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Health, environmental change and adaptive capacity; mapping, examining and anticipating future risks of water-related vector-borne diseases in eastern Africa

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The health effects of future climate and other environmental changes have been projected to be substantial, often negative and to vary geographically (Semenza, 2014). The impacts will be felt most acutely among the most vulnerable members of society, for instance the poor, who already carry a disproportionately high share of the burden of environmentally sensitive diseases, with sub-Saharan Africa a focus of adverse health impacts (Tosam and Mbih, 2015). No region is completely immune (Watts *et al*., 2015): populations in the developed world are also at risk, as changes in environment drive the emergence of new diseases, and alter the distribution and epidemic potential of existing infectious diseases. Environmental change will impact health in a multitude of ways, with impacts mediated through other factors (Papworth *et al*., 2015), such as poverty, access to health facilities and nutritional security. The impacts may be direct, in terms of outbreaks of disease among human populations, or indirect, in the form of outbreaks of diseases that affect domesticated animals or plants, and therefore jeopardise food security, agriculture-based economic activities and trade. Concern has, however, tended to focus on the future distribution and spread of infectious diseases, in the context of increasing population mobility (Tatem, 2014), and in particular the negative health impacts of changes in transmission and outbreaks of vector-borne diseases (VBDs) as a result of anthropogenic climate change (Campbell-Lendrum *et al*., 2015).

These concerns provided the motivation for the HEALTHY FUTURES research project (www.healthyfutures.eu). HEALTHY FUTURES (Health, environmental change and adaptive capacity: mapping, examining and anticipating future risks of water-related vector-borne diseases in eastern Africa) was a cooperative project funded under the European Commission (EC)'s Framework Programme 7 (FP7) Africa-2010 call. HEALTHY FUTURES ran for four years, terminating at the end of 2014, and involved more than 30 collaborating researchers based in 15 institutions in Africa, Europe and Asia, with Expert Review Panel members also from North America. The project aimed to build capacity in risk mapping for three water-related high-impact VBDs [malaria, Rift Valley fever (RVF) and schistosomiasis] in eastern Africa [specifically the constituent countries of the East African Community (EAC)] (Figure 1). The approach was based on the use of the latest generation of global climate models that contributed to the Intergovernmental Panel on Climate Change (IPCC) fifth assessment report (AR5) process, in addition to higher resolution regional climate model integrations conducted within the project, to drive a range of statistical and a new generation of dynamical disease models that provided a basis for the spatial assessment of disease hazard. The latter were then combined with spatially-explicit assessments of social vulnerability to provide assessments of overall disease risk. As such, HEALTHY FUTURES adopted the same approach to framing risk as outlined in Oppenheimer *et al*. (2014). A key vehicle for communicating the results was the HEALTHY FUTURES interactive atlas (Morper-Busch *et al*., 2015), which was developed as part of an ongoing interactive process in which HEALTHY FUTURES sought and obtained input from stakeholders, including health decision makers in the EAC countries of Burundi, Kenya, Rwanda, Tanzania and Uganda, and which is available through the project website.

In addition to the HEALTHY FUTURES atlas, other major outputs from the project comprised improved understanding of the sensitivities of the three target VBDs to environmental conditions, new state-of-the-art dynamic disease models, down-scaled environmental change model outputs and scenarios of future conditions based on the current reports (AR5) of the IPCC, and four PhDs, two of which were based at African universities (the University of Nairobi and the University of Rwanda). Moreover, HEALTHY FUTURES was represented at several major conferences, both international and those with a specific eastern Africa focus. Many of these outputs are represented in the papers that make up the remainder of this special issue (SI).

All 11 articles in this SI are based on research that was partly or entirely funded through the HEALTHY FUTURES project. Some of the articles were presented as oral papers at the HEALTHY FUTURES sessions at the EAC conference on health (held in Kigali, Rwanda, March, 2013) and at the Impact of Environmental Changes on Infectious Diseases conference held in Sitges, Spain, in March 2015. More preliminary versions of the papers were also aired at numerous in-region workshops and meetings held over the duration of the HEALTHY FUTURES project in Kenya, Uganda and Tanzania. A number of the contributions to this SI also received considerable support from the project Quantifying Weather and Climate Impacts on Health in Developing Countries (QWeCI; www.liverpool.ac.uk/qweci/), also funded by the EC under its FP7. Together QWeCI and HEALTHY FUTURES evolved considerable synergy due to their numerous common research objectives; several HEALTHY FUTURES researchers were also involved directly in QWeCI, notably the project leader and scientific coordinator of QWeCI Andrew Morse.

Papers in this SI fall into three categories: those that address relationships between environment and health, those that focus on the development of models of that relationship for particular diseases, and those that examine applications of climate-driven disease models. The environment-health nexus is explored in the context of land use change (LUC), using the latest generation earth system models that contributed to the IPCC process, by Tompkins and Caporaso (2016). In the models, LUC is driven both by internal (to a particular county) forces, such as urbanisation, and external factors, including large-scale land acquisitions and conversions for agriculture and climate change mitigation. Land use change can impact climate, and this in turn can potentially affect malaria transmission, although the authors are quick to point out that this is just one of many LUC-health interactions. Colón-González *et al*. (2016) assess the effects of air temperature and rainfall on malaria incidences using epidemiological data from Rwanda and Uganda. They find that trends in malaria incidence agree with variations in temperature and rainfall, although factors other than climate also play an important role as well. Many of these other factors, including those related to socio-economic conditions, and their influences on health are difficult to quantify. Overall the paper highlights the value in combining climatic and disease surveillance data, and highlights the great potential and challenges in the development of climate-driven disease early warning systems.

Tompkins and co-authors then ask the question whether historical malaria records in the period prior to the mass interventions of the 1960s can shed light on the climate-malaria relationship, using the national reports of the Ugandan health ministry during the colonial period of 1926 and 1960 (Tompkins *et al*., 2016). They attempt to identify periods of enhanced malaria cases, and use reconstructed station observations of temperature and humidity to drive a dynamical disease model ensemble for five locations in Uganda. Interestingly, only rainfall anomalies were highlighted in the contemporary reports; temperature was never discussed in the context of malaria outbreaks. The results show that malaria increases in the late 1950s could have been primarily driven by climate variability (anthropogenic land use change was blamed at the time), and that some of the successes of the interventions of the early 1960s can be explained by reversal of climate anomalies during the late 1950s.

As part of the second group of papers (those that focus on the development of models of that relationship for particular diseases), Tompkins and McCreesh (2016) analysed one year of mobile phone location data to determine the characteristics of journeys that result in an overnight stay, and are thus relevant for malaria transmission. This study was conducted in Senegal, outside the HEALTHY FUTURES focus region, due to the availability of the mobile phone dataset. Their analysis revealed, for example, that approximately 60% of people who spend nights away from home have regular destinations that are repeatedly visited. Such results were integrated in a new agent-based migration model, with a view to providing better estimations, within the new generation of dynamic disease models, of short-term migration patterns of populations potentially affected by VBDs. Rather than the host, the habitat of vectors of infectious disease is the focus of the article by Asare *et al*. (2016a), the research for which was conducted in Ghana due to the ability of a unique, long-term set of *in situ* observations of small-scale mosquito breeding sites. Evolution of pond area over time was modeled, taking into account rainfall, evaporation and infiltration. The authors of the paper go on to show that the equations that underpin the pond model can be generalized and incorporated into spatially-explicit models to derive an estimate of fractional pond coverage (mosquito breeding and early development habitat) over a land surface. The scheme was implemented in the vector borne disease community model of the Abdus Salam International Centre for Theoretical Physics, Trieste (VECTRI) dynamical malaria modelling system, which was developed within HEALTHY FUTURES and QWeCI (Tompkins and Ermert, 2013). Staying with a focus on the habitat of malaria mosquitoes, a second paper by Asare *et al*. (2016b) describes development of a model that can be used to predict the temperature of water in ponds. The model also showed a high level of skill in simulating mosquito larvae development times, when compared with actual observations. Moreover, model outputs showed significant improvement in predictive capability when compared with simulations based on an assumption that the temperature of water in ponds equates to the temperature of air 2 m overhead, and revealed the importance to the rate of larvae development of diurnal and sub-diurnal variations and the degree days parameter. Leedale and colleagues (2016a) present a major model development undertaking with the presentation of the new dynamical RVF model developed at the University of Liverpool within the project [the Liverpool RFV (LRVF) model]. Based on the framework of the successful Liverpool malaria model (Hoshen and Morse, 2004), LRVF model attempts to capture the salient aspects of the host-vector system in a distributed modelling system that accounts for climate impact on the disease vectors. A third new dynamical disease modelling system, this time for schistosomiasis, was developed at the University of Durham as part of HEALTHY FUTURES (McCreesh *et al*., 2015). The model focuses on the water temperature sensitivity of the snails that act as intermediate hosts for the parasite responsible for schistosomiasis infections. Stensgaard and coauthors (2016) examine the potential improvement that can be achieved by using the dynamical model output as an input to a statistically modelling framework. Such a hybrid approach has great promise, as the dynamical model acts as nonlinear operator to relate climate anomalies to disease hazard, rather than simply exposing a statistical relationship to a combination of polynomial functions of climate variables without recourse to the disease processes. At the same time, the statistical modelling components can account for variables, such as socioeconomic factors or interventions, which are sometimes difficult to incorporate accurately in a dynamical modelling framework.

As the title of the paper suggests, Leedale *et al*. *Projecting malaria hazard from climate change in eastern Africa using large ensembles to estimate uncertainty* (2016b) is grouped among those papers in this SI that examine applications of climate-driven disease models. In the paper, the authors utilise an ensemble of bias-corrected, downscaled climate change projections for eastern Africa to drive two dynamic disease (malaria) models – the Liverpool malaria model (LMM) and VECTRI. Both the LMM and VECTRI models are structured similarly, in that adult and immature vector development is compartmentalised in a way that allows the delay between the rainy season and the malaria transmission peaks to be represented. The climate models generally project warmer and wetter conditions over eastern Africa. Output from the two disease models is similar, in terms of the direction and spatial distribution of changes in transmission, and appears to be more under the control of temperature than rainfall. Malaria transmission increased in highland parts of the region, while decreasing in lowland, marginal transmission areas. Some differences in magnitude of changes in malaria transmission between the two disease models are evident, however. The latter highlights the need to increase the availability of independently developed dynamic disease models in order to compensate for uncertainties associated with any one model.

Building on the work of Leedale *et al*. (2016b), Taylor and colleagues (2016) describe the implementation of the LRVF model for predicting outbreaks of RVF, an emerging zoonosis endemic to large parts of sub-Saharan Africa. Model output is driven by climate change data from global circulation models run according to two radiative forcing scenarios, representative concentration pathways (RCP) RCP4.5 and RCP8.5, which are then combined with results of a spatial assessment of social vulnerability to the disease in eastern Africa. The combined approach allowed for analyses of spatial and temporal variations in the risk of RVF to the end of the current century. Results of both scenarios demonstrate the high-risk of future RVF outbreaks, including in parts of eastern Africa to date unaffected by the disease, and highlight the risk of spread within and beyond the EAC study area. The authors emphasized the value of considering the geography of future projections of disease risk and need to invest not only in surveillance and early warning systems, but also in the socio-economic factors that underpin social vulnerability in order to mitigate future RVF impacts related to climate change.

The last paper in this group was developed as part of the HEALTHY FUTURES funded PhD research programme of Jean Pierre Bizimana *Modelling homogeneous regions of social vulnerability to malaria in Rwanda* (2016). In the paper, the authors cite the recent decline in malaria incidence in Rwanda due to the success of intense interventions and suggest there is a real possibility for elimination of malaria as a public health problem in Rwanda. To succeed in this, the authors make a strong case that success of future elimination strategies must expand beyond approaches that focus solely on malaria epidemiology and also consider the socioeconomic, demographic and biological/disease-related factors that determine the vulnerability of potentially exposed populations. They analysed current levels of social vulnerability to malaria in Rwanda by integrating a set of weighted vulnerability indicators and used regionalization techniques as a spatially explicit approach for delineating homogeneous regions of social vulnerability to malaria. Using this approach, high levels of social vulnerability to malaria were mainly found in the highland areas of Rwanda and in remote areas where populations are more susceptible, lacking the capacity to anticipate mosquito bites, or not resilient enough to cope with or recover from malaria infection. By integrating multi-source spatial indicators, their results provided meaningful information about social vulnerability aspects in specific locations, indicating not only which areas are the most vulnerable, but also what is mostly driving that vulnerability according to a statistical analysis. They suggest interventions to improve the socioeconomic development in highly vulnerable areas could prove highly effective, and provide sustainable outcomes against malaria in Rwanda.

HEALTHY FUTURES was an active, dynamical and highly collaborative project involving partners dispersed over three continents, and representing a range disciplinary backgrounds and approaches. Assessments of potential changes in risk in malaria, schistosomiasis and RVF in eastern Africa resulting from climate and other environmental changes have been and are being used to inform health decision-makers and other stakeholders in the region. The assessments and approach adopted also have far wider appeal and relevance. However, the endeavor was not without major challenges. The work highlighted the difficulty in assessing uncertainty at all stages of the modelling process, from underlying greenhouse gas emissions and land use change scenarios, to climate model and disease modelling uncertainties and through to the uptake of scientific knowledge and understanding by the targeted user communities. Incorporating explicit treatments of uncertainties within offline complex-modelling systems is not straightforward, and recourse to multi-model stochastic ensembles remains the mainstay method of choice. The difficulty of coupling the dynamic disease modelling approaches and their uncertainty to assessments of population vulnerability also became evident through the project. Although important advances were made in assessments of social vulnerability and their integration within a risk framework, how to incorporate expert opinion and the use of established as well as novel methods for indicator integration challenges remain, including the bridging of different scientific approaches and techniques, as well as integrating complex science with the process of decision making. Above all, despite the best intentions of the project with multiple and frequent in-region workshops, the magnitude of the challenge to engage with decision-makers and other stakeholders was evident. Communicating aspects such as projection and model uncertainties and cost-loss ratios associated with decision points was at best a partially achieved goal, and the project only just began the process of attempting to interface the research with health policy as part of the respective national climate mitigation planning processes. And this was despite the fact that from the outset the project was built on the firm foundations of a bottom up, stakeholder first approach, with full involvement of in-region, research organisations and ministries of Health. Communicating project research goals and achievements, demonstrating research tools and ensuring the opinions and experience of those engaged in the health sector feed back to the research were are fundamental if the results of research are to be transmitted into action, a key aim of HEALTHY FUTURES.

The papers forming this SI provide an indication of the scope of HEALTHY FUTURES. However, the extent to which the aim that research findings lead to concrete action on the ground, in terms of facilitating the decision-making process (and hence adaptation to climate and other environmental changes), should become evident in coming years.

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Figure 1. The HEALTHY FUTURES case study area: the eastern Africa countries comprising the East African Community.