94%, indicating high robustness. Detailed information about cross validation is reported in the appendix. The main contributors to the accurate estimates in our analysis are the $PfPR_{2\text{-}10}$ data disclosure by the malaria atlas project [1], the climatic data provision by NASA [12], and the non-linear relationship between malaria infection rate and temperature with the availability of recent evidence [3,8,9]. Based on the highly accurate model, the influence of the temperature scenario changes can be isolated and extracted. In the near term, a substantial increase in temperature leads to a higher $PfPR_{2\text{-}10}$, especially in the most vulnerable region, namely Africa. However, in the medium and long terms, a further temperature rise ameliorates $PfPR_{2\text{-}10}$ drastically.

Extremely high temperature is definitely not an effective and efficient way to control malaria. At least, the by-product of climate change is not. Biologically, extremely high temperature is not a suitable environment for the arbovirus vectors' survival and propagation [19]. Therefore, extremely high temperatures curb the malaria infection rate on the surface. However, high temperatures' effects on human health are also severely adverse. Firstly, various diseases, such as cardiovascular disease [20], mental disease [21] and other non-transmissible diseases, are linked with hot temperature. Evidence shows that globally, 0.54% of death is attributable to high temperature in 2019 [22]. In the SSP5-8.5 scenarios, by 2100, the annual average temperature in Africa will exceed 27℃, and the average temperature in summer will be around 30℃. Obviously, in that case, most areas in Africa are not livable. Secondly, agriculture will also be hit by extreme weather [23]. In Africa, hunger is still a critical issue [24]. An increase in temperature will directly plunge local food production. More people there will suffer from hunger, and more children will be stunted [24]. Thirdly, natural environments will also be adversely affected. Anthropogenic climate change has caused more than 5-million-km^2 desertification from 1982 to 2015, and African countries are affected the most [25]. Furthermore, biodiversity and sustainability will slash, which might induce other transmissible epidemics except vector-borne diseases, like Coronavirus Disease 2019 [26]. In the medium and long terms, the high temperature might dwindle $PfPR_{2-10}$ globally, but we must treat this situation carefully because the negative impact of high temperature from other respects are unacceptable.

In the near term, the higher temperature scenarios, including SSP2-4.5, SSP3-7.0, and SSP5-8.5, would potentially elicit a $PfPR_{2-10}$ increase mainly in Africa. The WHO aims to reduce malaria case incidence by at least 90% by 2030 relative to the 2000 level and eliminate malaria in at least 35 countries by 2030 [2]. However, high temperature is a negative factor in this period. Although even in the most sustainable scenario, namely SSP1-2.6, the temperature will rise to the malaria-transmission peaking temperature, the efforts to achieve SSP1-2.6 delay the arrival of this peaking temperature. In other words, the efforts on climate change offer more time to organizations, mainly the WHO, to eliminate malaria. With no or limited malaria infections and enough prevention against re-establishment of malaria [2], it is impossible even though the temperature is ideal for the epidemic outbreaks. In this way, falling GHG emissions and curbing malaria incidence in the near term is the most reasonable and practical approach, rather than relying on the extremely high temperature.

Our study has several limitations. The difference in $PfPR_{2\text{-}10}$ between two scenarios is based on a strong assumption that except temperature-related variables, other conditions are the same under all scenarios. However, the societies, economic statuses would be diverse under different scenarios, according to the SSPs definition and the IPCC AR6 [10]. Although GHG emission reduction mainly influences the developed countries' population and economics, the malaria-epidemic developing countries will also be impacted to some degree. Moreover, greenness is associated with temperature [25,27]. High temperature causes desertification in the most vulnerable ecosystems, especially in Africa [25].

Our analysis assumes that the relationship between temperature and $PfPR_{2\text{-}10}$ is non-linear, according to previous evidence [8,9,13]. This non-linear association is the commonly used U-shape, though imperfect. However, in the real world, this relationship is more complex than our assumption. Furthermore, the temporal resolution is annual, which undercounts the short-term effects of temperature change, e.g., monthly or even real-time effects. Although we employ the yearly standard deviation of monthly temperature, the improvement is still marginal.

This study is also limited by gaps in the malaria control inventions data. We consider only one indicator, GDP per capita, to represent the ability of prevention because no information has been available on malaria control inventions in most non-African countries for a long time with a rational spatial resolution. Moreover, the GDP per capita data are country-level. Even though we take them into account, the heterogeneity within the countries is ignored. For this reason, unfortunately, we cannot estimate the economic loss of the impacts of an increase in temperature on malaria, which could be substantial.

In conclusion, climate change would increase the danger and risk of malaria in the most vulnerable regions in the near term. This study provides an impetus for policymakers to limit warming to a reasonable value. To achieve the ideal ending of malaria elimination, engaging civil societies and the public to reduce GHG emissions will be a potential possibility to help the people threatened by malaria. Because the malaria-transmission peaking temperature would come anyway in some regions, malaria elimination should be completed and prioritized there.

Declarations

Author contribution:

C.L. conducted the analyses and wrote the manuscript. S.M. conceived of the study and edited the manuscript. All authors reviewed the manuscript.

Ethics approval:

Not applicable.

Competing interests:

The authors declare no competing interests.

Role of the Funding Source

The funders had no role in the study design, data collection, data analysis, data interpretation, or writing of the report. The corresponding author had full access to all the data in the study and had final responsibility for the decision to submit for publication. All authors had access to the estimates presented in the paper.

Figure:

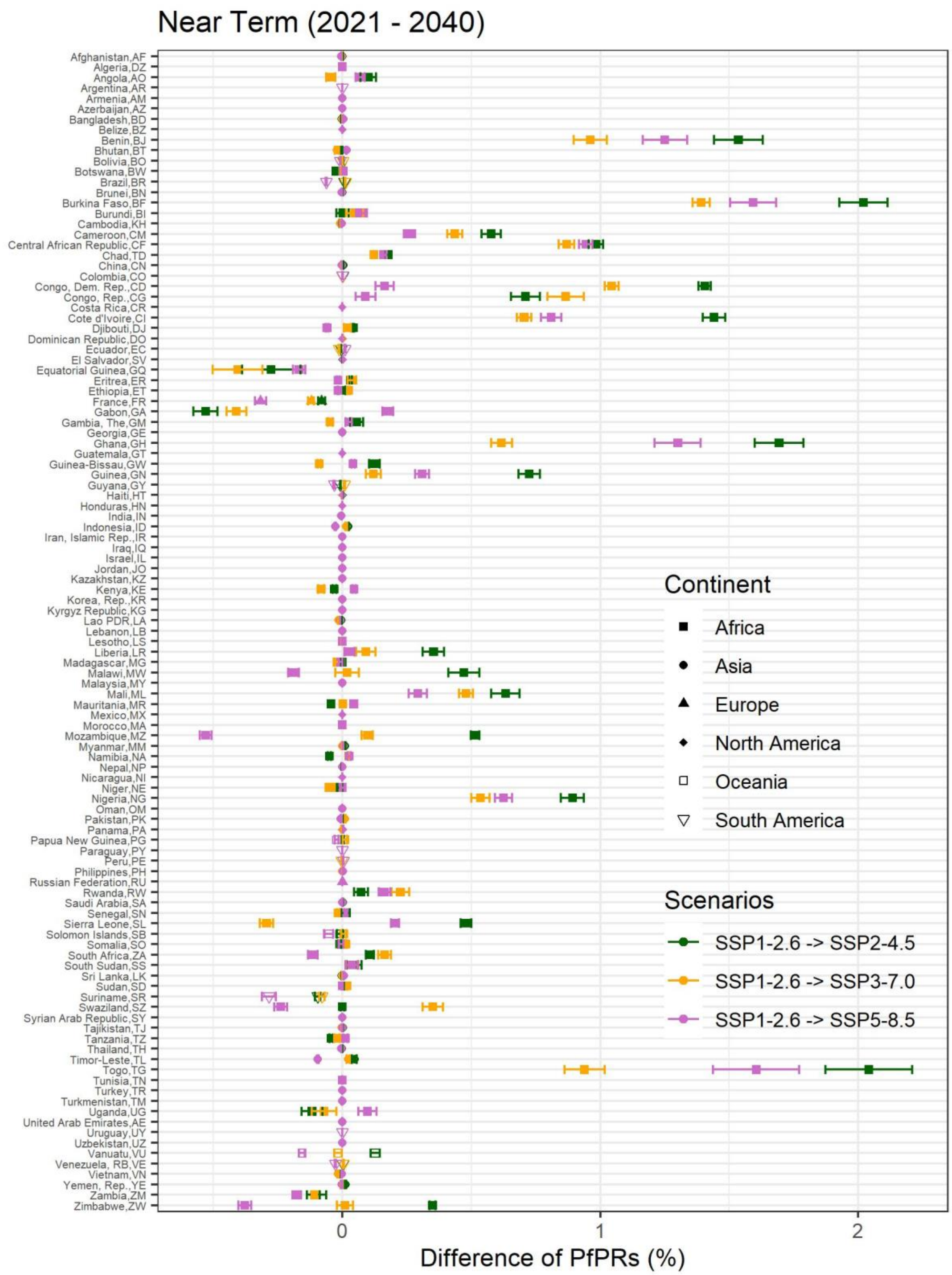


Figure 1: The Difference in $PfPR_{2-10}$ during 2021 – 2040

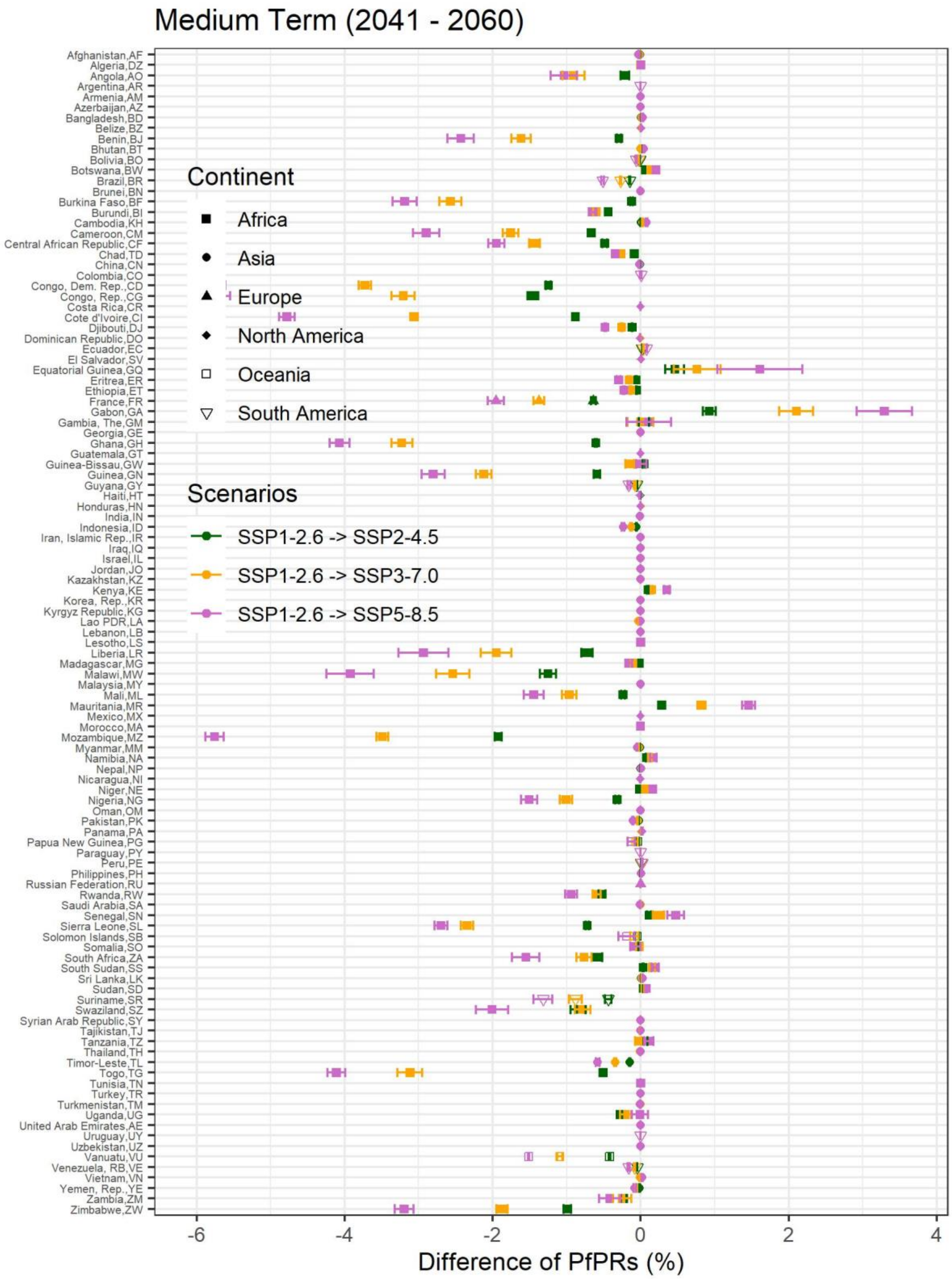


Figure 2: The Difference in $PfPR_{2-10}$ during 2041 – 2060

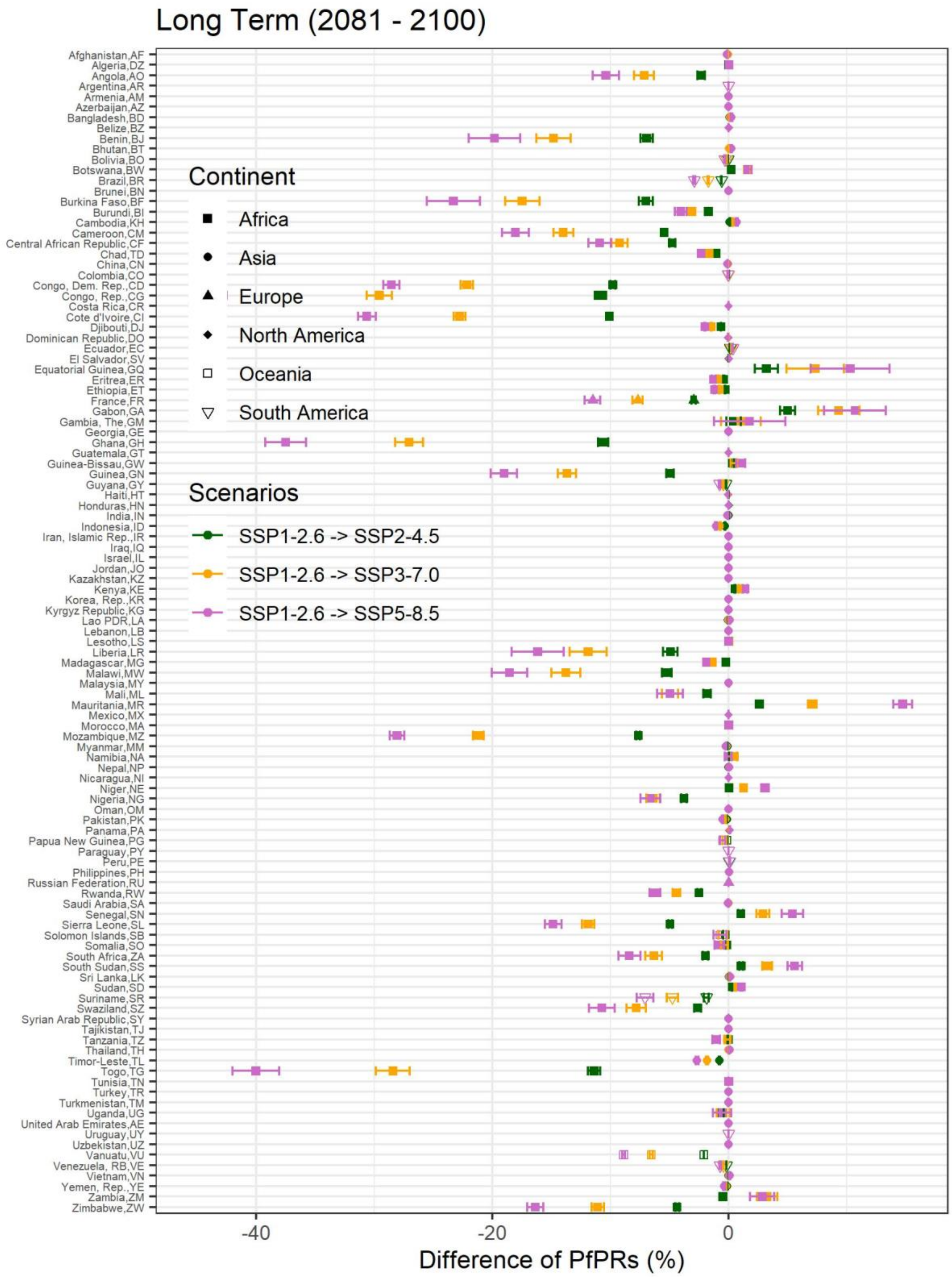
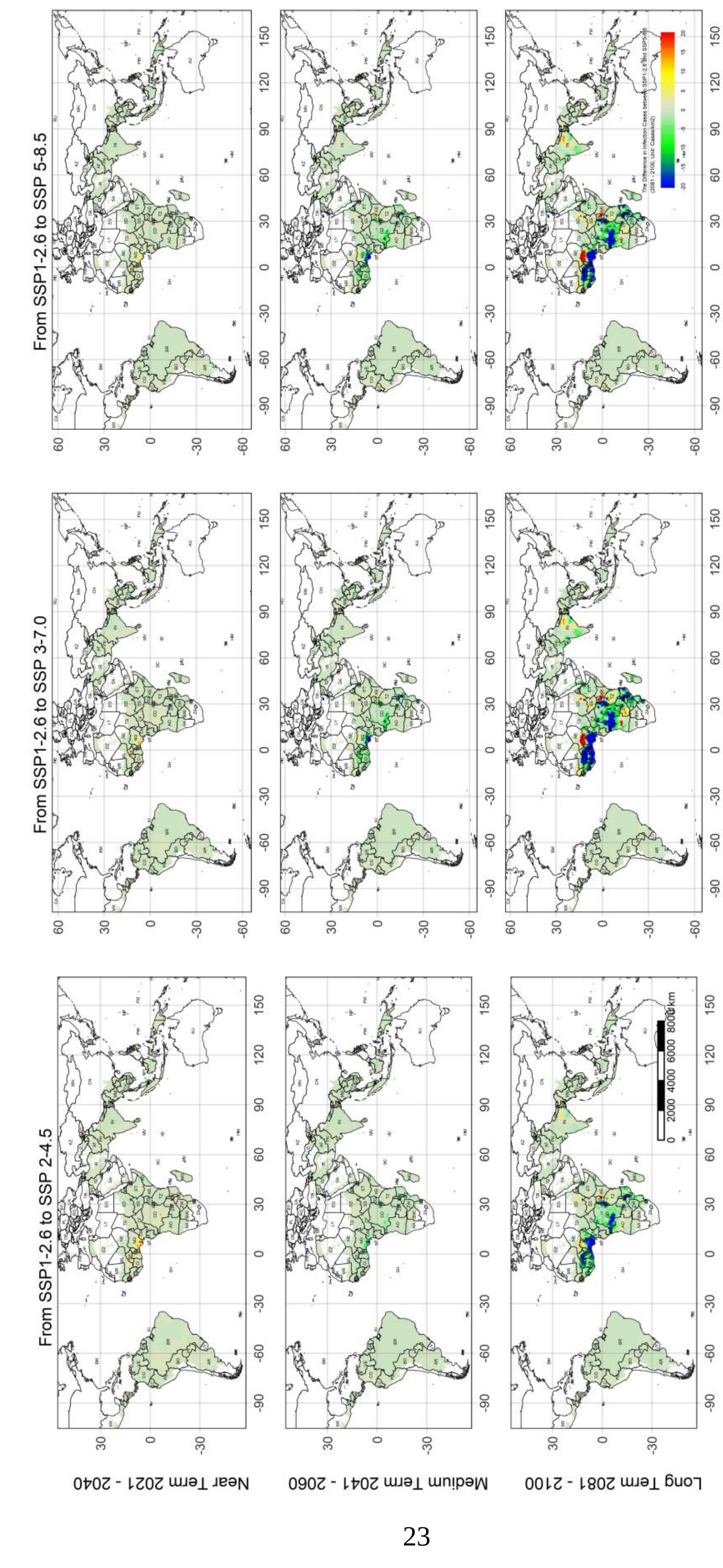


Figure 3: The Difference in $PfPR_{2-10}$ during 2081 – 2100



From SSP1-2.6 to SSP 2-4.5
From SSP1-2.6 to SSP 3-7.0
From SSP1-2.6 to SSP 5-8.5
Near Term 2021 - 2040
Medium Term 2041 - 2060
Long Term 2081 - 2100
0 2000 4000 6000 8000 km

Figure 4: The Grid-level Malaria Infection Case Changes of Three Scenario Shifts in Different Periods

Table:

Table 1: Average Difference in $PfPR_{2-10}$ between Two Scenarios

	Continent	From SSP1-2.6 to SSP 2-4.5	UI	From SSP1-2.6 to SSP 3-7.0	UI	From SSP1-2.6 to SSP 5-8.5	UI
2021 - 2040	Africa	0.409%	(0.400%-0.418%)	0.258%	(0.251%-0.265%)	0.139%	(0.132%-0.146%)
	Asia	0.003%	(0.002%-0.003%)	0.000%	(0.000%-0.001%)	-0.005%	(-0.006%--0.005%)
	Europe	-0.076%	(-0.090%--0.063%)	-0.115%	(-0.127%--0.103%)	-0.300%	(-0.324%--0.276%)
	North America	0.000%	(0.000%-0.000%)	0.000%	(0.000%-0.000%)	0.000%	(0.000%-0.000%)
	Oceania	0.002%	(-0.002%-0.007%)	0.009%	(0.001%-0.018%)	-0.023%	(-0.030%--0.017%)
	South America	0.003%	(0.003%-0.004%)	0.006%	(0.005%-0.007%)	-0.038%	(-0.039%--0.037%)
2041 - 2060	Africa	-0.376%	(-0.386%--0.366%)	-1.065%	(-1.089%--1.040%)	-1.601%	(-1.637%--1.564%)
	Asia	-0.013%	(-0.013%--0.012%)	-0.026%	(-0.027%--0.024%)	-0.043%	(-0.046%--0.041%)
	Europe	-0.605%	(-0.647%--0.563%)	-1.300%	(-1.390%--1.211%)	-1.850%	(-1.983%--1.716%)
	North America	0.000%	(0.000%-0.000%)	0.000%	(-0.001%-0.000%)	-0.001%	(-0.001%-0.000%)
	Oceania	-0.040%	(-0.053%--0.027%)	-0.070%	(-0.093%--0.046%)	-0.134%	(-0.183%--0.084%)
	South America	-0.086%	(-0.088%--0.083%)	-0.158%	(-0.163%--0.153%)	-0.299%	(-0.308%--0.290%)
2081 - 2100	Africa	-2.888%	(-2.952%--2.824%)	-6.696%	(-6.858%--6.534%)	-8.769%	(-8.989%--8.549%)
	Asia	-0.070%	(-0.074%--0.066%)	-0.147%	(-0.156%--0.138%)	-0.205%	(-0.219%--0.191%)
	Europe	-2.809%	(-3.020%--2.599%)	-7.284%	(-7.807%--6.761%)	-10.894%	(-11.686%--10.101%)
	North America	-0.001%	(-0.002%--0.001%)	-0.003%	(-0.004%--0.001%)	-0.005%	(-0.008%--0.003%)
	Oceania	-0.188%	(-0.257%--0.119%)	-0.378%	(-0.537%--0.220%)	-0.548%	(-0.784%--0.311%)
	South America	-0.366%	(-0.377%--0.355%)	-1.020%	(-1.052%--0.989%)	-1.697%	(-1.748%--1.645%)

Table 2: Malaria Infection Case Change due to the Shift of Development Scenarios

	Continent	From SSP1-2.6 to SSP 2-4.5	UI	From SSP1-2.6 to SSP 3-7.0	UI	From SSP1-2.6 to SSP 5-8.5	UI
2021 - 2040	Africa	0.329	(0.312 - 0.347)	0.189	(0.178 - 0.201)	0.147	(0.137 - 0.156)
	Asia	-0.009	(-0.010 - -0.007)	-0.011	(-0.012 - -0.009)	-0.008	(-0.009 - -0.007)
	Europe	-0.001	(-0.002 - 0.000)	-0.003	(-0.005 - -0.002)	-0.011	(-0.015 - -0.006)
	North America	0.000	(0.000 - 0.000)	0.000	(0.000 - 0.000)	0.000	(0.000 - 0.000)
	Oceania	-0.001	(-0.002 - 0.000)	-0.002	(-0.004 - 0.000)	-0.002	(-0.003 - 0.000)
	South America	0.000	(0.000 - 0.000)	-0.001	(-0.001 - 0.000)	-0.001	(-0.001 - -0.001)
2041 - 2060	Africa	-0.362	(-0.383 - -0.342)	-1.210	(-1.277 - -1.142)	-1.279	(-1.358 - -1.201)
	Asia	-0.016	(-0.018 - -0.015)	-0.036	(-0.039 - -0.033)	-0.025	(-0.031 - -0.018)
	Europe	-0.031	(-0.044 - -0.017)	-0.074	(-0.106 - -0.042)	-0.088	(-0.128 - -0.048)
	North America	0.000	(-0.001 - 0.000)	-0.001	(-0.001 - 0.000)	-0.001	(-0.002 - -0.001)
	Oceania	-0.003	(-0.006 - 0.000)	-0.009	(-0.015 - -0.003)	-0.007	(-0.018 - 0.004)
	South America	-0.002	(-0.003 - -0.002)	-0.006	(-0.009 - -0.004)	-0.008	(-0.010 - -0.005)
2081 - 2100	Africa	-3.883	(-4.105 - -3.661)	-11.690	(-12.357 - -11.024)	-7.978	(-8.567 - -7.389)
	Asia	-0.070	(-0.085 - -0.054)	-0.211	(-0.248 - -0.174)	-0.135	(-0.175 - -0.095)
	Europe	-0.167	(-0.242 - -0.091)	-0.618	(-0.887 - -0.349)	-0.468	(-0.685 - -0.252)
	North America	-0.002	(-0.003 - -0.001)	-0.008	(-0.011 - -0.005)	-0.006	(-0.008 - -0.004)
	Oceania	-0.014	(-0.032 - 0.005)	-0.030	(-0.088 - 0.027)	-0.018	(-0.065 - 0.029)
	South America	-0.010	(-0.013 - -0.006)	-0.038	(-0.051 - -0.025)	-0.035	(-0.048 - -0.023)

Note: the unit of this table is case/km^2.

References:

1. Bhatt S, Weiss DJ, Cameron E, et al. The effect of malaria control on Plasmodium falciparum in Africa between 2000 and 2015. *Nature* 2015; **526**(7572): 207-11.
2. World Health Organization. World malaria report 2021, 2021.
3. Mordecai EA, Ryan SJ, Caldwell JM, Shah MM, Labeaud AD. Climate change could shift disease burden from malaria to arboviruses in Africa. *The Lancet Planetary Health* 2020; **4**(9): e416-e23.
4. Brugueras S, Fernández-Martínez B, Martínez-De La Puente J, et al. Environmental drivers, climate change and emergent diseases transmitted by mosquitoes and their vectors in southern Europe: A systematic review. *Environ Res* 2020; **191**: 110038.
5. Kulkarni MA, Duguay C, Ost K. Charting the evidence for climate change impacts on the global spread of malaria and dengue and adaptive responses: a scoping review of reviews. *Globalization and Health* 2022; **18**(1).
6. Lafferty KD. The ecology of climate change and infectious diseases. *Ecology* 2009; **90**(4): 888-900.
7. Paaijmans KP, Blanford S, Bell AS, Blanford JI, Read AF, Thomas MB. Influence of climate on malaria transmission depends on daily temperature variation. 2010; **107**(34): 15135-9.
8. Mordecai EA, Paaijmans KP, Johnson LR, et al. Optimal temperature for malaria transmission is dramatically lower than previously predicted. *Ecology Letters* 2013; **16**(1): 22-30.
9. Johnson LR, Ben-Horin T, Lafferty KD, et al. Understanding uncertainty in temperature effects on vector-borne disease: a Bayesian approach. *Ecology* 2015; **96**(1): 203-13.
10. IPCC. Climate change 2022: impacts, adaptation and vulnerability, 2022.
11. Riahi K, Van Vuuren DP, Kriegler E, et al. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change* 2017; **42**: 153-68.
12. Rodell M, Houser PR, Jambor U, et al. The Global Land Data Assimilation System. *Bulletin of the American Meteorological Society* 2004; **85**(3): 381-94.
13. Parham PE, Michael E. Modeling the effects of weather and climate change on malaria transmission. *Environ Health Perspect* 2010; **118**(5): 620-6.
14. Rueda LM, Brown TL, Kim HC, et al. Species composition, larval habitats, seasonal occurrence and distribution of potential malaria vectors and associated species of Anopheles (Diptera: Culicidae) from the Republic of Korea. *Malaria Journal* 2010; **9**(1): 55.
15. Amadi JA, Olago DO, Ong'Amo GO, et al. Sensitivity of vegetation to climate variability and its implications for malaria risk in Baringo, Kenya. *PLoS One* 2018; **13**(7): e0199357.
16. Midekisa A, Senay G, Henebry GM, Semuniguse P, Wimberly MC. Remote sensing-based time series models for malaria early warning in the highlands of Ethiopia. *Malaria Journal* 2012; **11**(1): 165.
17. Sorichetta A, Hornby GM, Stevens FR, Gaughan AE, Linard C, Tatem AJ. High-resolution gridded population datasets for Latin America and the Caribbean in 2010, 2015, and 2020. *Scientific Data* 2015; **2**(1): 150045.

18. Linard C, Gilbert M, Snow RW, Noor AM, Tatem AJ. Population Distribution, Settlement Patterns and Accessibility across Africa in 2010. *PLoS One* 2012; **7**(2): e31743.

19. Mordecai EA, Caldwell JM, Grossman MK, et al. Thermal biology of mosquito-borne disease. *Ecology Letters* 2019; **22**(10): 1690-708.

20. Hu J, Hou Z, Xu Y, et al. Life loss of cardiovascular diseases per death attributable to ambient temperature: A national time series analysis based on 364 locations in China. *Science of The Total Environment* 2021; **756**: 142614.

21. Lee S, Lee H, Myung W, Kim EJ, Kim H. Mental disease-related emergency admissions attributable to hot temperatures. *Science of The Total Environment* 2018; **616-617**: 688-94.

22. Song J, Pan R, Yi W, et al. Ambient high temperature exposure and global disease burden during 1990–2019: An analysis of the Global Burden of Disease Study 2019. *Science of The Total Environment* 2021; **787**: 147540.

23. Anyamba A, Small JL, Britch SC, et al. Recent Weather Extremes and Impacts on Agricultural Production and Vector-Borne Disease Outbreak Patterns. *PLoS One* 2014; **9**(3): e92538.

24. Mason-D'Croz D, Sulser TB, Wiebe K, et al. Agricultural investments and hunger in Africa modeling potential contributions to SDG2 – Zero Hunger. *World Development* 2019; **116**: 38-53.

25. Burrell AL, Evans JP, De Kauwe MG. Anthropogenic climate change has driven over 5 million km2 of drylands towards desertification. *Nat Commun* 2020; **11**(1).

26. Lawler OK, Allan HL, Baxter PWJ, et al. The COVID-19 pandemic is intricately linked to biodiversity loss and ecosystem health. *The Lancet Planetary Health* 2021; **5**(11): e840-e50.

27. Lamchin M, Lee W-K, Jeon SW, et al. Long-term trend and correlation between vegetation greenness and climate variables in Asia based on satellite data. *Science of The Total Environment* 2018; **618**: 1089-95.