CLIMATE IMPACTS
ON MALARIA IN AFRICA

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EXECUTIVE SUMMARY

Climate change is expected to exacerbate the global burden of malaria, particularly in Sub-Saharan Africa, which currently bears the highest impact of the disease. Malaria is highly sensitive to climate shift. While gradual, long-term changes to conditions such as temperature, precipitation, and humidity impact transmission, increasingly, extreme weather events are disrupting malaria prevention and control. Boston Consulting Group and the Malaria Atlas Project have conducted the first quantitative analysis of how the impact of extreme weather events, such as floods and cyclones, affects the malaria burden on the continent, as well as the implications of long-onset climate change. This research involved developing a climate model to predict changes in intensity, duration, and frequency of floods and cyclones across the continent. Additionally, it estimated the impact of these climate change-driven events on malaria-related deaths through the year 2049. This analysis builds on existing work by the Malaria Atlas Project regarding the effects of long-onset climate change on malaria and will complement forthcoming peer-reviewed publications.

More than 550,000 additional malaria deaths attributable to climate change are predicted from the year 2030 to the year 2049 based on model outputs of current intervention coverage levels. Both long-onset and extreme weather impacts drive these deaths, which are in addition to the expected deaths that would occur in a world without climate change. **Extreme weather events drive 92%** of

the projected mortality increase. The model showed that most countries are predicted to see increases in malaria deaths under long-onset climate change alone and that extreme weather exacerbates this increase. Ten countries that would have expected a decrease in malaria deaths due to the reduction of vectorial capacity from rising temperatures associated with long-onset climate change are instead predicted to experience an overall increase in malaria deaths with the addition of extreme weather.

Gains achieved through increased coverage of existing interventions will be harder to sustain under climate change in the future—as much as 17% of the impact of full intervention coverage could be lost due to disruptions from climate change. Additionally, 1.3 billion people in Sub-Saharan Africa are expected to live in places where eradication will become harder under climate change in the late 2040s, which represents 75% of the expected population. Thirty-three countries will have areas where extreme increases in additional effort are needed to eradicate malaria due to climate change by the late 2040s.

These results highlight the need for additional investment areas in the fight against malaria, including adaptation of existing malaria interventions to ensure climate resilience, flexible funding for climate-resilient tools and interventions, malaria control funding, malaria prevention funding, as well as data and decisioning support, especially for early warning systems and health systems strengthening. **Pushing toward eradication as early as possible helps mitigate the most consequential impacts of climate change and improves the feasibility of eradication.**

HOW DOES CLIMATE CHANGE IMPACT MALARIA?

Malaria is a major cause of global morbidity and mortality: in 2022, there were an estimated 249 million malaria cases and 608,000 malaria deaths.[1] Africa carries the majority of this burden, accounting for 233 million malaria cases (94% of all cases) and 580,000 malaria deaths (95% of all deaths) in the same year.[1] Children under five years of age accounted for 80% of these deaths on the continent.

Malaria is one of the health areas with the greatest estimated magnitude of climate impact on disease burden.[1] Climate change is expected to impact malaria through multiple pathways, including long-onset climate change, extreme weather, and other downstream impacts from both long-onset and extreme weather factors.

Long-onset climate change describes gradual and long-term shifts in temperature, humidity, and rainfall patterns, which affect malaria transmission via effects on mosquito and parasite populations.[2,3] Key examples of long-onset climate change impacts on malaria include the increasing risk of malaria transmission in Ethiopian and Kenyan highland areas.[4,5] Long-onset impacts also have implications for longer-term population displacement and habitability, including shifts in population density over time to areas of potentially higher malaria risk, which is outside the scope of this effort.[3] Long-onset impacts are attributable to gradual shifts in climate over time and are distinct from climate shocks, which are extreme climatic events causing damage and disruptions to health care delivery services.

Extreme weather—the focus of this report—describes climate shocks that lead to weather-related disasters. The impacts of extreme weather include surges in malaria incidence due to floods, cyclones, and other natural disasters. Meanwhile, the frequency, severity, spread, and duration of these extreme weather events are expected to increase due to climate change.[6] For the purposes of this effort, extreme weather describes floods and cyclones.

Extreme weather is expected to drive significant additional climate-related malaria burden through several factors, including disruption to housing access, insecticide-treated net (ITN) loss, disruption to health care access, and changes to larval habitats. These disruptions are expected to lead to increased climate-driven malaria incidence and increased climate-driven malaria death. Incidence increases will be driven primarily through changes in larval habitat along with loss of protection from key malaria interventions, namely ITNs and indoor residual spraying (IRS). This loss of protection arises from either a loss of housing, and with it, ITNs, or from disrupted ITN campaign distributions among other health care services. Disruption to health care access will further drive climate-related incidence and deaths, especially as it relates to diagnostic testing for malaria with rapid diagnostic tests (RDTs) and case management with effective antimalarial treatment like artemisinin combination therapy (ACT).

Extreme weather events disrupt health systems and the malaria services they provide. As extreme weather events like floods and cyclones happen more frequently and with greater intensity due to climate change, the health system has less resilience in its ability to recover, exposing countries to potential risk for spikes in malaria burden. This lack of resilience has been observed during surges in other disease areas, including in Liberia and Sierra Leone during the 2014 to 2016 West Africa Ebola Virus disease outbreak.[7,8]

Downstream impacts of climate change on malaria are numerous and relate to both long-onset and extreme weather factors. These impacts include factors like population displacement, gender, health systems, urbanization, land use changes, animal health, future pandemics, food security and nutrition, as well as economic stability and resilience.

Several downstream impacts are particularly important in the context of long-onset impacts, such as the potential for reintroduction of malaria in areas where it has recently been eliminated and food security, which has a downstream impact on nutritional status and can lead to additional risk of severe malaria disease and early death. Additionally, several service delivery consequences of long-onset climate change exist, like increased cost of service delivery under increasing temperatures and difficulty in maintaining temperature-controlled storage.[3] While our modeling results do not include downstream impacts, we have separately analyzed selected case studies to estimate the potential effects of population displacement due to conflict and migration on malaria in the context of climate change, given existing evidence that climate change will lead to additional conflict and migration events.[9,10]

The effects of climate change on the burden of malaria are already evident today. Extreme weather events with some linkage to climate change—such as floods and cyclones—have resulted in increases in malaria cases and deaths. These events have likewise negatively impacted malaria control programs at the country level.

Pakistan Floods, 2022

Over 30 million people were affected by severe flooding in Pakistan in 2022, which destroyed more than one million homes and damaged over 500,000 km of roads.[11] The intensity of this flooding was increased due to climate change and led to a significant surge in malaria cases in the country—from 2.6 million suspected cases reported in in 2021 to 3.7 million in 2022.[12,13] The floods left a significant number of people without access to health care, without improved housing, and without access to malaria prevention tools like ITNs or IRS.[11] This health system breakdown and the subsequent surge in malaria cases speaks to the tenuous nature of current progress in the fight against malaria and the potential negative impact of climate change on the malaria burden.

East Africa Floods, 2024

In 2024, floods in East Africa affected more than 637,000 people in the region, including the displacement of over 230,000 people.[14] These floods have led to additional burden of vector-borne diseases, including malaria, partially due to an extended breeding season enabled by the flooding.[15] Aside from the malaria transmission impacts of the floods in East Africa, this extreme weather has exposed health system vulnerabilities in responding to emergencies.

There is a critical need for emergency response budgets, the lack of which constrains the extent to which health systems can respond to climate shocks from both a health service delivery perspective and a physical infrastructure perspective.[15,16]

Cyclone Idai, 2019

Cyclone Idai is the deadliest cyclone recorded in Southern Africa. Causing over 1,000 deaths, significant damage to infrastructure, and displacement of residents, the cyclone led to immense health crises, including a surge in malaria cases.[17,18] Within the first month after the cyclone, nearly 15,000 malaria cases were reported in affected areas.[17] Idai had longer-lasting impacts on malaria control as well. Research indicates that over 60% of people surveyed in an affected village had sustained damage to their homes during the cyclone. People with household damage had nearly three times higher odds of malaria infection a year after the storm than those with no household damage.[19] The cyclone serves as a key present-day example of the threat extreme weather poses to malaria control efforts.

Boston Consulting Group (BCG) and the Malaria Atlas Project (MAP), with funding support from the Gates Foundation, have embarked on the most rigorous effort to date to estimate climate change impacts on future malaria burden. Our predictions are based on raster data at 5 km resolution and leverage the latest climate modeling techniques.[20,21] Notably, our analysis considers both long-onset transmission impacts and extreme weather impacts on additional malaria cases and deaths attributable to climate change through the end of the first half of the century.

This work is in response to the need for more robust and comprehensive climate modeling for malaria burden. While a growing body of research has examined the impact of long-onset climate change on malaria burden in the coming decades, there is a dearth of research on the impacts of extreme weather events. The last work to quantify the impact of climate change on malaria deaths was conducted by the World Health Organization (WHO) in 2014; this work was limited to long-onset climate change and used a different methodology at a less granular level of geographic detail.[22] Additional work from the WHO Strategic Advisory Group on Malaria Eradication (SAGme) and the Lancet Commission has highlighted the increased malaria burden due to climate change. Meanwhile, the 2023 World Malaria Report presents an analysis of the impacts of climate change on malaria conducted by MAP.[23,24] The Malaria Atlas Project has conducted additional modeling on long-onset climate change using its industry-standard spatiotemporal model, the results of which are integrated into this extreme weather analysis.

As extreme weather events become more frequent and severe due to climate change, there is a growing need for data on related malaria impacts. Results from this work will be instrumental in understanding the expected quantitative impact of climate change on malaria burden, driving climate-aware malaria programming, and adapting to a changing climate. Critical malaria and climate stakeholders, including those at the country and global levels, can benefit from these quantitative projections in climate adaptation and malaria program planning exercises.

Overall methodology and scope

Our analysis is focused on Africa because, as of 2022, the continent accounts for 94% of malaria cases and 95% of malaria deaths. Within Africa, we focused on 41 malaria-endemic countries.[1]

Our analysis aimed to quantify the plausible impacts of extreme weather on malaria burden. We first simulated contemporary frequency and severity of floods and cyclones, projecting forward through 2049 using a bespoke climate model under shared socioeconomic pathway (SSP) SSP2-4.5, a middle-of-the-road warming scenario.

We conducted a literature review to identify the extreme weather events with the strongest and most proximal links to malaria impact— while drought, heatwaves, and heavy rain are important extreme weather events connected to climate change, we focused on floods and cyclones given the magnitude and quality of evidence between these events and malaria impact. (See Appendix.)

We account for both long-onset impacts and broad impacts of extreme weather events in this work. Long-onset transmission impacts of climate change are accounted for through MAP's existing work on long-onset climate change impacts on malaria. Extreme weather impacts are captured through descriptive elements, including extent and duration, and malaria impact factors, including transmission factors (larval habitat changes), loss of protection (from ITNs and improved housing), and disruptions to service delivery (health care access). Results are presented as incremental impacts of climate change—this is the contribution of climate change to the malaria burden beyond what would be expected in a world without climate change.

Population growth and secular trends in housing quality and urbanization are accounted for in our climate scenarios. We did not account for unpredictable shifts in migration (the impacts of which we expect to lead to additional malaria burden above and beyond long-onset, extreme weather, and other downstream climate impacts).

Our work is based on a comprehensive literature review to capture the state of climate and malaria research, including academic, humanitarian, and popular media sources. We made a particular effort to engage stakeholders in malaria-endemic countries for input into this work and for guidance on the most prominent real-world impacts of climate change on malaria. This included conversations with national malaria programs, academics, scientists, global coordinating organizations, public health practitioners, emergency responders, and humanitarian experts who have provided their firsthand perspectives on the impacts of climate change on malaria burden. For example, we tested assumptions on disruption to health care service delivery, housing access, and ITN access; recovery times for roads, bridges, health care centers, and housing; and variations across key variables like urban and rural settings. A full listing of these impact factors and assumptions is presented in the Appendix.

These results have been tested heavily with the community, including a broad range of stakeholders in the climate community, academia, global stakeholders including the UN and WHO, advocacy organizations, and the private sector to ensure reasonable and actionable conclusions.

This work does not seek to forecast malaria deaths or cases in a particular year or region, nor does it serve as an early warning system for extreme weather events. Additionally, our model does not account for the impacts of Anopheles stephensi expansion on the continent or accelerated parasite or vector resistance against interventions.

Finally, our model does not explicitly account for all potential impacts of climate change, for example, impacts on other diseases, longer-term or broader health system considerations, and downstream impacts like gender, land-use changes, animal health, economic stability, and climate-driven migration outside of secular trends captured for urbanization.

3

## AFRICA IS EXPECTED TO SEE MORE FLOODING AND SEVERE CYCLONES THROUGH 2050 DUE TO CLIMATE CHANGE

Our modeling shows that climate change is expected to lead to 13% to 18% more flood area-days (based on frequency, intensity, spread, and duration) in Sub-Saharan Africa through 2050 compared to the contemporary frequency of floods.[2] These results are in line with IPCC conclusions, which suggest an increase in pluvial flooding across Sub-Saharan Africa, except in the southwest.[6] Our flood model suggests a

particularly acute increase in Central Africa (including the Democratic Republic of the Congo, Congo, and Gabon), Southern Africa (including parts of Mozambique), and East Africa (including Tanzania). (See Exhibit 1.)

Cyclones are expected to shift in seasonality, with a seasonal peak in January instead of in March. Cyclones will stay relatively flat in frequency, with a slight increase in events across both climate scenarios. Cyclones are expected to see a modest increase in severity in SSP5-8.5. (See Exhibit 2.) These findings align with IPCC's conclusions that the severity of cyclones will increase and that frequency will decrease.[6]

These results are spatiotemporally-specific and indicate plausible future flood and cyclone scenarios that are then used to predict disruptions to malaria services, protection from ITNs and adequate housing, and disruptions to larval habitats due to projected extreme weather events.
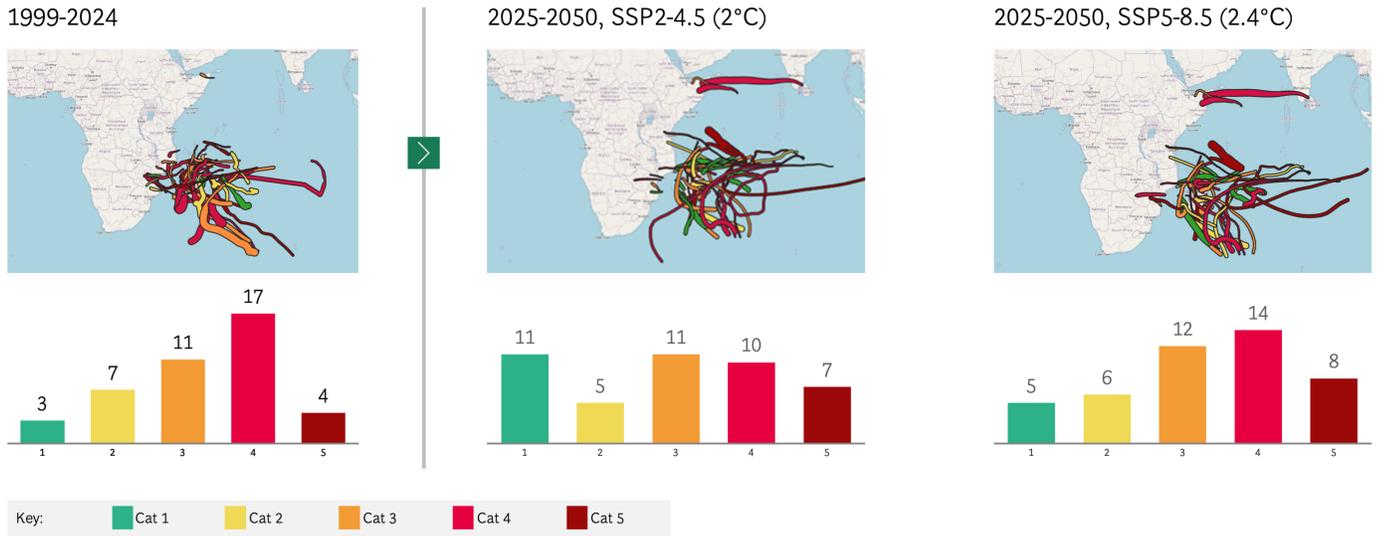
EXHIBIT 1: FLOOD AREA-DAYS THROUGH 2049 WILL INCREASE 13% TO 18% COMPARED TO CONTEMPORARY FLOOD FREQUENCY
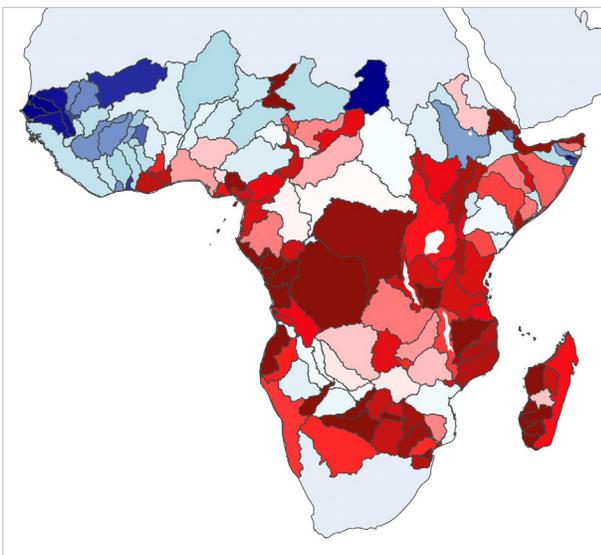
-100%   +100%

% increase compared to contemporary floods

EXHIBIT 2: CYLONES ARE EXPECTED TO SEE A SLIGHT INCREASE IN FREQUENCY AND SEVERITY

1999-2024

2025-2050, SSP2-4.5 (2°C)

2025-2050, SSP5-8.5 (2.4°C)

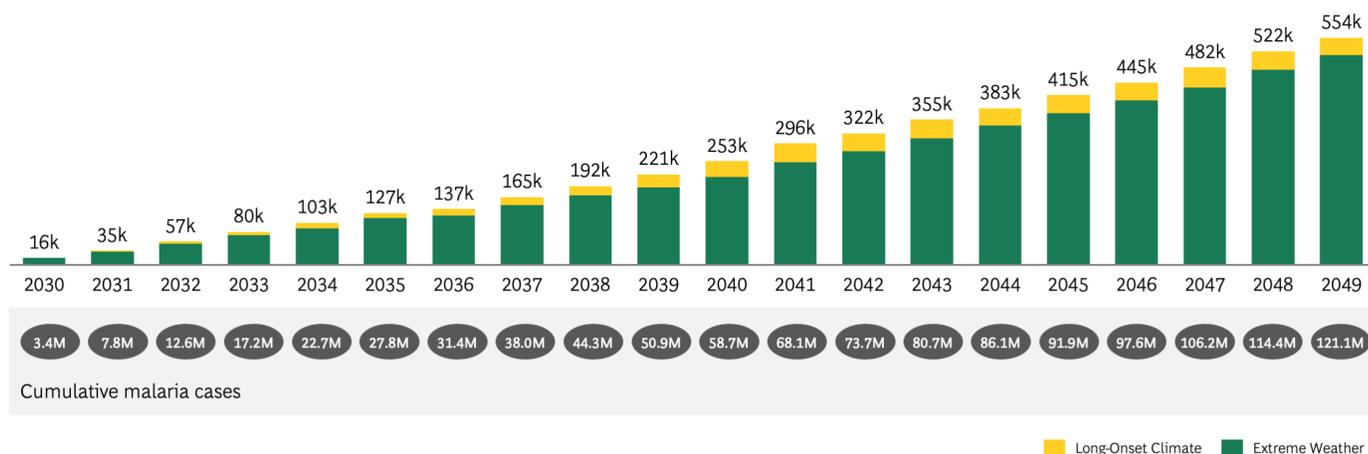Key: ■ Cat 1 ■ Cat 2 ■ Cat 3 ■ Cat 4 ■ Cat 5

4

CLIMATE CHANGE IS EXPECTED TO LEAD TO OVER 550,000 ADDITIONAL MALARIA DEATHS FROM 2030 TO 2049

Our model suggests that climate change is expected to lead to over 550,000 additional climate-related malaria deaths from the year 2030 to 2049 (range: approximately 480,000 to approximately 690,000 among three GCMs under SSP2-4.5). (See Exhibit 3.) These malaria deaths are due to climate change alone and are over and above malaria deaths expected under current climate conditions, limited to the 41 countries we analyzed in this model. Nigeria, Uganda, Mali, Democratic Republic of the Congo, and Tanzania are expected to contribute over 60% of these deaths.

Additionally, climate change is expected to lead to about 121 million additional climate-related malaria cases from 2030 to 2049, over and above the malaria cases expected under current climate conditions in the 41 countries we analyzed in this model.

	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049
Annual	16k	35k	57k	80k	103k	127k	137k	165k	192k	221k	253k	296k	322k	355k	383k	415k	445k	482k	522k	554k
Cumulative malaria cases	3.4M	7.8M	12.6M	17.2M	22.7M	27.8M	31.4M	38.0M	44.3M	50.9M	58.7M	68.1M	73.7M	80.7M	86.1M	91.9M	97.6M	106.2M	114.4M	121.1M

Long-Onset Climate ■ Extreme Weather

Source: Malaria Atlas Project, BCG Analysis

Projecting malaria cases and deaths

We projected malaria cases and deaths from the year 2030 to 2049 using inputs from our climate model and assumptions on the impact of extreme weather events on key malaria impact factors such as larval habitat, ITN access, housing quality, and health care access.

For each extreme weather event, the model adjusts housing protection, ITN coverage, health care access (as a proxy for treatment and case management coverage), and larval habitat variables based on the spatiotemporally-specific impact of the extreme weather event. Recovery times to previous coverage levels of improved housing, ITNs, and health care access are based on assumptions and define the duration of loss of coverage. For each event, we quantified the change in malaria cases and deaths compared to contemporary extreme weather trends and compared to no long-onset climate change.

A full description of all methods is presented in the Appendix.

Extreme weather events lead to an increase in malaria burden due to changes in larval habitat, loss of protection from key malaria interventions like ITNs and IRS, and disruption to health care access for rapid diagnostic testing and case management with effective antimalarial treatment.

When compared to the incremental impact of long-onset climate change, extreme weather events contribute significantly to the expected increase in malaria deaths. Our analysis reveals that, among all 41 countries considered, 92% of the net increase in climate-related malaria deaths expected from 2030 through 2049 is due to extreme weather events.

The addition of climate-driven malaria deaths due to extreme weather leads to three archetypes compared to previous work, which considered long-onset climate change alone.

Thirty countries had a net increase in malaria deaths under long-onset climate change alone and a further increase under extreme weather events. Ten countries had a decrease in malaria deaths under long-onset climate change alone but showed an increase under extreme weather events, leading to a net increase in malaria deaths. Just one country had a decrease in malaria deaths under long-onset climate change with an insufficient increase in deaths due to extreme weather events to lead to an overall increase in deaths. (See Exhibit 4.) For a table of data on the ten countries with the highest expected additional climate-attributable malaria deaths, see the Appendix.

EXHIBIT 4: EXTREME WEATHER CHANGES THE MALARIA TRAJECTORY

SSP 2-4.5, through 2049
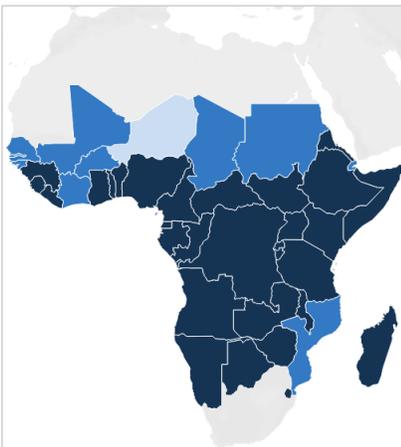
	Excess malaria deaths attributed to		
	Long-Onset	Extreme Weather	Total Impact
Countries with a net increase in malaria deaths under long-onset alone that further increases under extreme weather	⌃	⌃	⌃
Countries with a decrease in malaria deaths under long-onset alone and an increase under extreme weather, leading to a net increase in malaria deaths	⌄	⌃	⌃
Countries with a decrease in malaria deaths under long-onset alone and an increase under extreme weather that does not lead to a net increase in malaria deaths	⌄	⌃	⌄

5

CLIMATE CHANGE INCREASES THE FRAGILITY OF GAINS MADE THROUGH HEAVY SUPPRESSION OF MALARIA

The WHO Global Technical Strategy for Malaria 2016–2030 (GTS) is a framework to guide countries in accelerating progress toward malaria elimination. The GTS framework sets targets for reducing global malaria incidence and mortality rates by at least 90% by the year 2030.[25] Assuming the world can reach or exceed GTS targets by 2030 through increases in ITN coverage and case management coverage, overall malaria burden will decrease significantly as a result; however, climate change is expected to weaken the impact of these gains. Compared to a world with no climate change, we lose up to 17% of gains made through intensive malaria suppression efforts under climate change in the years 2030 through 2049—this loss is expected even if we ramp up efforts with existing tools.
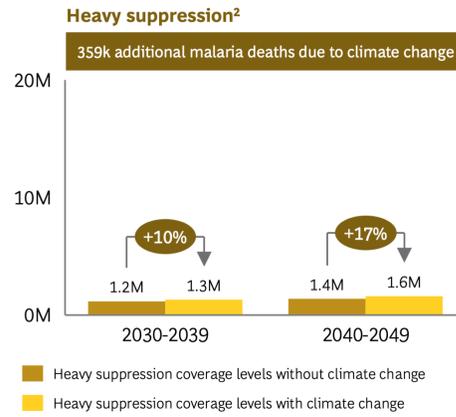
Measuring losses under climate change

We compared the projected contribution of climate change to malaria deaths under present-day malaria control with a situation where we increased intervention coverage to maximum levels. Under current intervention practices, a 3% increase in malaria deaths is projected from 2030 to 2039 and 2040 to 2049 compared to a world where climate change doesn't exist. In comparison, when assuming heavy suppression intervention coverage at maximum levels of 95% effective ITN coverage and 95% case management coverage, a 10% increase in malaria deaths is projected from 2030 to 2039 and a 17% increase from 2040 to 2049 compared to a world where climate change doesn't exist. Our analysis shows that the same level of effort does not go as far under climate change.

EXHIBIT 5: CLIMATE CHANGE WEAKENS THE IMPACT OF INCREASED INTERVENTION COVERAGE

Cumulative malaria deaths, 2030-2049

Present-day intervention coverage[1]

554k additional malaria deaths due to climate change

- Present-day coverage levels without climate change
- Present-day coverage levels with climate change

Heavy suppression[2]

359k additional malaria deaths due to climate change

- Heavy suppression coverage levels without climate change
- Heavy suppression coverage levels with climate change

1. For ITN coverage: 10% to 81%, for treatment coverage: 20% to 72%
2. For both ITN & treatment coverage: 95% to align to highest observed coverage values. Source: Malaria Atlas Project, BCG Analysis

6

CLIMATE CHANGE
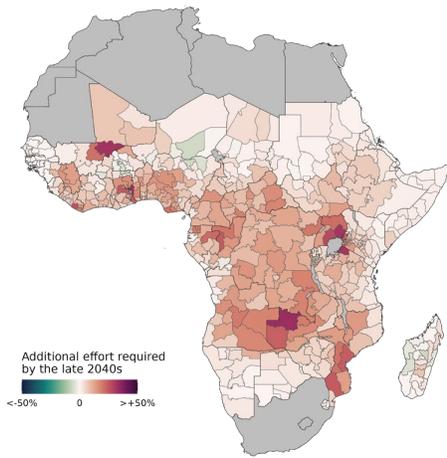## MAKES ERADICATION
MORE DIFFICULT

Climate change will make the task of malaria eradication even harder, and the level of effort needed increases with each passing day. By the late 2040s, about 1.3 billion people will live in places where more effort will be required to eradicate malaria. This represents 75% of the projected population in Sub-Saharan Africa in 2049. Additionally, 33 countries have areas that will require an extreme—or greater than 50%—increase in the effort needed to eradicate malaria. The task of malaria eradication is expected to require greater effort if we delay even by a decade: Of the 41 countries we analyzed in Sub-Saharan Africa, 50% of provinces will require more effort to eliminate malaria in the late 2040s than the late 2030s. (See Exhibit 6.)

Quantifying eradication effort

The Relative Effort to eradicate is defined as the Rc value at a given time point, as impacted by both long-onset and extreme weather climate effects, under present-day levels of control. This is compared to a counterfactual at that same time point in the absence of climate change. These results are at the highest level of spatiotemporal detail available in the model and speak to the remaining areas where eradication efforts will be the most expensive and most difficult.

EXHIBIT 6: CLIMATE CHANGE MAKES ERADICATION MORE DIFFICULT ACROSS SUB-SAHARAN AFRICA

Additional effort required by the late 2040s

<-50%   0   >+50%

1.3B
People

will live in areas where eradication requires more **effort due to climate change.**[1] This effort increases the longer we wait[2]

This represents about 75% of the projected population in Sub-Saharan Africa in 2049

33
Countries

have areas that will require an extreme (>50%) increase in the effort needed to eradicate malaria[1]

1. Relative 'Effort' to eradicate is defined as the Rc value at a given time point, as impacted by both long-onset and extreme weather climate effects, under present-day levels of control. This is compared to a counterfactual at that same time point in the absence of climate change.

7

DOWNSTREAM IMPACTS: CONFLICT AND MIGRATION

This model did not consider several downstream impacts of climate change on malaria that will be important in the changing climate and malaria landscape and the broader health landscape. These include conflict, migration, gender, health systems, urbanization, land use changes, animal health, future pandemics, food security and nutrition, economic stability and resilience, reintroduction of malaria, and service delivery disruptions. These downstream impacts are related to both extreme weather events and long-onset impacts.

A growing body of research suggests that climate change will increase the incidence and extent of conflicts and of unplanned migration events.[9,10] For example, in 2022 alone, over 7.4 million new internal displacements occurred in Africa due to disasters, including floods.[26] While not included in our analysis, we recognize the importance of conflict and migration as climate-sensitive issues that may have appreciable contributions to the malaria burden over and above the existing estimates. For example, research in the Democratic Republic of the Congo has shown that conflict exacerbates the malaria burden.[27]

We analyzed four discrete conflict events as case studies, aiming for variation in conflict duration, extent of health system disruption (full or partial), and geographic spread. Conflict-related malaria deaths were modeled mainly based on disruption to health care services using contemporary (present-day) intervention coverage and health care access levels, rather than historical coverage levels from the original

date of the conflict. We made this decision to analyze the potential future impacts of conflicts with similar scope and scale, not to retrospectively examine the additional malaria burden attributable to actual historical conflicts. The specific conflicts used in case studies serve as templates in terms of size, duration, and location of conflict, not as estimates of the true historical death toll attributable to any specific conflict.

Conflicts with complete health system disruption increased malaria deaths significantly. Compared to baseline malaria deaths, or what would have happened without a conflict, total malaria deaths increased by 97% to 161%. Conflicts with partial health system disruption increased malaria deaths by 12% to 87% compared to baseline malaria deaths. (See Exhibit 7.)
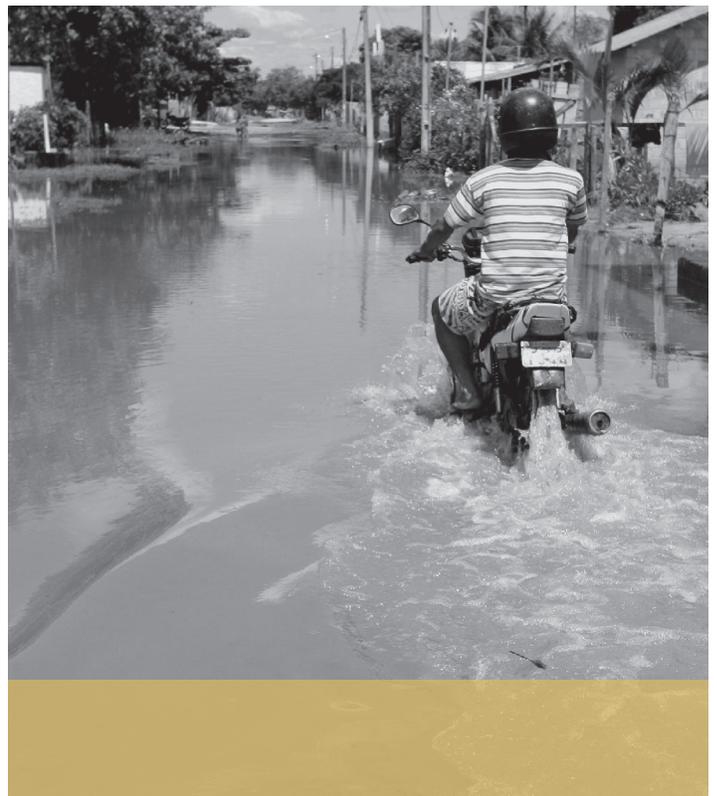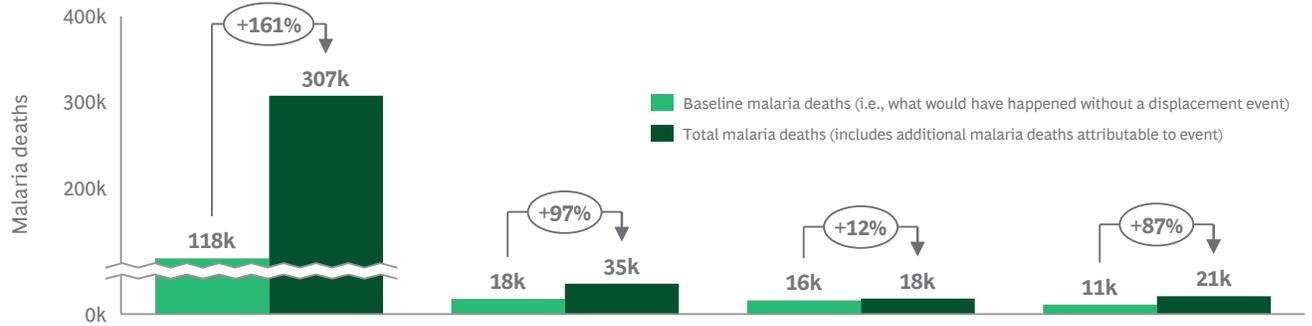
EXHIBIT 7: CLIMATE-DRIVEN POPULATION DISPLACEMENT EVENTS ADD TO THE MALARIA BURDEN

Malaria deaths

Legend:
- Baseline malaria deaths (i.e., what would have happened without a displacement event)
- Total malaria deaths (includes additional malaria deaths attributable to event)

Event A: 118k → 307k (+161%)
Event B: 18k → 35k (+97%)
Event C: 16k → 18k (+12%)
Event D: 11k → 21k (+87%)

	Event A	Event B	Event C	Event D
Duration	~5 years	4 months	~5 years	~7 years
HC system disruption extent	Full disruption		Partial disruption	
Non-malaria deaths (est.)	2.5M-5M[1]	~3k[2]	~10k[3]	~300k[4]
Historic example	2nd Congo War	2nd Ivorian Civil War	Kivu Conflict	Sudan Conflict

8

INVESTMENT IS NEEDED TO MINIMIZE ADDITIONAL CLIMATE-RELATED MALARIA DEATHS

Given the impact of climate change on malaria, there are multiple priority areas for financing, including climate investments, broad health system investments, and malaria investments. There is a gap in mitigation financing as well as adaptation and resilience financing. Mitigation financing is growing but currently only reaches about 15% of the $8.4 trillion per year expected to be needed by 2030. Adaptation financing has similarly grown in recent years, but current financing only reaches 30% of the $212 billion per year needed by 2030 for developing countries alone.[28] Within the broader health context, health systems strengthening is an important funding area that underpins many areas of potential investment in the climate and malaria space through higher quality health care and addressing malaria risk factors. Health systems funding in the context of climate change and malaria includes focusing on integrated service delivery, strengthened governance, and creating the conditions for additional funding at the country level. Similarly, emergency preparedness and emergency response efforts—specifically, the integration of malaria service delivery into emergency preparedness and response planning—are essential in the context of climate change. Malaria-specific funding is also below target, with only about half of targeted funding attained in 2022, representing a significant gap in the funding needed to remain on track to reach GTS targets.[3]

While intensive scale-up of existing malaria tools like ITNs and case management has a large impact on reducing malaria burden, paradigm-shifting tools are needed to change course toward accelerated eradication and solidify gains in the face of climate change. A changing climate requires the integration of malaria interventions and programming into broader health system adaptation activities. As of 2022, most countries were not on track to reach GTS targets given insufficient malaria funding, indicating a barrier to reaching high intervention coverage levels.

There is growing recognition that climate and malaria efforts need to be integrated, but the need for investment in this area remains unmet. There are several key areas that will require additional investment to respond to the growing threat that climate change poses to malaria control. These areas broadly apply to climate change driven by long-onset transmission factors and extreme weather events, with the understanding that individual country priorities may be driven by expected impacts of either long-onset transmission factors or extreme weather events individually. For example, countries with significant expected increases in extreme weather events may focus more funding on the prepositioning of commodities than countries where the increased climate-attributable malaria burden will be driven chiefly by long-onset impacts. This country-by-country approach aligns to the Gates Foundation's Principles for Allocating Finance for Development and Climate Goals.[29]

Adaptation of malaria interventions is critical to ensure resilience to climate disruptions and resulting surges in malaria burden. These adaptations include community delivery of malaria services, pre-positioning malaria commodities for both long-onset and extreme weather drivers of climate change at the regional and local levels, and planning interventions around changes to peak malaria transmission seasons, especially for long-onset climate change drivers.

Flexible funding is needed for tools and interventions that protect vulnerable populations after extreme weather events and other climate-driven disruptions. As the impacts of climate change continue to affect the progress of malaria control, there is a growing need to mobilize resources at the intersection of climate and malaria. Enabling this flexible funding starts with bolstering political commitments and solidifying the integration of malaria into National Adaptation Plans (NAPs) and Health National Adaptation Plans (H-NAPs). This funding applies to both extreme weather events—to foster interventions that are more resilient to service delivery disruptions caused by extreme weather events—and to long-onset climate change, which makes temperature-controlled storage more difficult and may increase the overall costs of delivering existing interventions due to shifting climate conditions.

Malaria control funding must continue in the face of climate change, including managing malaria cases in anticipation of climate-driven spikes. This includes a continued focus on vector control and case management and the expected introduction of new tools like single-encounter radical cure (SERC), as they are available.

From an extreme weather perspective, these actions include prepositioning commodities and reducing the number of encounters for radical cure. While these also apply to long-onset climate change, long-onset impacts may be driven by added complexity due to changes in temperature and population distribution.

Malaria prevention funding is similarly crucial in the face of climate change, especially in planning for increasing climate-driven extreme weather events and building resilience to potential disruptions to care and personal protection during extreme weather. These interventions also protect against reintroduction in areas with recent elimination and high receptivity due to long-onset climate change. Funding for a second-generation malaria vaccine and genetic vector control interventions (such as a gene drive) is essential to solidify progress in the fight against malaria.

Data and decision support enable better decision-making in a changing climate. For example, early warning systems (EWS) for malaria transmission seasons enable more adaptive and resilient health service provision through the planning of intervention timing and stock planning at the local level to preempt potential disruptions to health care access in the wake of an extreme weather event. This funding is also essential for routine case data reporting, commodity delivery and stock reporting data, and other service delivery indicators. These systems underpin a successful elimination effort at the country level and are important under extreme weather and long-onset climate change factors.

9

AVERTING CLIMATE-RELATED MALARIA DEATHS AND ERADICATING MALARIA IN A WARMING WORLD

Current gains in the fight against malaria are fragile even without considering the impacts of climate change.[3] Our analysis shows that climate change will lead to further loss of impact, additional malaria deaths under current intervention coverage levels, and an even larger proportional number of deaths if we expand intervention coverage to the highest levels. These results highlight that relying on the current toolbox of malaria prevention and control interventions alone is insufficient to build adequate resilience of malaria control programs in the face of climate change.

Pushing toward eradication as early as possible avoids the worst of climate change and minimizes the additional effort needed to eradicate malaria, which increases as time goes on. Eradication is a good buy and efficient use of resources in the face of climate change, compared to relying only on perpetual coverage of existing interventions.

Estimating the cost of malaria control and eradication

We compared three malaria intervention scenarios to discern whether eradication is a good buy compared to maximizing the coverage of existing interventions in the context of climate change. These three scenarios are outlined below.

Business as usual. This scenario assumes present-day coverage levels of existing WHO-recommended malaria interventions through 2080.

Heavy suppression. This scenario assumes present-day coverage levels of existing WHO-recommended malaria interventions scaled to maximum observed coverage by 2030 and continued through 2080.

Eradication. This scenario assumes present-day coverage levels of existing WHO-recommended malaria interventions with the addition of paradigm-shifting "new tools" in the 2030s to reach eradication by 2050. We chose 2080 as a proxy for ongoing spending in perpetuity, balancing the duration of spending with the logical constraints of extending the model decades into the future.

We included WHO-recommended interventions such as ITNs, IRS, RDTs, ACTs, chemoprevention, MDA, active surveillance, and research and development (excluding product development costs for all R&D areas). We aligned our methods to existing malaria cost estimates (WHO GTS) and previous eradication estimates (Aspiration to Action) and leveraged standard data sources where possible, including those from the UN, WHO, UNICEF, World Bank, and the Global Fund. Malaria case and death estimates are aligned directly to the malaria model outputs under "business as usual" and "heavy suppression" coverage levels of ITNs and case management (ACTs).

These results likely underestimate the cost-benefit of eradication because we have not assumed a decline in the cost of existing tools with the deployment of paradigm-shifting new tools, nor have we included population displacement impacts, which may lead to additional people at higher risk of malaria.
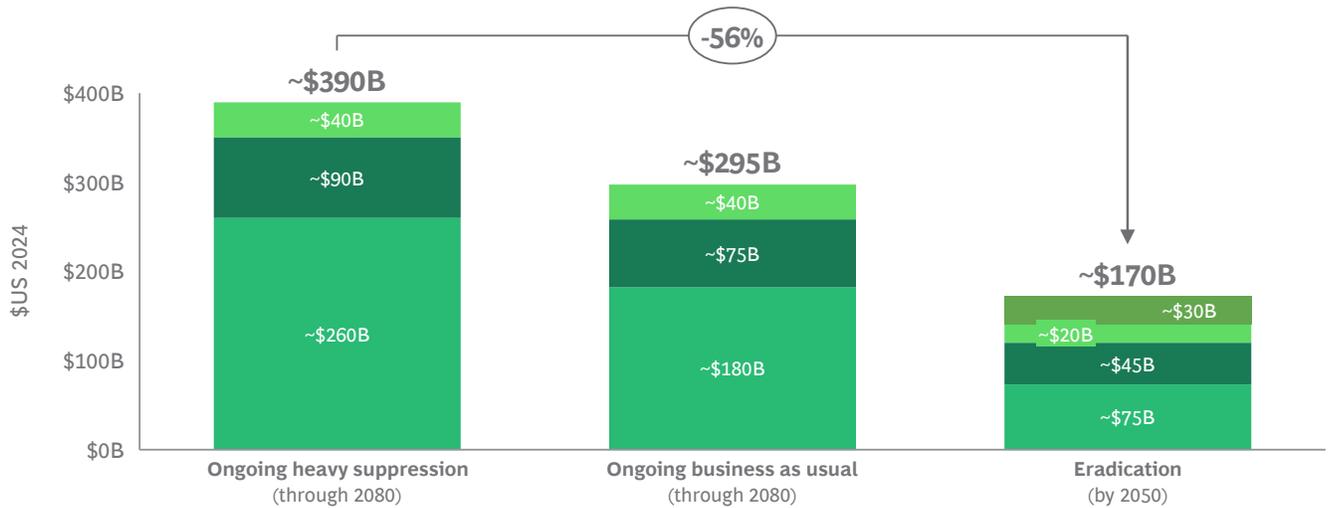
Given the high lifetime costs of heavy suppression, eradication is a good buy if it costs meaningfully less than the expected cost to maintain ongoing heavy suppression spend for many decades and an even better buy if achieved for less than the cost of maintaining today's business as usual coverage for many decades. Our estimates suggest eradication by 2050 will cost significantly less than maintaining heavy suppression of malaria using current tools, given the promise of paradigm-shifting new tools, including a second-generation vaccine and low-threshold gene drive.

We estimate the cost of eradication by 2050 to be about $170 billion, which represents at least a 55% smaller investment through 2080 than continuous heavy suppression of malaria through high intervention coverage and at least a 40% smaller investment through 2080 than if we maintain current intervention coverage levels continuously. (See Exhibit 8.) A sensitivity analysis on inflation and discounting (inflation of 3% per annum and discount rate of 6% per annum) shows that eradication savings through 2080 remain intact.

$US 2024

-56%

~**$390B**
~$40B
~$90B
~$260B

~**$295B**
~$40B
~$75B
~$180B

~**$170B**
~$30B
~$20B
~$45B
~$75B

$400B
$300B
$200B
$100B
$0B

Ongoing heavy suppression
(through 2080)

Ongoing business as usual
(through 2080)

Eradication
(by 2050)

The cost of eradicating malaria is significantly more affordable the sooner it is achieved. Eradication in 2045 is about 14% cheaper than eradication occurring just five years later in 2050. If eradication by 2050 is unsuccessful, additional high-cost years to identify the remaining cases will add significantly to costs through 2055, up to 40% higher than the 2050 eradication date. (See Exhibit 9.) These high-cost years are driven primarily by surveillance and the relatively high per-case cost in the final steps leading to eradication.

-14%   +40%

$240B
(worst case)

$172B

$148B

$201B
(best case)

2045   2050   2055
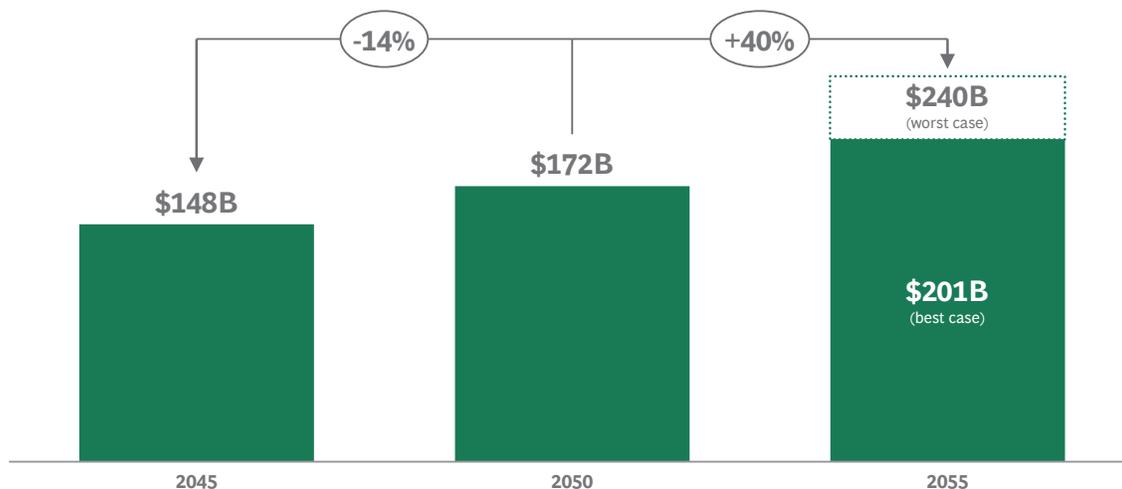
Eradication by 2050 is a good buy in the context of climate change. Paradigm-shifting new tools, such as a second-generation vaccine that provides multiple years of protection, can facilitate sustainable progress in the fight against malaria. This approach is more effective compared to prevention methods like SMC, which depend on precise timing around peak malaria transmission seasons to be most effective. These long-lasting solutions are less vulnerable to interruptions caused by extreme weather events, as they require less frequent distribution. This sets the stage for renewed efforts and progress in combating malaria.

Eradicating malaria requires investment in both climate initiatives and malaria control efforts to achieve success. The modeled impacts of climate change on malaria highlight the importance of prioritizing adaptation and resilience in malaria interventions at the country level. Additionally, innovative funding opportunities at the global planning level are essential to unlock further progress.

10

INVESTMENT IN MALARIA ERADICATION IS ESSENTIAL

Climate change is projected to result in over 550,000 malaria deaths between 2030 and 2049. This increase is primarily driven by more frequent extreme weather events, such as floods and cyclones, linked to climate change. To address the growing malaria burden, the introduction of innovative tools that will help establish climate-resilient solutions is necessary. Eradication becomes increasingly challenging the longer we wait as increased effort is needed to eradicate malaria introduced by climate change as time progresses.

Investing early in eradication efforts could be up to 55% less expensive than heavy suppression of malaria through continuous high-intervention coverage. Early investment also avoids excess mortality compared to ongoing suppression of the malaria burden. To make progress toward eradication, future modeling work should focus on understanding the specific roles, costs, and implementation strategies for new tools, as well as the downstream impacts of climate change on malaria.

11

REFERENCES

1. Fact sheet about malaria [Internet]. [cited 2024 Oct 10]. Available from: https://www.who.int/news-room/fact-sheets/detail/malaria

2. Li C, Managi S. Global malaria infection risk from climate change. Environ Res. 2022 Nov 1;214:114028.

3. World malaria report 2023 [Internet]. [cited 2024 Oct 14]. Available from: https://www.who.int/teams/global-malaria-programme/reports/world-malaria-report-2023

4. Endo N, Eltahir EAB. Increased risk of malaria transmission with warming temperature in the Ethiopian Highlands. Environ Res Lett. 2020 Apr;15(5):054006.

5. Alsop Z. Malaria returns to Kenya's highlands as temperatures rise. The Lancet. 2007 Sep 15;370(9591):925–6.

6. AR6 Synthesis Report: Climate Change 2023 — IPCC [Internet]. [cited 2024 Oct 14]. Available from: https://www.ipcc.ch/report/sixth-assessment-report-cycle/

7. Kieny MP, Evans DB, Schmets G, Kadandale S. Health-system resilience: reflections on the Ebola crisis in western Africa. Bull World Health Organ. 2014 Dec 1;92(12):850.

8. Ako-Egbe L, Seifeldin R, Saikat S, Wesseh SC, Bolongei MB, Ngormbu BJ, et al. Liberia health system's journey to long-term recovery and resilience post-Ebola: a case study of an exemplary multi-year collaboration. Front Public Health. 2023 Jun 19;11:1137865.

9. Environmental Migration | IOM, UN Migration | Environmental Migration Portal [Internet]. [cited 2024 Oct 14]. Available from: https://environmentalmigration.iom.int/environmental-migration

10. International Organization for Migration [Internet]. [cited 2024 Oct 14]. Conflict Drives Displacement Amidst Rising Climate Shocks: New Africa Migration Report. Available from: https://www.iom.int/news/conflict-drives-displacement-amidst-rising-climate-shocks-new-africa-migration-report

11. "It was just the perfect storm for malaria" – Pakistan responds to surge in cases following the 2022 floods [Internet]. [cited 2024 Oct 14]. Available from: https://www.who.int/news-room/feature-stories/detail/It-was-just-the-perfect-storm-for-malaria-pakistan-responds-to-surge-in-cases-following-the-2022-floods

12. Otto FEL, Zachariah M, Saeed F, Siddiqi A, Kamil S, Mushtaq H, et al. Climate change increased extreme monsoon rainfall, flooding highly vulnerable communities in Pakistan. Environ Res Clim. 2023 Mar;2(2):025001.

13. Malaria – Pakistan [Internet]. [cited 2024 Oct 14]. Available from: https://www.who.int/emergencies/disease-outbreak-news/item/2022-DON413

14. Eastern Africa: Heavy rains and flooding Flash Update #1 (3 May 2024) - Kenya | ReliefWeb [Internet]. 2024 [cited 2024 Oct 14]. Available from: https://reliefweb.int/report/kenya/eastern-africa-heavy-rains-and-flooding-flash-update-1-3-may-2024

15. July 2024 DN// 08. Devex. 2024 [cited 2024 Oct 14]. East African health systems struggle to manage floods fallout. Available from: https://www.devex.com/news/sponsored/east-african-health-systems-struggle-to-manage-floods-fallout-107882

16. Financing Global Early Warning Systems Country Case Study: Kenya | Milken Institute [Internet]. 2024 [cited 2024 Oct 15]. Available from: https://milkeninstitute.org/content-hub/research-and-reports/reports/financing-global-early-warning-systems-country-case-study-kenya

17. Nearly 15,000 cases of malaria reported in areas of Mozambique affected by Cyclone Idai – UNICEF [Internet]. [cited 2024 Oct 14]. Available from: https://www.unicef.org/press-releases/nearly-15000-cases-malaria-reported-areas-mozambique-affected-cyclone-idai-unicef

18. Williams S. 'The sea is rising, the climate is changing': the lessons learned from Mozambique's deadly cyclone. The Guardian [Internet]. 2021 Jan 2 [cited 2024 Oct 14]; Available from: https://www.theguardian.com/world/2021/jan/02/the-sea-is-rising-the-climate-is-changing-the-lessons-learned-from-mozambiques-deadly-cyclone

19. Searle KM, Earland DE, Francisco Bibe A, Novela A, Muhiro V, Ferrão JL. Long-lasting household damage from Cyclone Idai increases malaria risk in rural western Mozambique. Sci Rep. 2023 Dec 7;13(1):21590.

20. CMIP6: the next generation of climate models explained - Carbon Brief [Internet]. [cited 2024 Oct 14]. Available from: https://www.carbonbrief.org/cmip6-the-next-generation-of-climate-models-explained/

21. CMIP Phase 6 (CMIP6) - Coupled Model Intercomparison Project [Internet]. 2022 [cited 2024 Oct 14]. Available from: https://wcrp-cmip.org/cmip6/

22. Quantitative risk assessment of the effects of climate change on selected causes of death, 2030s and 2050s | WHO | Regional Office for Africa [Internet]. 2024 [cited 2024 Oct 14]. Available from: https://www.afro.who.int/publications/quantitative-risk-assessment-effects-climate-change-selected-causes-death-2030s-and

23. WHO advisory body releases malaria eradication report [Internet]. [cited 2024 Oct 14]. Available from: https://www.who.int/news/item/20-04-2020-who-advisory-body-releases-malaria-eradication-report

24. Endo N, Yamana T, Eltahir EAB. Impact of climate change on malaria in Africa: a combined modelling and observational study. The Lancet. 2017 Apr 1;389:S7.

25. Global technical strategy for malaria 2016-2030, 2021 update [Internet]. [cited 2024 Oct 15]. Available from: https://www.who.int/publications/i/item/9789240031357

26. International Organization for Migration. Africa migration report: connecting the threads, linking policy, practice and the welfare of the African migrant. second edition. Addis Ababa: International Organization for Migration; 2024. 1 p.

27. Hawkes M, Katsuva JP, Masumbuko CK. Use and limitations of malaria rapid diagnostic testing by community health workers in war-torn Democratic Republic of Congo. Malar J. 2009 Dec 23;8:308.

28. CPI [Internet]. [cited 2024 Oct 16]. Global Landscape of Climate Finance 2023. Available from: https://www.climatepolicyinitiative.org/publication/global-landscape-of-climate-finance-2023/

29. Bill and Melinda Gates Foundation [Internet]. [cited 2024 Oct 28]. How strategic financing can drive progress on development and climate. Available from: https://www.gatesfoundation.org/ideas/articles/development-climate-finance-foreword

30. NASA Global Daily Downscaled Projections, CMIP6 | Scientific Data [Internet]. [cited 2024 Oct 17]. Available from: https://www.nature.com/articles/s41597-022-01393-4

31. Sparks N, Toumi R. The Imperial College Storm Model (IRIS) Dataset. Sci Data. 2024 Apr 24;11(1):424.

32. Weiss DJ, Lucas TCD, Nguyen M, Nandi AK, Bisanzio D, Battle KE, et al. Mapping the global prevalence, incidence, and mortality of Plasmodium falciparum, 2000–17: a spatial and temporal modelling study. The Lancet. 2019 Jul 27;394(10195):322–31.

33. Projecting 1 km-grid population distributions from 2020 to 2100 globally under shared socioeconomic pathways | Scientific Data [Internet]. [cited 2024 Oct 16]. Available from: https://www.nature.com/articles/s41597-022-01675-x
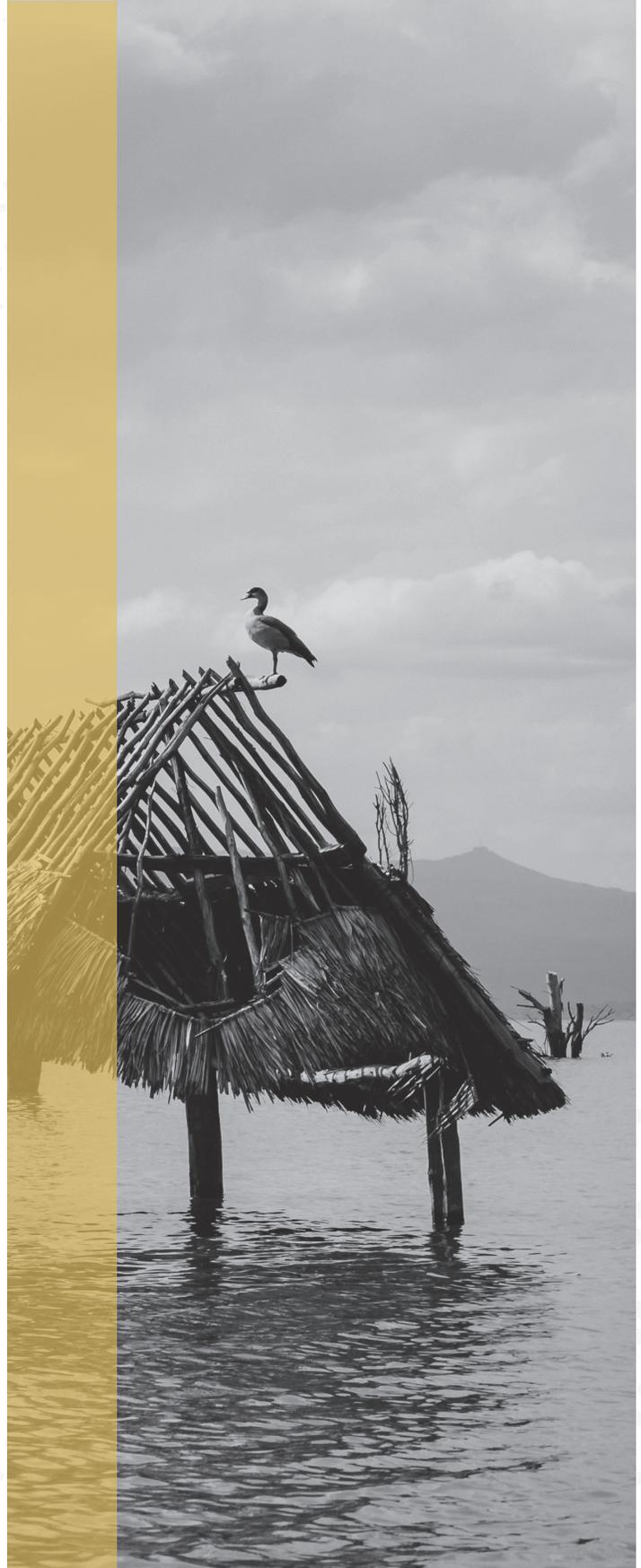
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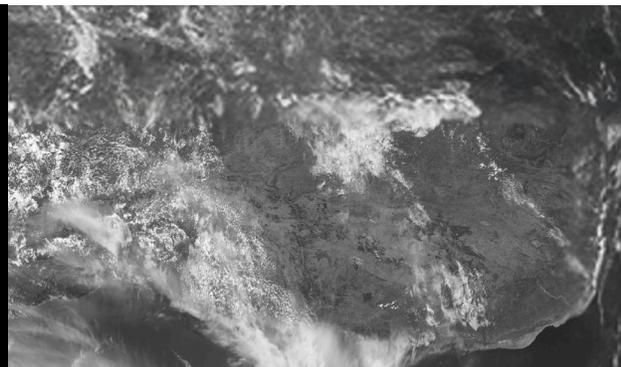
12.1

ADDITIONAL MALARIA BACKGROUND

Our modeling effort is underpinned by an extensive literature search, which assessed major climate-driven shocks (extreme weather events) including floods, cyclones, heavy rain, drought and heatwaves. We reviewed the quality of evidence and magnitude of association between these key extreme weather events and the four malaria impact factors of interest: larval habitat, healthcare access, ITN access and housing displacement, damage and destruction. (Exhibit A1) The search elucidated clearest linkages between floods and cyclones and the four malaria impact factors. (Exhibit A2)
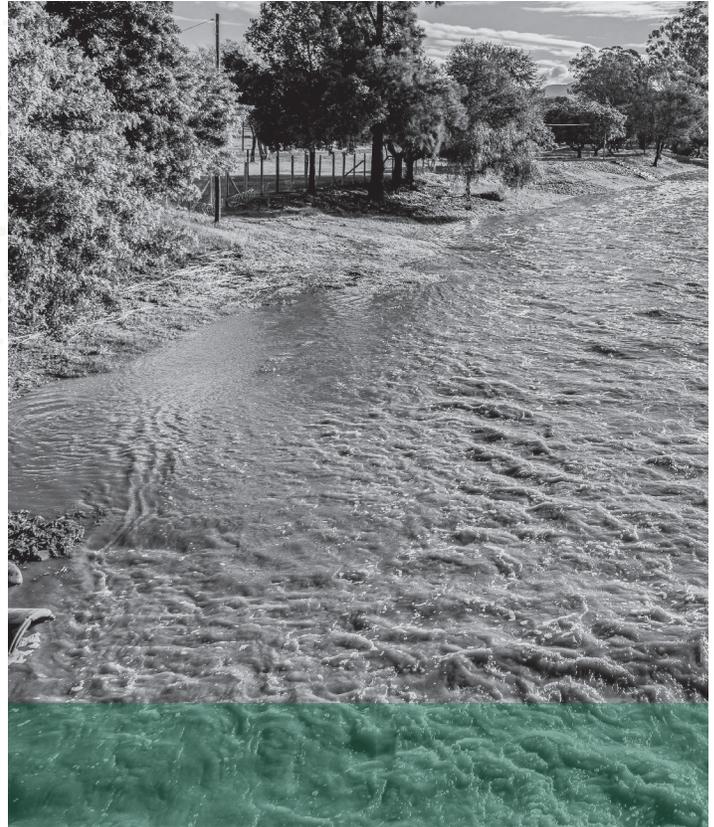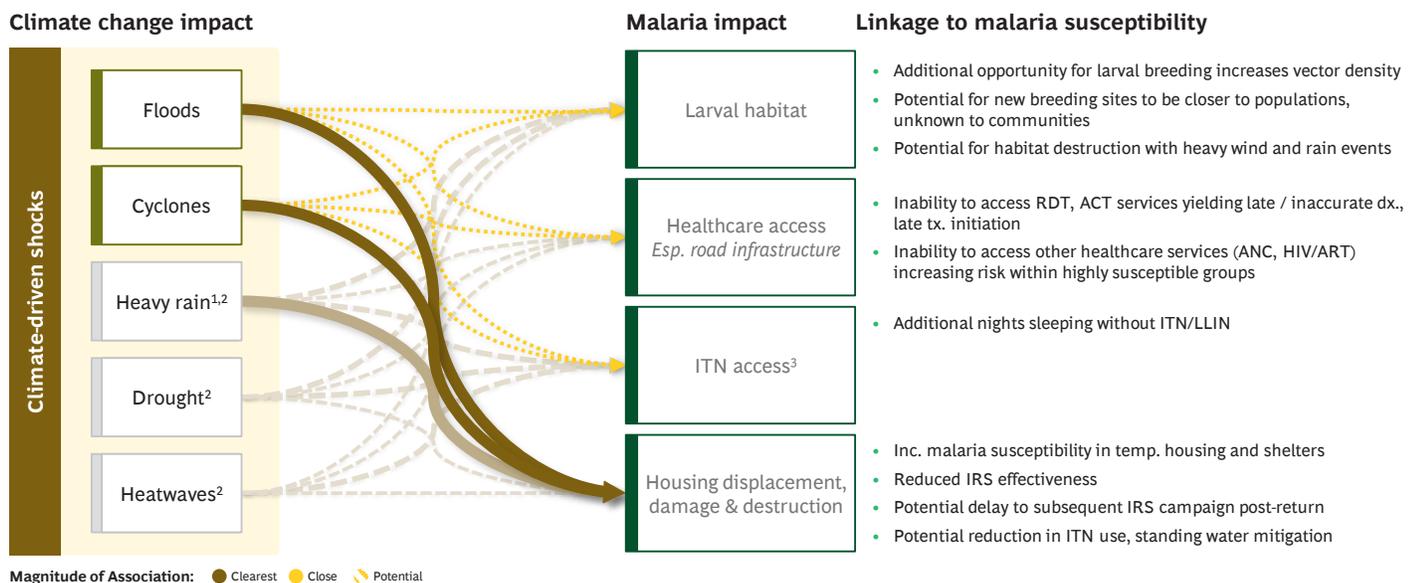

EXHIBIT A1: KEY TAKEAWAYS FROM AN EXTENSIVE LITERATURE SEARCH WHICH MAPS EXTREME WEATHER EVENTS TO THE FOUR MALARIA IMPACT FACTORS OF INTEREST BASED ON MAGNITUDE OF ASSOCIATION AND QUALITY OF EVIDENCE

Climate change impact

Climate-driven shocks

- Floods
- Cyclones
- Heavy rain[1,2]
- Drought[2]
- Heatwaves[2]

Malaria impact

- Larval habitat
- Healthcare access *Esp. road infrastructure*
- ITN access[3]
- Housing displacement, damage & destruction

Linkage to malaria susceptibility

- Additional opportunity for larval breeding increases vector density
- Potential for new breeding sites to be closer to populations, unknown to communities
- Potential for habitat destruction with heavy wind and rain events

- Inability to access RDT, ACT services yielding late / inaccurate dx., late tx. initiation
- Inability to access other healthcare services (ANC, HIV/ART) increasing risk within highly susceptible groups

- Additional nights sleeping without ITN/LLIN

- Inc. malaria susceptibility in temp. housing and shelters
- Reduced IRS effectiveness
- Potential delay to subsequent IRS campaign post-return
- Potential reduction in ITN use, standing water mitigation

Magnitude of Association: ● Clearest ● Close ⟋ Potential

1. Not resulting in floods, 2. Specific to climate-driven shock events, long onset already covered in MAP model, 3. Loss of access incurred due to (a) short-term displacement (nets left behind) and (b) loss/damage to net. Note: All searches geographically limited to Africa, larval habitat searches further limited to malaria. Defined search terms per malaria impact & weather event, general inclusion criteria & database selection *a priori*, collated relevant results after each individual search & summarized key findings. 34 total sources found, represented multiple times per malaria impact factor in some cases

EXHIBIT A2: KEY TAKEAWAYS OF A LITERATURE SEARCH ON FLOODS AND CYCLONES AND THEIR LINKAGE TO FOUR KEY MALARIA IMPACT FACTORS BASED ON MAGNITUDE OF ASSOCIATION AND QUALITY OF EVIDENCE

	Larval Habitat	Access to Healthcare (esp. roads, infrastructure)	ITN loss	Housing (short-term displacement, damage)
Floods	Potential linkage to malaria burden / High volume of quality evidence with good consensus	Potential linkage to malaria burden / Methodological challenges identified, acceptable peer-reviewed sources	Close linkage to malaria burden / High consensus in associated work, limited direct research	Clear association with malaria burden / High volume of quality evidence with good consensus

Floods

Larval Habitat
- Floods contribute to malaria epidemics, in part by improving larval habitat[1,2,3,8]
- Floods contribute to prolonged and prolific larval breeding[4,5]
- Larval source management less effective in areas affected by floods[6,7]
- Potential for previously existing larval habitats to be destroyed in floods, esp. given good drainage[22]

Access to Healthcare (esp. roads, infrastructure)
- Floods reduce walking access (by ~20%) to facilities due to road quality deterioration from floods[10]
- Floods also damage or destroy facilities and reduce options[11]
- Incomplete road mapping limits precision of quant. estimates[12]

ITN loss
- Floods lead to delays in ITN distribution campaigns[9,16]
- Longer duration without LLIN access associated with higher malaria test positivity[1]

Housing (short-term displacement, damage)
- Floods lead to housing displacement and destruction[18]
- Informal settlements are at high risk for flood damage[19]
- Temporary housing conditions post-flood increase malaria risk[20]
- Length of displacement related to increased malaria risk[1]

Cyclones

	Larval Habitat	Access to Healthcare	ITN loss	Housing
Cyclones	Potential linkage to malaria burden / Limited volume, high consensus	Potential linkage to malaria burden / High volume of quality evidence with good consensus	Close linkage to malaria burden / Limited volume, high consensus	Clear association with malaria burden / High volume of quality evidence with good consensus

Larval Habitat
- Vector breeding sites can be established following cyclone events[9]
- Potential for previously existing larval habitats to be destroyed in cyclones

Access to Healthcare
- Facility destruction from cyclones decreases health access[13,14]
- Barriers and road constraints from cyclones decrease health access[15]
- These infrastructure challenges lead to malaria outbreaks[9]

ITN loss
- Unexpected spending on disasters (include cyclones) hampers regular ITN distribution efforts[9]
- Cyclones lead to housing destruction, which led to reduced ITN usage[17]
- Malaria burden increases post-cyclone despite ITN distribution[14]

Housing
- Housing damage and destruction from cyclones leads to increased malaria positivity[17]
- Cyclones drive people to temporary housing with limited services[21]
- Housing destruction from cyclones delays IRS campaigns[9]

Magnitude of Association: ● High ◑ Medium: Close linkage ◐ Medium: Potential linkage ✎ Low   **Quality of evidence:** ● High ● Medium ● Low

Note: All searches geographically limited to Africa, larval habitat searches further limited to malaria. Defined search terms per malaria impact & weather event, general inclusion criteria & database selection *a priori*, collated relevant results after each individual search & summarized key findings. Source: 1. Xu et al., 2024, 2. Thomson et al., 2017, 3. Boyce et al., 2016, 4. Chirebyu & Chimbari, 2015, 5. Castro et al., 2010, 6. Fillinger & Lindsay, 2011, 7. Majambere et al., 2010, 8. Dambach et al., 2009, 9. Mbunge et al., 2021, 10. Mroz et al., 2023, 11. Codjoe et al., 2020, 12. Petricola et al., 2022, 13. Adriano et al., 2023, 14. Mugabe et al., 2021, 15. Hierink et al., 2020, 16. Boyce et al., 2022, 17. Searle et al., 2023, 18. Kelly-Hope et al., 2023, 19. Salami et al., 2017, 20. Kondo et al., 2002, 21. WHO, 2019, 22. Castro et al., 2010

12.2

COMPREHENSIVE MODELING METHODS

12.2.1 Climate Modeling

We projected flood and cyclone events separately through 2050. For both floods and cyclones, we created a backward event catalogue and projected future events based on these historic catalogues. We validated our results against IPCC AR6 findings. For both floods and cyclones, we modeled forward probability based on three GCMs (ACCESS-CM2, EC-Earth3-Veg-LR and MPI-ESM1-2-LR) which were downscaled and bias-corrected[30] and under two SSP-RCP scenarios (SSP2-4.5, SSP5-8.5). We reviewed the flood and cyclone model's ability to representENSO via proxy by including sea surface temperature and sea surface temperature anomaly. The malaria model was applied to each of the three ensemble members independently, yielding three sets of predicted results which were then recombined into a mean, minimum and maximum to reflect the inter-model variation.

12.2.1.1 Floods

Backward Catalog: We created a historic catalogue of floods at the Level 4 Basin (Pfafstetter codes) level using bias-corrected historic data from certain floods in Floodbase to balance granularity and complexity, yielding 251 total L4 subunits. Floodbase uses a convolutional neural network based on MODIS satellite imagery at 230m resolution.
From this baseline, we joined floods in the same L4 basin and month by extent and duration (i.e., max(start_date) – min(start_date)). We further separated these into unique L4 basin x calendar month units to arrive at final model

inputs. Flood events were also assigned climate variables from the month of the given flood event. Floods in the same L3 basin and month were grouped for both forward and backward catalogues; however, the original duration of each flood and basin is retained at the L4 level. We included pluvial (surface) and fluvial (river) floods. No coastal floods were recorded or available in the Dartmouth Flood Observatory (DFO) or Floodbase; we excluded these to avoid quantifying the impact of long-onset climate change through sea level rise, focusing on extreme weather impacts for this exercise.

Forward Catalog: The forward catalogue models probability of floods and includes severity, extent, area and duration. We used a random forest classifier on historic events (monthly flood events by L4 basin [n=~251]) to determine important features. Training data included historical flood events from the backward catalogue including relevant climate data by basin, topology and land cover. We also used the Fathom dataset in the forward catalogue to ascertain future flood risk by return period. Seventy percent of the data were used for training and 30% were used for the test dataset. We oversampled the training dataset due to data imbalance (an optimized rate of 3.7x flood events was selected using the Python package 'scikit-learn'). Accuracy was calculated on the test dataset, which was a realistic (not oversampled) dataset. The AUC for the frequency model was 0.84, R2 for the duration model was 0.83 and R2 for the extent model was 0.81.

12.2.1.2 Cyclones

Backward Catalog: We used IBTrACS (International Best Track Archive for Climate Stewardship) as a baseline of historic cyclone events, overlaid with CMIP6 global climate model data. We note the potential for missing

data in this dataset while recognizing its utility as the gold standard for historic cyclone cataloguing. We created a spatiotemporal backward catalogue (a shapefile) with the track of each historic cyclone and temporal features as lines. We classified cyclones from 1-5 using the Saffir-Simpson Hurricane Wind Scale. We then filtered for historic cyclones which made landfall or which were within 50km of the coast of Africa (n=192 from 1980-2024), based on the assumptions that only these cyclones which make landfall or which are close (<=50km) to the coast would be likely to drive meaningful malaria burden impact. Finally, we excluded extratropical cyclones due to their minimal impact on malaria burden.

Forward Catalog: The forward catalogue models spatial extent per projected cyclone and temporal track and features of projected cyclones separately, based on recent research using the Imperial College Storm Model (IRIS) Datasets. (31) We first modeled the spatial probability of LMI (Lifetime Maximum Intensity) locations and months for future cyclones making landfall in Africa. This is based on coordinates of past cyclones' first observations and observance of Poisson's law (frequency and distribution has equal mean and variance). We then projected the cyclone track: for each LMI point, we projected synthetic tracks based on statistical correlation with climate drivers and past tracks. We finally projected the maximum sustained wind speed per projected event using statistical correlation with climate drivers. Only cyclones with landfall and with wind of at least a Category 1 wind speed on the Saffir-Simpson Hurricane Wind Scale are included in the forward catalogue. Modeling begins at the LMI; time steps before LMI are excluded. Decaying tropical cyclone tracks are terminated at the point at which wind speed falls below the tropical depression threshold. Notably, basins are simulated independently, so any inter-basin dependence is not present in the forward catalogue. Given the choice to limit tropical cyclones to at least Category 1 wind speed, the model will underestimate damage slightly: in the past 20 years, 14 tropical storms below Category 1 wind speed have occurred, of which four have caused material damage or displacement.

12.2.2   Malaria Modeling

Geospatial Malaria Model: The Malaria Atlas Project has developed a model linking high-resolution environmental, socio-economic and intervention coverage (ITNs, IRS, effective treatment) data with observed malaria risk in Africa, producing geospatial estimates of malaria risk, disease burden, and the impact of interventions and the climate.[32] Using this modelling framework, we estimated malaria burden at both contemporary and heavy levels of suppression for each member of the climate model ensemble and baseline to produce an ensemble of clinical incidence and mortality projections, the mean of which was used for the estimates presented here. Population projections were extracted from Wang et al, 2022.[33]

Estimating Impact of Extreme Weather on Malaria Drivers: The link between extreme weather and malaria transmission was characterised by associating with each event a spatio-temporal of four key drivers: larval habitat post-flooding; access to improved housing; ITN coverage; and access to effective treatment for clinical malaria. The magnitude and duration of these impacts were event class and severity-specific and were parameterized based on comprehensive literature review and stakeholder engagement (35+ interviews, Exhibit A3). Our parameters were chosen to represent unmitigated impacts of extreme weather on malaria control, so that e.g., an ITN once lost would not be replaced through an emergency mass campaign.

EXHIBIT A3: MALARIA DRIVERS, IMPACT EXTENT, AND RECOVERY TIME WITH COMMENTARY

Malaria Driver	Description	Urbanicity	Max Impact Extent (% of community)	Recovery Time (months) 50% (Median)	99%	Commentary
Housing	Housing displacement in immediate wake of extreme weather event	All	50-70% (cyclones) 70-100% (floods)	N/A	N/A	• Drawn from DFO, EM-DAT and IFRC databases/reports; composite summary based on flood duration, summary; water recession estimate from Li et al., 2022 • Encapsulates a wide variety of impact/severity levels and baseline level of improved housing • Goal is to define a broad average/range
	Housing damage after extreme weather event	Urban	25%	12	36	• While urban housing (excluding peri-urban informal settlements) may have less damage, longer recovery times on average because of higher costs to repair and more difficulty in obtaining materials (e.g., metal roofs) • Some quant geospatial data used to assess housing damage where available • Socialized and pressure-tested with humanitarian aid workers, national malaria control leaders and other global health experts to define broad ranges • E.g., 23% of houses damaged in urban areas in 2022 Nigeria floods
	Housing damage after extreme weather event	Rural	25%	12	36	• Rural housing (including peri-urban informal settlements) may be subject to greater damage, but recovery is often shorter for mud construction given materials are readily available and work is performed by community members • Some quant geospatial data used to assess housing damage where available • Socialized and pressure-tested with humanitarian aid workers, national malaria control leaders and other global health experts to define broad ranges • The final houses to be repaired have an extended (>36mo) recovery • E.g., 54% of houses damaged in urban areas in 2022 Nigeria floods
ITN Access	ITN loss in immediate wake of extreme weather event	All	Equivalent to max housing displacement: If 70% displaced, all 70% leave ITN in home	N/A	N/A	• Expert interviews with malaria implementation and humanitarian orgs confirmed that in emergencies, households are unlikely to take nets with them despite them being light and easy to transport • Expert interviews also note difficulty in deploying nets in temporary housing situations (unable to hang nets in tents or in converted areas including schools)
	Extended ITN loss following an extreme weather event	All	N/A	18 (next campaign)	18 (next campaign)	• Expert interviews confirmed that there are sometimes efforts to push mass distribution campaigns up if an extreme weather event occurs soon after a recent distribution – often procurement delays limit the extent to which these efforts are successful • Expert interviews confirm efforts to use continuous distribution stocks after an extreme weather event to deliver ITNs to highest need areas; after multiple storms, stocks can be depleted quickly • Malawi cyclones provide further evidence that emergency stocks are depleted quickly (Malawi MOH research shows emergency reserves of 10,000 nets)

1. 'Metalled' (UK) roads are equivalent to 'paved' (US) roads, made of layers of small stones compacted into a hard, durable surface

Malaria Driver	Description	Urbanicity	Max Impact Extent (% of community)	Recovery Time (months)		Commentary
				50% (Median)	99%	
Healthcare Access (to sufficient extent to provide malaria treatment)	Housing displacement in immediate wake of extreme weather event	All	50-70% (cyclones) 70-100% (floods)	N/A	N/A	• Assumption validated through expert interviews • Considered a cumulative impact of road, bridge, healthcare center, staffing and supply chain concerns in the immediate wake of a weather event in which interruption of any access p athway interrupts treatment access
	Housing damage after extreme weather event	Urban	25%	12	36	• Any gravel / dirt road will return to service as soon as floodwaters recede • Metalled1 roads in urban areas are expected to be repaired before rural metalled roads given extent of travel and usage • Full recovery of metalled roads expected to be on extended timeline (if at all) • E.g., ~25% of highways in Sudan damaged in 2020 floods
	Housing damage after extreme weather event	Rural	25%	12	36	• gravel / dirt road will return to service as soon as flood waters recede • Metalled roads in rural areas are expected to be repaired after urban metalled roads given extent of travel and usage • Full recovery of metalled roads unclear for rural areas (likely that some will not be repaired) • E.g., ~57% of roads never repaired after Kenya flooding in 2017
	ITN loss in immediate wake of extreme weather event	All	Equivalent to max housing displacement: If 70% displaced, all 70% leave ITN in home	N/A	N/A	• Expected that some facilities in urban areas will return to service quickly • Per expert discussions, expect urban facilities to have more infrastructure needs than rural health posts • Expected extended timeline for full return to service for all health centers • Limited mitigating impact of community health workers in maintaining service delivery: community health workers live in affected communities, have limited stock and have varying levels of ability to provide treatment
	Extended ITN loss following an extreme weather event	All	N/A	18 (next campaign)	18 (next campaign)	• Expected that rural facilities will return to service quickly given simpler infrastructure and more limited breadth of services • Per expert discussions, expect rural facilities and treatment provision to come online relatively quickly, even if entire facility is not operable; potentially more sensitive to supply chain disruptions than urban • Expected extended timeline for full return to service for all health centers • Limited mitigating impact of community health workers in maintaining service delivery: community health workers live in affected communities, have limited stock and have varying levels of ability to provide treatment • Post-Idai satellite imagery research shows some rapid repair of rural health centers (<3 mo.) (Glowac et al., 2024 preprint)

For all malaria drivers, we collected data on the acute impact (in the immediate aftermath of a flood or cyclone, what is the maximum fraction of a community with relevant impact) and the lasting impact (both time to 50%/median recovery and time to 99%/full recovery). We collected a range of values for all drivers and derived a single point estimate for each for input into the MAP model.

EXHIBIT A4: VISUAL DESCRIPTION OF MAXIMUM IMPACT AND RECOVERY TIMES BY TRANSMISSION DRIVER

Illustrative example: Housing access

a Acute impact

Access loss to ~**70%** of houses in immediate aftermath of an extreme weather event
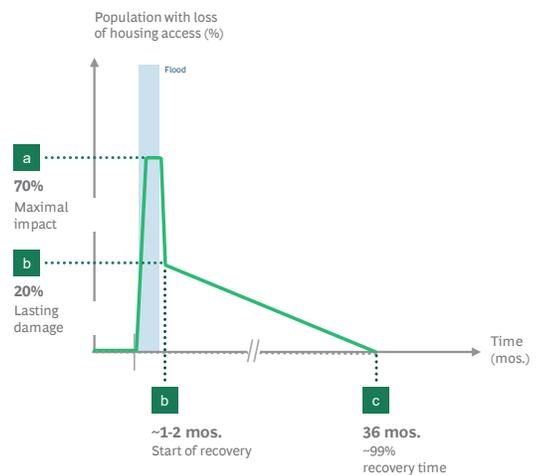
b Lasting impact

After ~**1-2 months**, flood waters recede and ~80% of the population can return to their homes. **20% have damaged homes**

c ~99% recovery

~100% of access is regained as new homes are built over the next ~**36 months**

These points are translated into a recovery path

Population with loss of housing access (%)

Flood

a 70% Maximal impact

b 20% Lasting damage

Time (mos.)

b ~1-2 mos. Start of recovery

c 36 mos. ~99% recovery time

These values were used to parameterise recovery curves (see Exhibit A4). ITN, access to improved housing, and access to healthcare were then perturbed by these curves for each event footprint and duration. These were then combined with long-onset climate drivers (from the relevant downscaled and bias-corrected GCM outputs) in the malaria model, yielding estimated malaria burden and mortality. Comparison to estimates generated with the contemporary baseline scenario thus yielded a delta in burden and mortality attributable to climate change.

We validated these malaria impact factor inputs extensively, including through socialization calls, a literature review and review of humanitarian reports to align on agreeable values for impact factors.

12.3

LIMITATIONS AND CONSIDERATIONS

Our results should be interpreted within the context of their inherent limitations. There is limited consensus between climate models on the extent and scale of change in the climate factors considered here, partially mitigated by our use of a three GCM ensemble and medium-term 2049 horizon.

No new tools are considered in the modeled malaria death and case estimates, only ITN, IRS and access to effective antimalarial treatment parameterized in the model. Other tools, (SMC, vaccine, and IPTp) were not considered in the modeling, and climate extremes impacting delivery of these interventions would lead to additional estimated cases and deaths. We assume continued efficacy of all tools in the model at 2023 levels. There is no explicit consideration of resistance and all coverage estimates are effective coverage (specifically for ITNs – this captures effective ITN coverage or the actual proportion of people sleeping under an ITN).
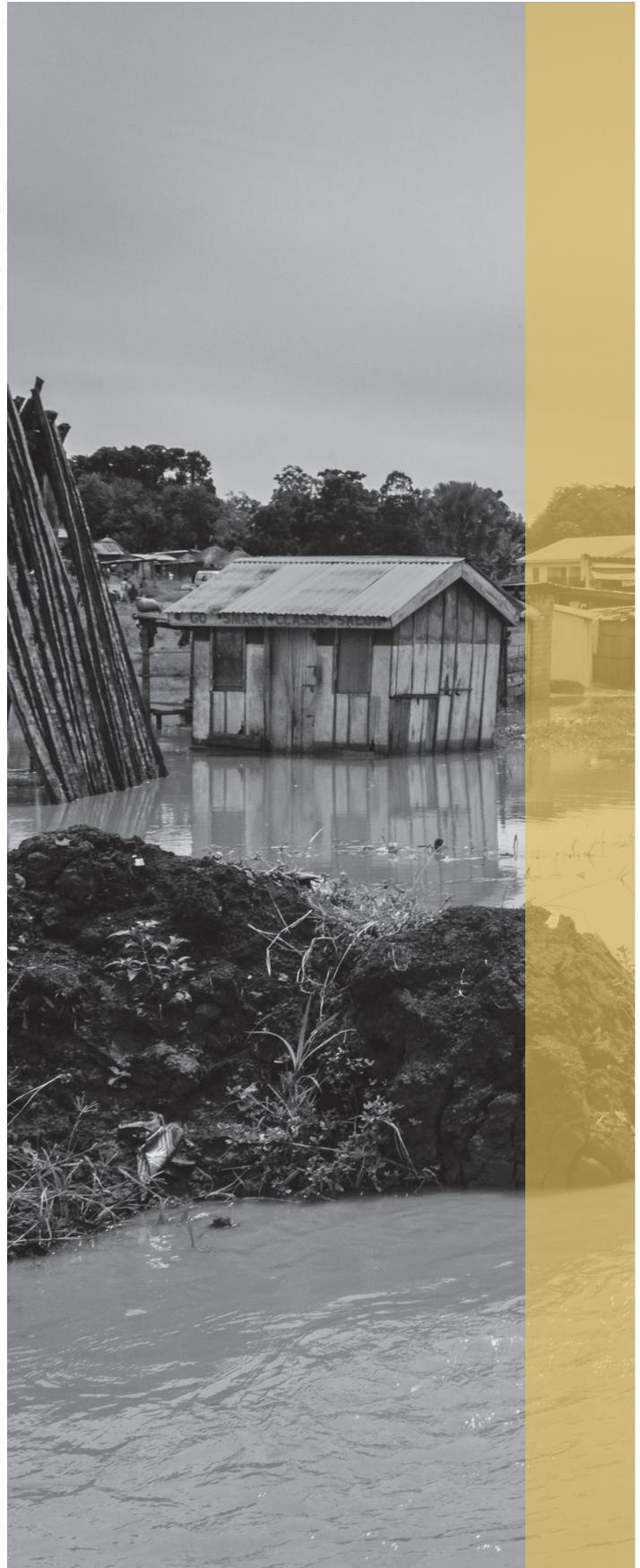
12.4

ADDITIONAL RESULTS

12.4.1 Climate Deep Dive

The following exhibits outline detailed climate methods, outputs, and validation.

> **EXHIBIT A5:** UNDER SSP5-8.5, FLOODING IS EXPECTED TO INCREASE 23-31% TO 2050 (VERSUS HISTORICAL CATALOG)

Methodology for projections

Basis: Climate models (GCMs) provide spatio-temporal projections of climate variables under different shared socio-economic pathways (SSPs)

Floods: Relative importance of climate and geographical features in historical events was used to project the probability, duration and extent of flooding by month and water basin to 2050

Cyclones: Using physical and statistical principles of cyclogenesis, cyclones were projected forward to 2050, leveraging an existing synthetic database for cyclone tracks (ICL, 2024)

Rainfall | Sea Level Pressure | Wind (U) | Wind (V)

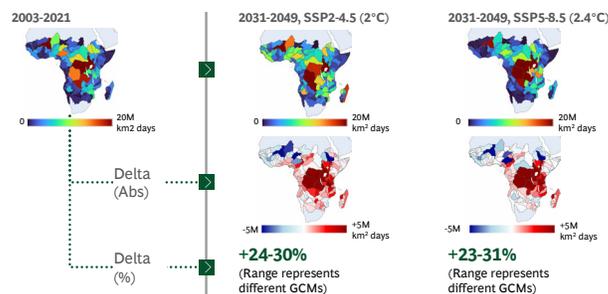Legend: Historical — SSP2-4.5 (2°C) — SSP5-8.5 (2.4°C)
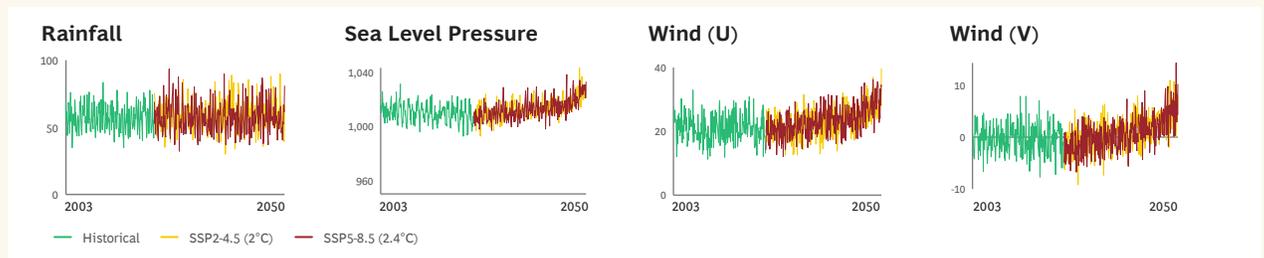
Limitations

- Modelling ceteris paribus: no changes in land cover or use are assumed
- Excludes Tropical Storms (< Cat 1), of which 4 of 20 have caused damage in past 20 years

Outputs
(Visualizations show ACCESS CM2, ranges represent outputs across ACCESS CM2)
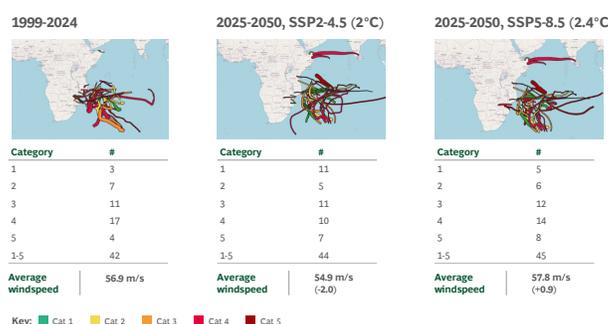
Validation

Floods
Flooding is projected to increase ~23-31%, with little variation seen between climate models

2003-2021 | 2031-2049, SSP2-4.5 (2°C) | 2031-2049, SSP5-8.5 (2.4°C)

Delta (Abs)

Delta (%)

+24-30% (Range represents different GCMs) | **+23-31%** (Range represents different GCMs)

The IPCC AR6 concludes a high confidence in increase in heavy rain and pluvial flooding across Sub-Saharan Africa, except in south west. Greater deviation between scenarios expected from ~2045, as per GCMs

Cyclones
Cyclones are projected to increase in severity the worst case scenario (+0.9 m/s wind-speed); Frequency of Cat 1-5 projected to increase slightly (~4-7%), implying a decline in Tropical Storms (lower than Cat 1)

The IPCC AR6 concludes a moderate confidence in the increase in severity and decrease in frequency of cyclones

1999-2024		2025-2050, SSP2-4.5 (2°C)		2025-2050, SSP5-8.5 (2.4°C)	
Category	**#**	**Category**	**#**	**Category**	**#**
1	3	1	11	1	5
2	7	2	5	2	6
3	11	3	11	3	12
4	17	4	10	4	14
5	4	5	7	5	8
1-5	42	1-5	44	1-5	45
Average windspeed	56.9 m/s	**Average windspeed**	54.9 m/s (-2.0)	**Average windspeed**	57.8 m/s (+0.9)

Key: Cat 1 — Cat 2 — Cat 3 — Cat 4 — Cat 5

Methodology

Using historical flood events (Floodbase) and GCMs downscaled and bias corrected using cumulative distribution functions, four models trained to project attributes of future floods:

Frequency: Likelihood of a flood occurring in a given basin in a given month

Duration: Number of days of flooding event

Extent: Number of km2 flooded in an event

Areas: Grid cells flooded for each extent
- Each cell allocated a flood risk based on (70% weighting) frequency of historical floods and (30% weighting) Fathom risk scores. Cells are flooded until extent reached

Total flooding is presented as km2 days of flooding to account for frequency, duration and extent
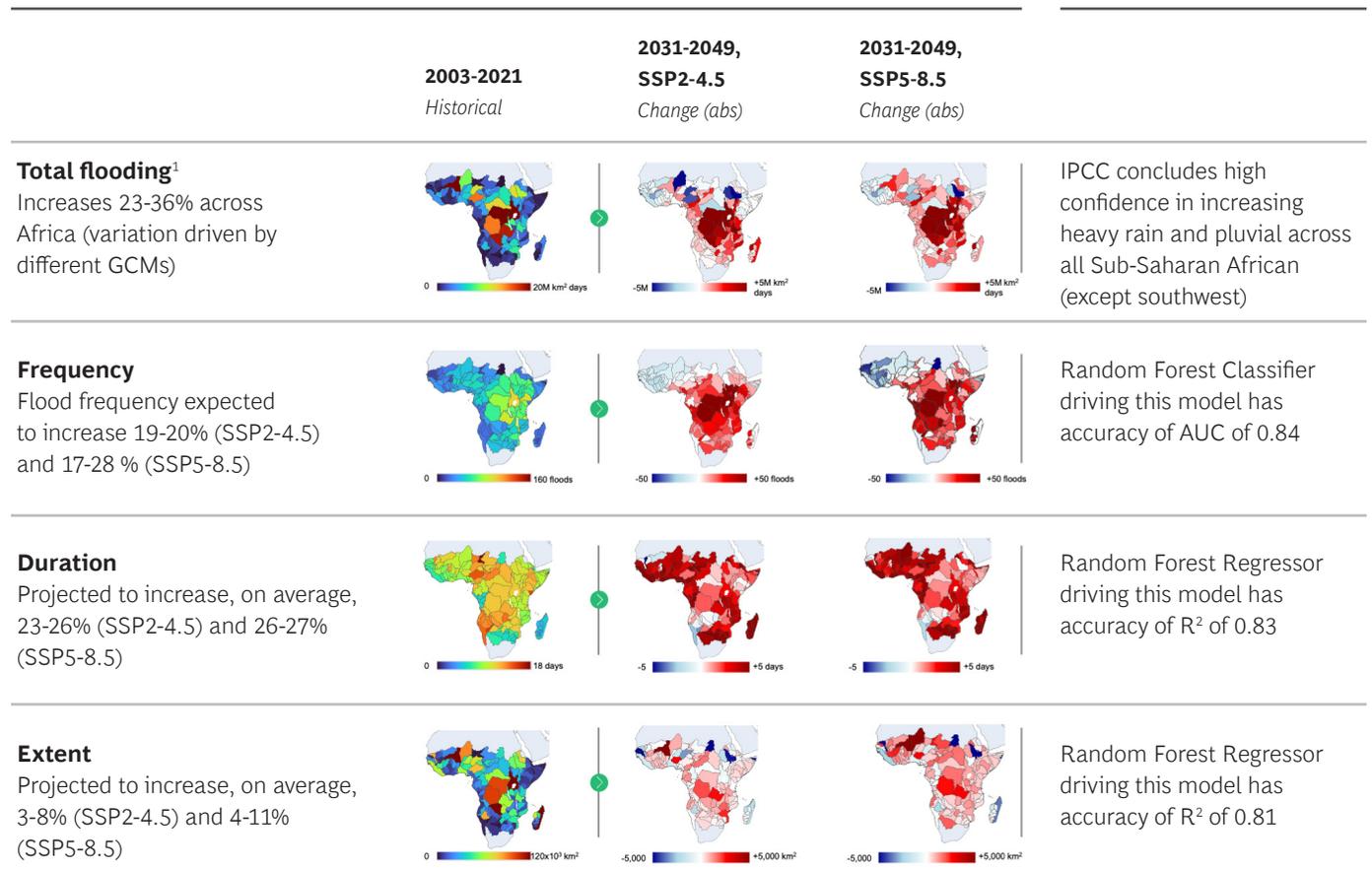
Limitations

Modelling *ceteris paribus*: no changes in land cover or use are assumed

Further GCMs could be use to further improve accuracy of findings

Accuracy of 'area' flooding a function of granularity of water basins – greater accuracy could be achieved with greater granularity across basins

Outputs: Attributions of projections

Validation

|	2003-2021 *Historical*	2031-2049, SSP2-4.5 *Change (abs)*	2031-2049, SSP5-8.5 *Change (abs)*	
Total flooding[1] Increases 23-36% across Africa (variation driven by different GCMs)	0 — 20M km² days	-5M — +5M km² days	-5M — +5M km² days	IPCC concludes high confidence in increasing heavy rain and pluvial across all Sub-Saharan African (except southwest)
Frequency Flood frequency expected to increase 19-20% (SSP2-4.5) and 17-28 % (SSP5-8.5)	0 — 160 floods	-50 — +50 floods	-50 — +50 floods	Random Forest Classifier driving this model has accuracy of AUC of 0.84
Duration Projected to increase, on average, 23-26% (SSP2-4.5) and 26-27% (SSP5-8.5)	0 — 18 days	-5 — +5 days	-5 — +5 days	Random Forest Regressor driving this model has accuracy of R^2 of 0.83
Extent Projected to increase, on average, 3-8% (SSP2-4.5) and 4-11% (SSP5-8.5)	0 — 120x10³ km²	-5,000 — +5,000 km²	-5,000 — +5,000 km²	Random Forest Regressor driving this model has accuracy of R^2 of 0.81

1. Total flooding represented as km² days of flooding, to account for changes in frequency, duration and extent

EXHIBIT A7: FACTORING IN FREQUENCY, DURATION, AND EXTENT, FLOODING IS PROJECTED TO INCREASE BETWEEN 24% AND 30% ACROSS ALL AFRICA UNDER SCENARIO SSP2-4.5 VS HISTORICAL CATALOG

Shows % difference, SSP2-4.5

Historic (2003-2021)

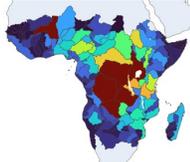463M area days (km² days)
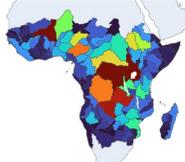
0   20M km² days

Absolute >

Percentage change >

Projections under SSP2-4.5 (2031-2049)

GCM: ACCESS-CM2
601M area days (km² days)

0   20M km² days

+138M (+30%) total area days (km² days)

-100%   +100%

GCM: EC-Earth3-Veg-LR
575M area days (km² days)

0   20M km² days

+112M (+24%) total area days (km² days)
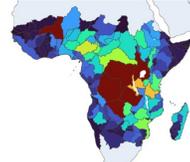
-100%   +100%

GCM: MPI-ESM1-2-LR
576M area days (km² days)

0   20M km² days
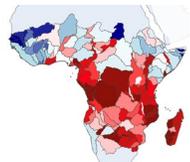
+113M (+24%) total area days (km² days)
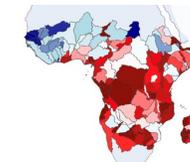
-100%   +100%

Note: Area days used to capture frequency, duration and extent of flooding

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Methodology for projections

As outlined by Sparks, N., and Toumi, R. (2024):

Determine spatial probability of Lifetime Maximum Intensity (LMI) locations and month for future cyclones that make landfall in Africa using coordinates of past cyclones' first observations & observations of Poisson's Law

Project cyclone tracks for each LMI point using statistical correlation with climate drivers and past tracks

Project maximum sustained wind speed using statistical correlation with climate drivers

Limitations

Result from use of latest methodology & datasets published in April 2024 [1]:

- Only cyclones that reach at least Category 1 are included (i.e., tropical storms and any associated damage are excluded)

This is likely to result in an underestimate of potential damage. Of 14 tropical storms in past 20 years, 4 have caused material damage.
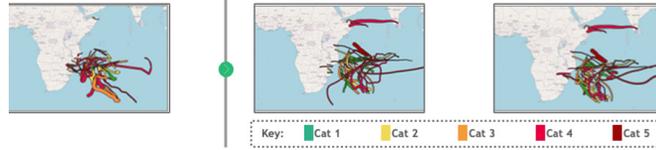
Outputs: Attributions of projections

Validation

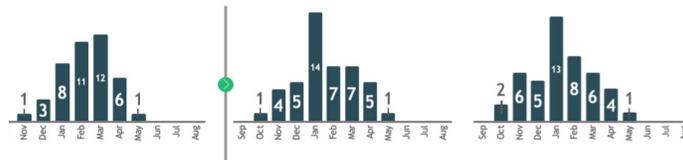|	1999-2024	2025-2050, SSP2-4.5	2025-2050, SSP5-8.5	
Cyclone Tracks Projected cyclone tracks fall within the South-East of Africa, including Madagascar		Key: Cat 1 Cat 2 Cat 3 Cat 4 Cat 5		Similar morphology is seen as per historical catalogues, with cyclone radii increasing at landfall driven by surface drying [2]
Seasonal fluctuation Seasonal fluctuations observed, with a shift of the peak to January aligning with floods				Cyclone occurrence remains within cyclone season. Seasonal advance is observed with a left-shift of the peak [3]
Frequency and severity of events Increase in most severe cyclones (Cat 5), and an increase in average windspeed				High confidence in ↑ in severity & ↓ in frequency (IPCC AR6) [4]. This is consistent with projections (with implied decrease of tropical storm frequency, which is not included in model outputs)

Cyclone Tracks (1999-2024):
Seasonal fluctuation: Nov 1, Dec 3, Jan 8, Feb 11, Mar 12, Apr 6, May 1

Seasonal fluctuation (SSP2-4.5): Sep 1, Oct 4, Nov 5, Dec 14, Jan 7, Feb 7, Mar 5, Apr 1

Seasonal fluctuation (SSP5-8.5): Sep 2, Oct 6, Nov 5, Dec 13, Jan 8, Feb 6, Mar 4, Apr 1

Frequency and severity (1999-2024):
Category	#
1	3
2	7
3	11
4	17
5	4
1-5	42
Avg. windspeed (m/s)	56.9

Frequency and severity (SSP2-4.5):
Category	#
1	11
2	5
3	11
4	10
5	7
1-5	44
Avg. windspeed (m/s)	54.9 (-2.0)

Frequency and severity (SSP5-8.5):
Category	#
1	5
2	6
3	12
4	14
5	8
1-5	45
Avg. windspeed (m/s)	57.8 (+0.9)

Data Source: IBTrACS References: [1] Sparks, N., Toumi, R. The Imperial College Storm Model (IRIS) Dataset. Sci Data 11, 424 (2024). https://doi.org/10.1038/s41597-024-03250-y [2] Chen, J., and D. R. Chavas, 2020: The Transient Responses of an Axisymmetric Tropical Cyclone to Instantaneous Surface Roughening and Drying. J. Atmos. Sci., 77, 2807–2834, https://doi.org/10.1175/JAS-D-19-0320.1 [3] Shan, K., Lin, Y., Chu, PS. et al. Seasonal advance of intense tropical cyclones in a warming climate. Nature 623, 83–89 (2023). https://doi.org/10.1038/s41586-023-06544-0 [4] IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 35-115, doi: 10.59327/IPCC/AR6-9789291691647.

12.4.2 Country-Level Climate Change Impacts on Malaria

The countries with the greatest net impact of climate change on malaria deaths are listed in Exhibit 9 below (Nigeria, Uganda, Mali, DRC, Tanzania, Burkina Faso, Kenya, Mozambique, Sudan and Ghana).

EXHIBIT A9: COUNTRY IMPACT OF CLIMATE CHANGE ON MALARIA DEATHS THROUGH 2049

SSP 2-4.5, through 2049

Country	Current projection, no climate change	Contribution of Climate Change Drivers to Death						Net impact[1]			Net deaths under climate change
		Long onset			Extreme weather						
Nigeria	5,477K	25K	0.5%	⌃	155K	2.8%	⌃	180K	3.3%	⌃	5,657K
Uganda	546K	12K	2.1%	⌃	36K	6.6%	⌃	48K	8.7%	⌃	594K
Mali	555K	-4K	-0.8%	⌄	48K	8.6%	⌃	44K	7.8%	⌃	598K
DRC	1,973K	7K	0.3%	⌃	35K	1.8%	⌃	41K	2.1%	⌃	2,014K
Tanzania	732K	4K	0.5%	⌃	35K	4.8%	⌃	39K	5.4%	⌃	771K
Burkina Faso	475K	-7K	-1.4%	⌄	28K	5.9%	⌃	21K	4.5%	⌃	496K
Kenya	309K	9K	2.8%	⌃	11K	3.7%	⌃	20K	6.6%	⌃	329K
Mozambique	535K	-3K	-0.6%	⌄	17K	3.2%	⌃	14K	2.7%	⌃	550K
Sudan	194K	-2K	-1.0%	⌄	15K	7.7%	⌃	13K	6.7%	⌃	208K
Ghana	301K	1K	0.3%	⌃	11K	3.6%	⌃	12K	3.9%	⌃	313K

1. Sum of long onset & extreme weather contributions, may not sum exactly due to rounding
Source: Malaria Atlas Project, BCG Analysis

⌄ Fewer deaths   ⌃ More deaths

12.4.3   Cost Analysis Assumptions

■ **EXHIBIT A10:** SUMMARY OF COST ASSUMPTIONS

Variable	Calculation Description	Overview of Assumptions
Vector Control (ITN)	Cost per ITN (including import and delivery) * ITN coverage target * population at risk divided by the product of (people per net * net replacement frequency)	• For all scenarios, use GFATM reference costs for pyretrhroid-chlorofenapyr nets ($2.65), add a markup of 68% on cost of net for import and delivery based on lit. estimates, assume a two-year replacement timeline based on the GTS 'Accelerate 2' scenario and assume 1.8 people covered per net based on literature estimates and pressured tested by IDM. • For all scenarios, use the full population at risk (regardless of number vaccinated in eradication scenario) • For BAU and eradication, use current coverage levels. For heavy suppression, scale current coverage levels to 95% by 2030 and maintain through 2049/2080.
	Cost of IRS per person (including import and delivery) * IRS coverage * population at risk	• For all scenarios, use GFATM reference costs for IRS sachets ($12.95 per sachet) and add 68% markup on cost of chemical for import and delivery based on lit. estimates, taking assumptions for number of sachets per household (1 per 200m2 dwelling, using 8L diluted insecticide, assuming ~6.9 people per household). • For all scenarios, use the full population at risk (regardless of number vaccinated in eradication scenario) • Keep coverage levels constant for all scenarios over time (current coverage level).
Treatment (ACT)	Cost of course of ACT (including import and delivery) * number of cases * ACT coverage (cases vary based on SSP: either SSP2-4.5 or SSP5-8.5)	• For all scenarios use GFATM reference costs for ACT (ASPY: $1.32) and a 70% markup on cost of treatment for import, delivery and community-based treatment costs based on literature estimates. • For all scenarios, capture estimated cases for two SSPs: 2-4.5 and 5-8.5. For all scenarios, use number of cases direct from MAP estimates (regardless of number of people vaccinated) • For BAU and eradication, use current coverage levels. For heavy suppression, scale current coverage levels to 95% by 2030 and maintain through 2049/2080.
Diagnostic Testing (RDT)	Cost of RDT (including import and delivery) * number of non-malaria fevers * population at risk * RDT coverage (number of non-malaria fevers varies based on age group)	• For all scenarios, use GFATM reference costs for RDTs (EXW1 cost of Pan-LDH, HRP2, pf-LDH tests: $0.48) and add a 55% markup on cost of RDT for import and delivery. Assume one non-malaria fever (NMF) for people over 5, and 3.5 NMF for those 5 and under. • For all scenarios, use the full population at risk (regardless of number vaccinated in eradication scenario) • For all scenarios, assume 95% diagnostic coverage.
Chemoprevention (SMC)	Cost of four cycles of SMC (one season, including import and delivery) * three rounds of SMC * population under 5 * SMC coverage	• For all scenarios, use GFATM reference costs for SP-AQ * four cycles ($0.27 * 4 = $1.84), add a markup of 70% on cost of treatment for import and delivery based on lit. estimates. • For all scenarios, use the full population at risk (under 5) • Derive current coverage levels from the WHO world malaria report and assume three rounds based on # children treated and # of treatments distributed. • For BAU and eradication, use current coverage levels. For heavy suppression, scale current coverage levels to 95% by 2030 and maintain through 2049/2080. • For eradication, discontinue coverage in 2036 (after vaccine introduction in 2035)

1. Ex-works (e.g., cost of a product when it leaves the factory)

Variable	Calculation Description	Overview of Assumptions
Chemoprevention (IPTp)	Cost of IPTp treatment * coverage of IPTp * approximation of total pregnant people	• For all scenarios, use GFATM reference costs for SP * four doses ($0.31 * 4 = $1.84), add a markup of 15% on cost of treatment for import and delivery based on lit. estimates. • For all scenarios, use the full population at risk (regardless of number of people vaccinated) • Approximate total pregnant people using UN crude birth rates. Approximate coverage through several assumptions: Assume 90% coverage of IPTp in all scenarios, assume 50% of pregnant population is eligible (in 2nd or 3rd trimester) and assume 72% of pregnancies end in live birth to arrive at 32% coverage of total population.
MDA	Cost of MDA treatment * MDA coverage * eligible population (only for settings with API <250)	• For all scenarios, use GFATM reference costs for DP + SLD-PQ ($1.68), add a markup of 70% on cost of treatment for import and delivery based on lit. estimates. • Approximate total eligible population using WHO malaria guidelines reference data (on average, 1% of total population at risk). • For all scenarios, apply costs when API is <250 from present to 2049/2080.
RandD	Annual global cost of RandD	• For BAU and heavy suppression, use average actual RandD spending (2013-2022) of $685M p.a., 2024-2080. For eradication, use average actual RandD spending (2013-2022) for all RandD categories except vaccine and vector control. For vaccine and vector control, use RandD target spend (2021-2030) for a total RandD spend of $793M p.a., 2024-2049
Surveillance	Cost per case investigation * number of cases * case	• For all scenarios use a cost per case of $426.96 based on available literature estimates. • For all scenarios, capture estimated cases for two SSPs: 2-4.5 and 5-8.5. • For all scenarios, use number of cases direct from MAP estimates (regardless of number of people vaccinated) • For all scenarios, use a sliding coverage scale based on API, based on literature: 4 <= API <=100: 15% of cases, 3 <= API <=4: 30% of cases, 2 <= API <=3: 50% of cases, 1 <= API <=2: 70% of cases, 0.5 <= API <=1: 90% of cases, 0.5 <= API : 100% of cases). • For eradication, extend surveillance costs through 2052 (target eradication 2049)
Vaccine	Cost per person vaccinated * population vaccinated	• For the eradication scenario, use a cost of $10 for full protection (spread across 3 doses given in the same year) based on available TPP estimates. Ignore effectiveness (set at 100% for illustration, but no impact on future cases or deaths in the model). Implement an all-ages campaign covering 75% of the population in 2035, and a subsequent campaign with the same coverage in 2038. Assume 3 years of protection per round. For campaigns, add $0.60 per dose administered. • For other years after 2035, proxy child immunization coverage through DTP3 (12-23mo) coverage based on latest UNICEF values (2021) and literature estimates (to support specific vaccine proxy choice). Achieve 95% childhood vaccine coverage (1 year olds) by 2040 and maintain coverage through 2049.
Gene Drive	Cost per capita * population	• Use an area-based method starting in 2031 and ending in 2036 • Area-based: Apply a 'releases-per-km' metric to full country area and model cost per release (cost per mosquito [production and packaging] x 15k mosquitos per release, ground transport). Add an upfront $2M CapEx cost for production facilities in each country (on average, to account for scope/ scale/ implementation differences) and account for $350k OpEx per site, per year. • Run two scenarios: one with one release campaign per year and one with two release campaigns per year • Add $1M per country, per year for monitoring costs based on PMI MOP entomologic monitoring spending

ORGANIZATIONS

Boston Consulting Group (**BCG**) is a global management consulting firm and a leading advisor on business strategy. BCG works with organizations in the social, public, and private sectors to deliver solutions to the most complex problems in contemporary society.

Malaria Atlas Project (**MAP**) is an international research collaboration and designated World Health Organization Collaborating Centre in Geospatial Disease Modelling that tracks the global fight against malaria. MAP combines innovative data and analytics, global collaboration and local engagement to deliver insights for impactful malaria policy and control.

Guided by the belief that every life has equal value, the **Bill and Melinda Gates Foundation** works to help all people lead healthy, productive lives. In developing countries, it focuses on improving people's health and giving them the chance to lift themselves out of hunger and extreme poverty. In the United States, it seeks to ensure that all people—especially those with the fewest resources—have access to the opportunities they need to succeed in school and life. Based in Seattle, Washington, the foundation is led by CEO Mark Suzman, under the direction of chair Bill Gates and the board of trustees.

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Gething, P., Symons, T., Woods, W., Sukitsch, N., Potere, D., Desai, N., Balzorolo, A., & Moran, A. (2024). *Climate impacts on malaria in Africa.* The Kids Research Institute Australia, Curtin University and Boston Consulting Group.

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ACKNOWLEDGEMENTS