Climate change and malaria: how to prepare for the radical reconfiguration of the epidemic?

Malaria is one of the most climate-sensitive diseases. Indeed, changes in temperature and rainfall patterns significantly affect the seasonality of vector transmission, density, distribution and behavioural traits. They also widely redefine the perimeter of malaria-endemic areas. Local factors, such as the characteristics of the various species of mosquito, the immunity of infected persons, population movements, parasite drug resistance, and environmental changes (land use, for example) are also key to understanding the potential impact of climate change on malaria epidemiology. Mathematical models help outline scenarios and devise measures that can mitigate its impact. But without an operational translation of these models into coherent public health policies, the preparation for future changes (pandemic preparedness) could be seriously undermined.

The World Health Organization (WHO) paints a very bleak picture in its review on climate change and health[1]: 250,000 additional annual deaths expected by the 2030s, partly due to the effects of climate change on diseases such as malaria and on rising sea levels in coastal regions. However, these estimates remain cautious and the modelling is complex and inherently uncertain, in particular when it comes to taking risks into account, such as droughts and migratory developments. In addition, this figure uses a definition that **does not take into account the effect of climate change** on the nutrition of children and women, and does not look at the combined effect of biodiversity loss, pesticide and antimicrobial resistance, pollution, and climate change.

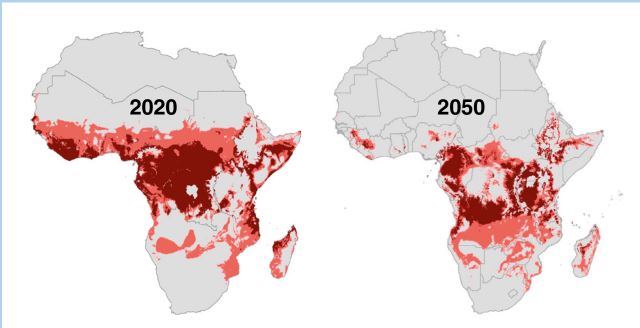
The objective of this policy paper is to summarise some of the trends emerging from the different models, and provide some keys to maximise their scope of interpretation.

1 https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health

LONG-TERM MODELS TO UNDERSTAND THE REGIONAL RECONFIGURATION OF ENDEMIC AREAS AND THE SEASONALITY OF MALARIA

Despite variations between the different models, and the lack of absolute consensus, many experts[2] agree that climate change may lead to an increase in cases of malaria, and in diverse contexts. Consequently, higher temperatures and increased rainfall and humidity could cause a proliferation of mosquitoes carrying malaria parasites at altitudes and latitudes that were previously free of the parasite[3], or bring back the disease to areas that were on their way to pre-elimination[4]. At the same time, in areas where malaria is endemic, warmer temperatures could modify the incubation period of the parasite in mosquitoes, meaning it will develop faster, which will increase the duration of transmission with implications on the burden of the disease[5]. However, the reality is more complex and other factors, such as improving socio-economic conditions, rapid access to treatment, and the implementation of routine vector control measures could act as a barrier to the emergence or intensification of the dynamics of malaria.

In one of the models published recently, Ryan et *al.*[6] have taken a "One Health" approach and have opted to consider the imbalance between interdependent elements, which include the environment, animal health, and human health. They have produced a model combining climate data (temperature, humidity level as opposed to rainfall), biological data (on mosquitoes and parasites), and population projections. The authors provide two scenarios for 2030, 2050 and 2080. **This model shows two broad trends.** Firstly, the **displacement of malaria areas towards the South and East of Africa**, towards populations with little immunity who are thus at risk of developing more serious forms of infection. Consequently, the scenario for the end of the century (2080) foresees endemic areas concentrated in regions previously unaffected or marginally affected, namely the high plateaus of East Africa (Uganda, Kenya, Tanzania) and Southern Africa (Angola, Zambia). At the same time, the authors estimate that vast coastal areas from the West African coast to the Horn of Africa will exceed the thermal tolerance of mosquitoes, which would therefore no longer be able to adapt. The second trend is the **highly probable change in the seasonality of malaria**, which will need to be taken into account to adapt strategies: in some cases, malaria could thus shift from being a seasonal disease burden to a year-round burden.



Maps showing the model results of the evolution of endemic malaria transmission areas in dark red (i.e. 10-12 months of transmission per year) and seasonal transmission areas in pink (i.e. 7-9 months of transmission per year). Maps from Ryan, S.J., C.A. Lippi & F. Zermoglio, Shifting Transmission Risk for Malaria in Africa with Climate Change: A Framework for Planning and Intervention, Malar J 19, 170 (2020), article under a Creative Commons Attribution 4.0 International license which authorises the use, sharing, adaptation, distribution and reproduction.

According to the authors' estimates, these changes would have a **significant impact on the burden and distribution of the disease** by 2080: approximately 197 million people in Eastern and Southern Africa who had previously been unaffected could be exposed to some degree of risk of malaria transmission. East Africa would be hardest hit with, in the worst-case scenario, 73.4 million additional people exposed to year-round transmission.

2 Thomson, M.C. & L.R. Stanberry, Climate Change and Vectorborne Diseases, N Engl J Med, 387: 1969-1978 (2022).
3 Parham, P. E. & E. Michael, Modeling the Effects of Weather and Climate Change on Malaria Transmission, Environmental Health Perspectives, 118(5), 620-626 (2010).
4 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
5 Rogers, D.J., Changes in Disease Vector Distributions, in: "Climate Change and Southern Africa: An Exploration of Some Potential Impacts and Implications in the SADC Region", M. Hulme (Ed.), Climate Research Unit, University of East Anglia, Norwich (1996): p.49-55.
6 Ryan, S.J., C.A. Lippi & F. Zermoglio, Shifting Transmission Risk for Malaria in Africa with Climate Change: A Framework for Planning and Intervention, Malar J 19, 170 (2020).

PREDICT THE SHORT-TERM INCIDENCE: A COMPLEX MODEL FOR A COMPLEMENTARY APPROACH

On a completely different time scale and with another more refined approach, Beloconi et *al.*[7] have used known climate and non-climate data (a total 26 of parameters) for 2008-2019 **for a region of Kenya with high malaria transmission.** They have thus **retrospectively tested the predictive nature of their model on the incidence of malaria and morbidity-mortality** and questioned the weight of each parameter. The authors have found a clear association between the increase in malaria cases in a given month and the increase in rainfall during the same month and the three previous months. The average temperature during the two previous months also influences the incidence of malaria. The authors have found that a 1°C increase in daytime land surface temperature (an air temperature indicator) was associated with a 9% reduction in the incidence of malaria, while a 10 mm increase in rainfall was associated with a 4% increase in the incidence of malaria. The proportion of insecticide-treated net users is also important in refining the prediction strength of the model. However, several limits should be noted. Firstly, this model is unable to take population age into account, whereas it is a fundamental parameter for predicting malaria-related mortality. Furthermore, while it can provide good one to two-year forecasts in a detailed context, its forecasting capacity rapidly deteriorates beyond this. In any event, these more detailed modelling approaches are still a valuable tool to complement early warning systems and inform intervention scenarios to improve preparedness and response to meteorological variability.

PREVENT THE RE-EMERGENCE OF URBAN MALARIA: MODELS FOR ACTION

Malaria prevalence rates are generally lower in urban areas than in rural areas. This is mainly due to the urbanisation process, which tends to eliminate breeding sites (for example, by appropriating cropland, filling in water points, and polluting water reservoirs) and results in beneficial changes in the habits of the urban population (such as the increased use of mosquito nets and mosquito repellent products). However, this does have paradoxical effects: while urban populations are less exposed, they can still develop serious clinical forms as their immune resistance is usually weak and slow to react.

In any case, several models suggest that the **historical trend of a decline in the prevalence of malaria in cities could now be reversed** by the arrival of the ***Anopheles stephensi*** in Sub-Saharan Africa from the Horn of Africa. Unlike other Anopheles mosquitoes (in particular *An. gambiae*, the main vector of malaria transmission), *An. stephensi* is perfectly adapted to the urban environment. Indeed, it is capable of using containers of standing water as egg-laying habitat. This has enabled it to not only recently invade the Horn of Africa, but especially large cities in this region, such as Djibouti which, while it was close to eliminating malaria, is now experiencing annual malaria epidemics. In addition, *An. stephensi* has a wider range of thermal tolerance than *An. gambiae*, which makes projections about it particularly alarming: it is estimated that by 2050, much of Africa will be conducive to a near-permanent transmission through this vector[8], with a high probability of its presence in a number of African cities where about 126 million people live[9]. These findings demonstrate the need to intensify entomological surveillance activities in areas at risk of transmission and the need to share and disseminate known distribution data[10]. There are also

7 Beloconi, A., B.O. Nyawanda, G. Bigogo et al., Malaria, Climate Variability, and Interventions: Modelling Transmission Dynamics, Sci Rep 13, 7367 (2023).
8 Ryan, S.J., C.A. Lippi, O.C. Villena et al., Mapping Current and Future Thermal Limits to Suitability for Malaria Transmission by the Invasive Mosquito Anopheles Stephensi, Malar J 22, 104 (2023).
9 Sinka, M.E., S. Pironon, N.C. Massey, J. Longbottom, J. Hemingway, C.L. Moyes and K.J. Willis, A New Malaria Vector in Africa: Predicting the Expansion Range of Anopheles Stephensi and Identifying the Urban Populations at Risk, Proc Natl Acad Sci U S A. 117(40): 24900-24908 (2020).
10 Vector Alert: Anopheles Stephensi Invasion and Spread in Africa and Sri Lanka, World Health Organization (2023).

mitigation opportunities to be seized: we particularly have in mind the dengue surveillance and control programmes which target *Ae. aegypti* and may be able to extend their control efforts to *An. stephensi* (as these two species have similar breeding sites), without a major investment in new resources.

CONCLUSIONS

While these models have existed for many years, they are still rarely used by national public health programmes for epidemic preparedness and management. One of the reasons is probably that **local surveillance systems** are limited or inadequate, combined with a scarcity of entomological human resources in the very countries that are the most exposed. This hinders the mobilisation and interpretation of quality data to support epidemic preparedness. These shortcomings could be remedied by testing new **approaches to surveillance and community-based vector control**, either through the communities themselves or through other local organisations. The anticipation of resurgence events and the development of local integrated mosquito control strategies along with their implementation are promising approaches to be considered in a broad range of contexts, in particular in urban settings.

Finally, in addition to sharing good practices, multi-sectoral collaboration is the cornerstone of an effective response, with a coordination of the health sectors, as well as the environment, urban planning, agriculture and sanitation sectors, for the design of local strategies for epidemic preparedness and the control of diseases such as arboviruses[11].

11 Multisectoral Approach for the Prevention and Control of Vector-borne Diseases, Geneva, World Health Organization (2020).

12 The views expressed in this policy paper are solely the responsibility of the author and do not necessarily represent the decisions, policies or opinions of the World Health Organization.

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