Chapter 12
Vector-Borne Diseases in a Changing Climate and World

Yesim Tozan, Ora Lee H. Branch, and Joacim Rocklöv

Introduction

The past few decades have marked significant reductions in many important infectious diseases at a global scale owing to large-scale concerted prevention and control efforts, significant advances in medical care and treatment, improved access to water and sanitation services, and overall development [1–3]. However, vector-borne diseases that are transmitted by mosquitoes, ticks, and other insect vectors continue to take a heavy toll on populations around the world, particularly in developing countries in tropical and subtropical regions [2]. Every year, more than 1 billion people are infected and more than 700,000 die from vector-borne diseases, including malaria, dengue, schistosomiasis, lymphatic filariasis, onchocerciasis, Chagas disease, and leishmaniasis [4]. The World Health Organization (WHO) estimates that these prominent vector-borne diseases together account for about 17% of the global burden of all infectious diseases [4]. In addition, other vector-borne diseases take a heavy toll on a population due to their targeting pregnant women and infants. For example, Zika virus is associated with congenital morbidity and

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Y. Tozan (✉)
Global Health and Environmental Public Health Sciences Program, College of Global Public Health, New York University, New York, NY, USA
e-mail: tozan@nyu.edu

O. L. H. Branch
Department of Research, College of Health & Human Services, Concordia University, Portland, OR, USA
e-mail: obranch@cu-portland.edu

J. Rocklöv
Department of Public Health and Clinical Medicine, Section of Sustainable Health, Umeå University, Umeå, Sweden
e-mail: joacim.rocklov@umu.se

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mortality even in symptomless mothers and fathers, which is a particularly insidious public health and reproductive population threat [5].

Vector-borne diseases are long known to be highly sensitive to the changes in weather and climate. The research community has extensively studied these diseases to understand the effects of climate and climate variability on their transmission dynamics [6–8]. Malaria, one of the most prominent vector-borne diseases and the primary focus of large-scale control and elimination efforts, has been decreasing in incidence globally [1], while persisting or increasing in certain locations [9, 10]. The incidence of arboviral diseases, such as dengue and chikungunya, have been increasing steadily to the great concern of the global health community over the past few decades [11, 12]. These arboviruses are now responsible for explosive and periodic epidemics in endemic populations [11, 13–15] and have already caused outbreaks in immunologically naïve populations in previously disease-free areas where competent mosquito vectors are readily present [16, 17]. Although climatic factors have been shown to influence the transmission dynamics of these arboviruses, a combination of non-climatic factors, such as unplanned urbanization, land use changes, and increasing human mobility at local and global scales, is likely to have complex effects on vector breeding habitats and vector–host–pathogen interactions in a warming climate and have contributed to their geographic spread [16]. These non-climatic factors are now better understood as drivers of arboviral disease transmission and outbreaks specifically [18–23] and vector-borne disease transmission more generally [6, 24]. In a globalized world, vector-borne disease risks are further mediated by factors such as emergence and spread of drug and insecticide resistance, for instance, in the case of malaria [25, 26], and fluctuating resources for disease prevention and control efforts due to constantly shifting public health priorities, as experienced during the 2016 Zika virus epidemic [27].

Against this backdrop, the current scientific evidence indicates a dramatic expansion in the geographic range of mosquito-borne diseases in the coming decades in response to rising global temperatures and more variable weather [28]. Much research has centered on the use of statistical and mathematical models to assess future changes in transmission risks of most prominent vector-borne diseases, such as malaria [6] and dengue [8, 29]. Most of these works considered the climatic changes predicted by the Global Climate Models (GMCs) at regional and global scales according to a range of greenhouse gas emission trajectories during the twenty-first century [30]. The trajectories represent a range of greenhouse gas emission scenarios for the world, known as the representative concentration pathways (RCPs), and are developed by the scientific community at the request of the Intergovernmental Panel on Climate Change (IPCC) [31]. One of the important challenges for vector-borne disease control is, however, to consider the dynamic and complex interplay of the aforementioned climatic and non-climatic factors that affect population exposure to the changes in transmission risks. Ultimately, the risk of vector-borne disease in a population is determined by that population's vulnerability, which is a measure of the capacity available to adapt and respond to the changes in the environmental suitability for mosquito vectors, pathogen replication, and disease transmission [28]. In this chapter, we review the current status and challenges in understanding vector-borne diseases dynamics in a rapidly changing climate and environment. We focus on mosquito-borne diseases due to their current high burden and widespread global distribution and highlight current knowledge base and knowledge gaps on this topic to stimulate future research in this field.

Mosquito-Borne Diseases: Drivers, Dynamics, and Risk

Climatic Drivers of Mosquito-Borne Diseases

Development rates of parasites and arboviruses that cause disease and of mosquito vectors that transmit these pathogens are sensitive to even small changes in temperature and precipitation. Understanding how the environmental suitability for mosquito vectors, pathogen replication, and disease transmission changes in response to short-term climate variability and longer-term climate change is key to our understanding of the consequences for human exposure [28].

Mosquito vector abundance and distribution are strongly influenced by climatic conditions. In the immature stages of their life cycle, mosquito vectors depend on fresh and clean water for oviposition and breeding. Air and water temperature govern the development rate of mosquitoes from larvae to pupae. Overall, a warmer environment leads to faster development. Recent studies have also shown that temperature during larval development has a direct effect on adult mosquito size [32]. Adult mosquito size can affect a number of epidemiologically significant traits, such as longevity, length of gonotrophic cycle (time between two consecutive blood meals), blood meal size, biting rate, immunocompetence, and infection intensity, all of which in turn are known to affect mosquito survival and pathogen development within vectors [32]. In the adult stages, mosquito vectors are affected by temperature predominantly for their survival. The relationship between vector survival and temperature has been studied extensively in experimental conditions. Overall, mosquito mortality increases rapidly with decreasing temperature [33]. Humid environments, on the other hand, are shown to favor vector survival at the same temperature and precipitation levels. Small increases in temperature lead to faster blood meal digestion, shorter gonotrophic cycle, and increased biting rates [34], resulting in a higher capacity for mosquito vectors to transmit the pathogen among humans, known as vectorial capacity.

The replication of parasites and arboviruses within vectors, which is another important determinant of disease transmission, is long known to be temperature sensitive [35]. Specifically, the duration of pathogen development within vectors, known as the extrinsic incubation period, is dependent on the temperature surrounding vectors. There is a threshold temperature below which a pathogen will not continue to develop in the vector (e.g., 15.4 °C for malaria parasite and 19 °C for dengue virus [36]). On the flip side, some pathogens stop developing above certain temperatures (e.g., 34.4 °C for malaria parasite and 31.7 °C for dengue virus [36, 37]). Any increase in temperature within these thresholds typically accelerates pathogen development within vectors and is expected to increase vectorial capacity. The extrinsic incubation period gets significantly prolonged at temperatures below the threshold value. Therefore, at decreasing temperatures, vectors may not outlive the extrinsic incubation period and are less likely to transmit pathogens to hosts. Above the threshold temperature, the development rates of both vectors and pathogens increase; however, such warming may also be associated with a drier climate characterized by reduced rainfall where vectors are less likely to survive and breed, and these conditions may negatively affect transmission dynamics [38].

In reality, mosquito vectors do not only experience a constant mean temperature, but are also exposed to fluctuating temperatures throughout their life cycle. Short-term variability in temperature, as well as extreme temperatures, may affect the ability of mosquito vectors to effectively transmit pathogens. For instance, diurnal temperature ranges (DTRs) have been found to be more important than changes in average temperature for transmission of malaria and dengue [39–42]. One study on malaria showed that daily temperature fluctuations can significantly alter the extrinsic incubation period of the malaria parasite and hence transmission rates [40]. The study findings indicated that DTRs around >21 °C slowed parasite development compared with constant mean temperatures, whereas DTRs around <21 °C sped up parasite development. On the other hand, extreme hot temperatures may increase mosquito mortality and decrease vectorial capacity and transmissions risk [43]. Further, a recent study on dengue examined the combined effect of temperature and DTR on the epidemic potential of this disease worldwide over a 200-year period (1901–2099) using historical and predicted climate data under the high greenhouse gas emission scenario (i.e., RCP8.5) [8]. The study found small increases in the dengue epidemic potential over the past 100 years while predicting larger increases in temperature by the end of this century in Northern Hemisphere regions (Fig. 12.1). Further, the study reported an overall increasing trend in the epidemic potential in temperate regions over time. These findings indicate that short-term temperature fluctuations and extreme temperatures need to be considered when investigating the impact of longer-term climatic changes on transmission dynamics of mosquito-borne diseases.

Similarly, precipitation extremes, whether associated with heavy rainfall or drought, have been found to be more important than changes in average precipitation [44]. Although heavy rainfall may temporarily reduce the risk of transmission by flushing out larvae and pupae from breeding sites, residual water pools create optimum breeding grounds for vectors. Extreme events, such as flooding and drying of riverbeds, may have a greater impact on the life cycle of mosquito vectors and the incubation of parasites and arboviruses, and strong associations were found between precipitation anomalies and mosquito-borne diseases [45–47]. According to the 2018 report of the Lancet Countdown, changes in extreme precipitation and droughts have already been observed and vary regionally, with the most significant increases occurring in South America and southeast Asia, highlighting the varying impact of climate change in different parts of the world [28].

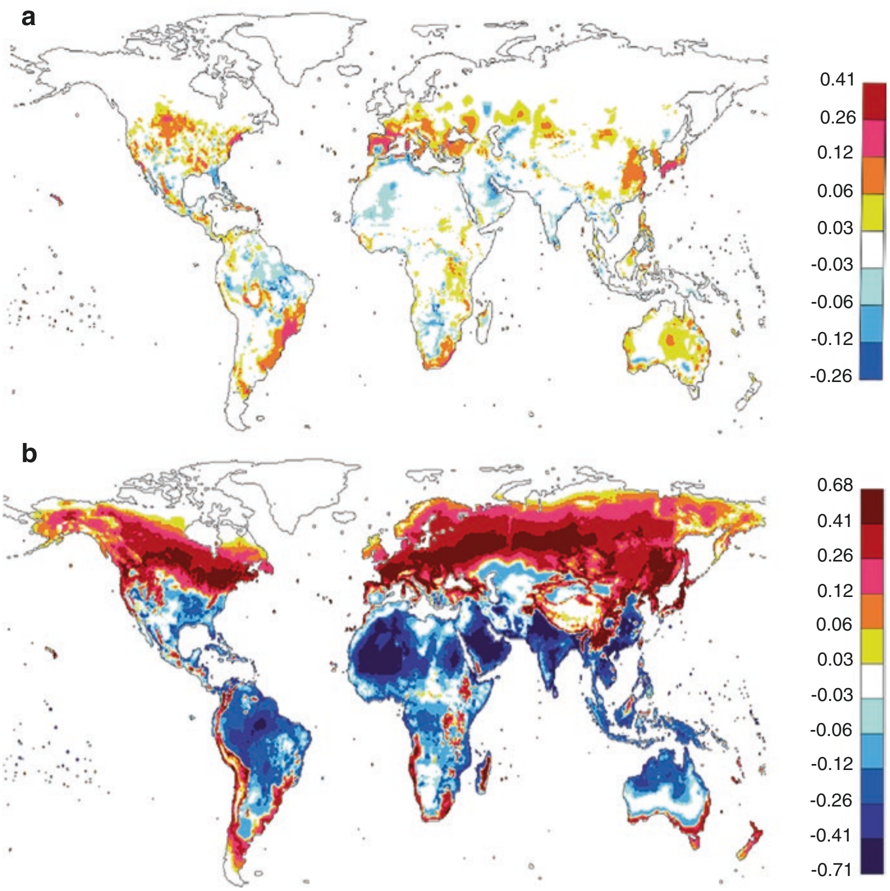


Fig. 12.1 Trend of global dengue epidemic potential (rVc) for the highest three consecutive months of the year. Differences in averaged rVc based on 30-year averages of temperature and DTR. (**a**) Differences between 1980–2009 and 1901–1930. (**b**) Differences between 2070–2099 and 1980–2009. The mean value of rVc was averaged from five global climate models under RCP8.5. The color bar describes the values of the rVc [8]

A growing number of studies have focused on investigating the associations between climatic factors and mosquito-borne disease risks across space and time. The objective is twofold. Identifying these spatiotemporal associations may improve our understanding of the impact of climatic variability on disease risk. Second, an improved understanding of the spatiotemporal distribution of disease risk may inform planning and implementation of effective interventions for mosquito-borne diseases. These studies have reported significant lag associations between temperature and rainfall and disease risk and have also revealed spatial heterogeneity in these associations [43, 48–51]. Of particular importance have been studies on the relationship of El Nino–Southern Oscillation to mosquito-borne diseases [17, 52].

A recent study on dengue in Sri Lanka found a strong association between the Oceanic Nino Index to weather patterns in the country and to dengue risk at a lag time of 6 months in a highly endemic district [53]. Furthermore, the study showed that increasing weekly mean temperature (above 29.8 °C) and increasing cumulative rainfall (above 50 mm) were associated with increased dengue risk, at 4 and 6 weeks of lag, respectively. This type of information can provide sufficient lead time to mount a timely response to abnormal disease events, including outbreaks. Shorter lags can, however, be expected in warmer climates where development rates of both vectors and parasites are faster. The study concluded that the considerable heterogeneity observed in dengue risk across the district at the same levels of temperature and rainfall could be due to the differences in population movements, human behavior, land use, and the effectiveness of dengue control interventions.

The aforementioned relationships highlight the complexities inherent in predicting the impact of changes in local climate and weather conditions on vector–pathogen–host systems in a rapidly changing climate. Despite this complexity, climatic factors constrain the geographic range of mosquito-borne diseases [54–58], determine their seasonal and year-to-year variability [59, 60], and have an important role in the longer-term shifts in their geographic distribution and transmission [61]. The Lancet Countdown's 2018 analysis showed that in 2016 the vectorial capacity increased by 27.6% for the transmission of malaria in highlands of Africa and by 9.1% for *Aedes aegypti* and 11.1% for *Aedes albopictus*, the primary vectors for the transmission of dengue, from the 1950s baseline (Fig. 12.2) [28]. According to this

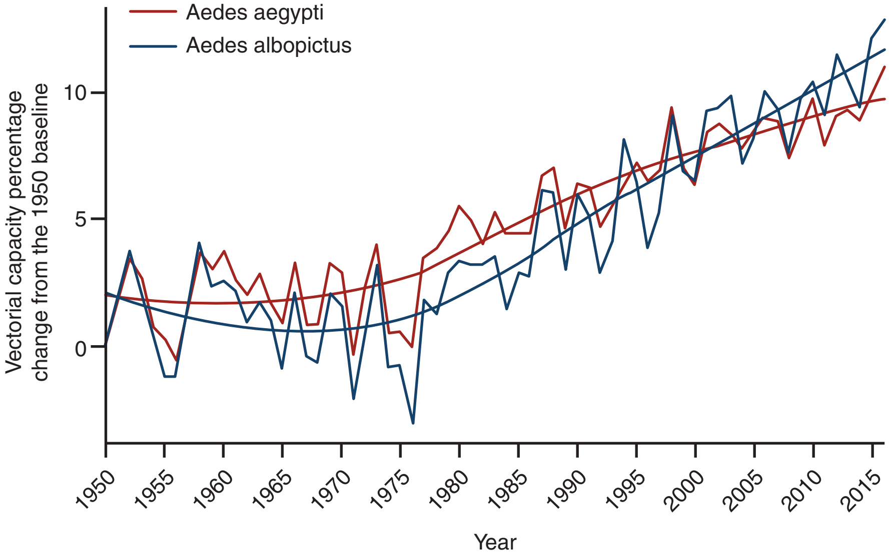


Fig. 12.2 Changes in global vectorial capacity for the dengue virus vectors *Aedes aegypti* and *Aedes albopictus* since 1950 [28]

analysis, the rise in global vectorial capacity for the transmission of dengue will continue given the projected increase in greenhouse gas emissions in the coming decades, which will be exacerbated by human mobility and globalization through their effects on the geographic spread of dengue virus and its competent mosquito vectors.

Non-climatic Drivers of Disease and Their Interactions with Climatic Drivers

In addition to climatic factors, there are a number of important non-climatic drivers of mosquito-borne diseases, such as changes in land use and human activity, human mobility, socioeconomic factors, and public health capacity. A comprehensive analysis of the impacts of climate variability and change should also consider the effects of non-climatic factors to determine the changes in exposure and vulnerability to mosquito-borne diseases in any given population. Changes in natural environments, such as unplanned urbanization and intensive agricultural activities with irrigation, combined with human mobility, can affect the distribution of mosquito vectors and pathogens, for instance, by increasing the environmental suitability for the proliferation of vectors as well as the density of susceptible populations.

The growth in air travel has accelerated introductions of pathogens to previously disease-free areas where competent vectors are already present and active. A recent study assessed the risk for chikungunya virus importation into France and Italy using air passenger journeys from international areas with active transmission as well as the risk of onward transmission by quantifying human mobility patterns using geocoded Twitter data during the 2017 outbreak [20]. The derived risk maps combining vectorial capacity and human mobility estimates had a good sensitivity in identifying at-risk areas for autochthonous chikungunya transmission during August–October 2017 (Fig. 12.3), with implications for targeting surveillance and outbreak response activities. Another recent study in Indonesia demonstrated the role of human mobility in the intra-urban spread of dengue by weighting local incidence data with geo-tagged Twitter data as a proxy for mobility patterns across 45 neighborhoods in Yogyakarta city during August 2016–June 2018 [19]. The study quantified the level of exposure to dengue virus in any given neighborhood by developing a new dynamic mobility-weighted incidence index, which was found to be a better predictor of dengue risk in a neighborhood than the recent transmission patterns in that neighborhood, or just the mobility patterns between neighborhoods.

The interactions between climatic, socioeconomic, and other factors are complex and dynamic. For example, in the case of dengue, non-climatic factors such as poor housing quality, limited access to safe water and sanitation, and poor waste management are likely to exacerbate the effects of climate change in crowded and highly

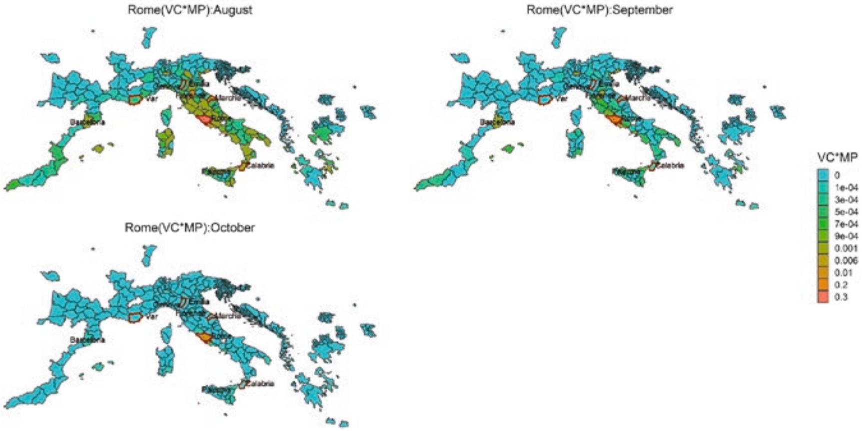


Fig. 12.3 Estimated areas of risk for chikungunya spread from the outbreak areas of Anzio and Rome in the Lazio region, Italy, based on combined VC and MP estimates, August–October 2017. Heavy outlines indicate the outbreak areas. MP, mobility proximity; VC, vectorial capacity [20]

connected urban settings. Long-term changes in climatic conditions and seasons can also affect mosquito vectors, human activity, and land use, which can further affect the spatial-temporal distribution and incidence of mosquito-borne diseases. Effective interventions and policies are key to respond to increasing risks from mosquito-borne diseases. These include awareness of mosquito-borne diseases and their impacts among key stakeholders, effective disease and vector surveillance systems, evidence-based prevention and control interventions, and increased support for research and development to understand current and future distribution of these diseases and their vectors. Socioeconomic conditions may, however, limit the capacity of public health systems to respond to changes, which in turn can increase the risks associated with any given level of climate change. For example, a statistical model, which combined projected changes in per capita gross domestic product with climate change, predicted that an additional 210 million people will be at risk of malaria by 2050 [62].

Human migration and other non-climate factors would arise from climate change and vector-borne diseases. For example, some populations might become denser after (or even in anticipation of) some geographic areas being non-desirable due to flooding or temperature changes.

As can be seen from the above discussion, combinations of these non-climatic drivers tend to increase vector abundance and/or host-vector interactions compared with the effects of each driver individually, with few combinations reducing the risks from mosquito-borne diseases [63]. The complexity of these interactions implies that the effects of climatic change on transmission risk will vary markedly by disease and geographic location in the face of non-climatic drivers of mosquito-borne diseases [64].

Predicting Climate Change Impacts on Mosquito-Borne Diseases: Current Status and Challenges

Scenario-based analysis is an integral part of climate change research and assessment. Last year marked the 30th anniversary of the IPCC, which has led the work on the development of the RCPs and, more recently, the Shared Socioeconomic Pathways (SSPs). The RCPs describe alternative scenarios of future radiative forcing relative to pre-industrial levels on the basis of a range of future global emission of greenhouse gases, which can then be expressed as an increase in the global mean surface temperature for the end of the twenty-first century [31]. While these climate change scenarios are not based on any socioeconomic narratives, emissions from short-term gases and land use changes are also incorporated [65]. Both GCM and regional climate models (RCM) use the RCPs as a basis for future projections of climate change over the course of this century.

Most studies have examined the changes in the range and intensity of mosquito-borne disease transmission according to these climate projections, employing an ensemble of climate models and using a diversity of modeling approaches ranging from statistical to mechanistic to hybrid [30, 66]. Climate projections over time can be made at global and regional scales, and this has allowed assessments of climate change impacts on disease transmission risk across different spatial and temporal scales [67]. Typically, assessments have used either the conservative low-emission scenario of RCP2.6 (radiative forcing of 2.6 W/m^2) or the drastic high-emission scenario of RCP8.5 (radiative forcing of 8.5 W/m^2), providing decision-makers with a range of worst-case and best-case scenarios. The increase in the global mean surface temperature for these two distinct scenarios is expected to range between 0.3–1.7 °C for RCP2.6 and 2.6–4.8 °C for RCP8.5 [68]. A recent review focusing on recent advances in modeling climate change impacts on mosquito-borne diseases has concluded that the use of different climate models and emission scenarios in future risk assessments has substantially improved with the availability of significantly greater funding for interdisciplinary research over the past decade [66]. The same review, however, highlighted that thorough validation of disease models is a continuing challenge due to a lack of field and laboratory data and that major uncertainties related to disease models, different climate models, and various emission scenarios should be clearly communicated to end users.

Over the past few years, the climate change research community has developed the SSPs for use within the scenario framework to represent different mitigation and adaptation challenges to climate change [63]. The SSPs comprise a set of five different socioeconomic development trajectories, describing a range of plausible futures under different demographic and economic development projections in which both the challenges to mitigation and adaptation are characterized as either high or low [69]. The SSPs are developed as reference pathways in the sense that these scenarios did not include any assumptions on climate change, its impacts, and climate policy responses, providing a starting point for developing integrated scenarios of the future [70]. A key aim of these integrated scenarios is to facilitate research to characterize the range of fundamental uncertainties in mitigation and adaptation efforts to achieve a given climate change target [69]. Future work must continue to combine the SSPs with the RCPs in earth system models for an integrated analysis of future climate impacts, vulnerabilities, adaptation, and mitigation [65]. The inclusion of socioeconomic development trajectories with climate change projections may allow for a more realistic assessment of future changes in the transmission risks of mosquito-borne diseases and support decision-maker needs from national to global levels [71].

Linking Climate and Climate Change Research to Health Policy and Programming: Current Initiatives

Research output on climate-driven risks on human health has increased significantly in recent years [72]. However, current research fails to match the demands of policymakers to enhance climate resilience in the health sector [64]. To increase the relevance to health programming, it is important to apply current research outputs to develop surveillance and response systems to anticipate, prevent, prepare for, and manage climate-related risks today [64]. In 2008, the member states represented on the World Health Assembly adopted a new resolution on health protection from climate change, harnessing a much higher level of commitment and engagement from the health sector [73]. The resolution called for close cooperation between the WHO, relevant organizations within and outside the United Nations, funding agencies, and member states to develop capacity to assess climate-driven risks on health and to implement effective response measures, by fostering interdisciplinary research and pilot projects in this area [64, 72].

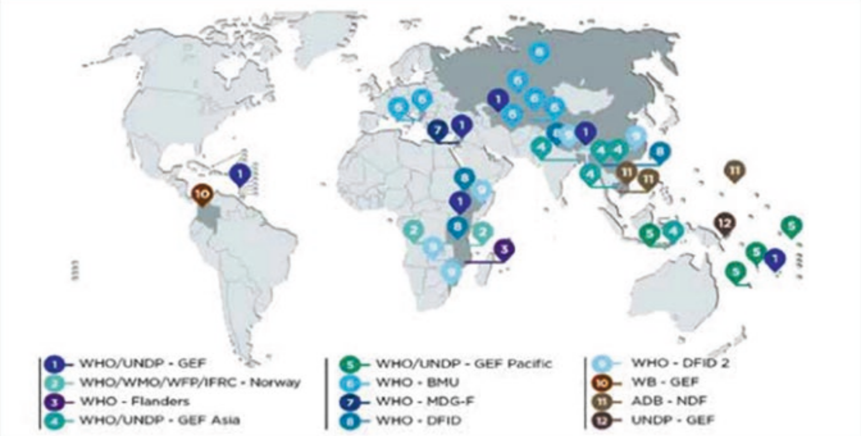
Over the past decade, experience in strengthening the climate resilience of health systems has accumulated significantly through pilot projects, which aims to add resilience measures to the six building blocks (leadership and governance, health workforce, health information systems, essential medical products and technologies, service delivery) common to all health systems (Fig. 12.4) [74]. More specifically, there is now growing interest in climate data and information products to improve disease surveillance and response [75]. A central challenge to robust analyses of climate risks has been the very limited access to quality-controlled climate and weather data [76]. If available and accessible, climate data and information products can be used to answer the specific questions of the health community. To that end, the World Meteorological Organization has proposed a Global Framework on Climate Services (GFCS) to provide end users with policy relevant climate information and has been working closely with WHO to support the connection to health-policy makers. The GFCS approach has been piloted in a number of African countries, including Tanzania, Malawi, and Ethiopia, for malaria control and nutritional and disaster risks [77]. There are several other broad policy frameworks (e.g., the Paris Agreement) and global mechanisms (e.g., the United Nations Framework

Convention on Climate Change, the Climate for Development in Africa Initiative) that call for action to address the impact of climate change on health [78].

On the applied research front, a prominent example is the multi-country multi-year research initiative in sub-Saharan Africa implemented by the Special Programme for Research and Training in Tropical Diseases (TDR), with support from the International Development Research Center (IDRC). The TDR IDRC research initiative aims to understand the impact of climate change on population vulnerability to vector-borne diseases, including malaria, schistosomiasis, Rift Valley fever, and African trypanosomiasis. Taking a holistic approach, the various projects investigate the changing context of the environmental, social, economic, and climate conditions and their impact on vector-borne disease transmission and burden to get a better understanding of the adaptation needs.

The focus is on the most vulnerable populations, with the aim of developing decision support tools and strategies for adaptation to climate change, in line with the National Adaptation Plans for Climate Change [78].

There are a number of pressing needs at present. First, vector-borne disease control programs that integrate management of the risks brought by climate change should be strengthened [64, 76]. Political support and financial investments at national levels are key to scaling up innovative interventions and programs that address climate risks. There is also a need to better facilitate collaborations between Ministries of Health and other line ministries to ensure integration of health and



UNDP, United Nations Development Programme; GEF, Global Environment Fund; WMO, World Meteorological Organization; WFP, World Food Programme; IFRC, International Federation of Red Cross and Red Crescent Societies; BMU, Federal Minister for the Environment, Nature Conservation and Nuclear Safety (Germany); MDG-F, Millennium Development Goals Achievement Fund; DFID, Department for International Development (United Kingdom); WB, World Bank; ADB, Asian Development Bank; NDF, Nordic development Fund

Fig. 12.4 Completed, ongoing, or approved projects on health adaptation to climate change, 2008 to the present [74] climate considerations in government-wide strategies while empowering public health practitioners, researchers, and communities [79, 80].

Future Directions for Research

Admittedly, studying vector-borne diseases is complex. Transmission results from dynamic and complex interactions between humans, vectors, and pathogens. These interactions are mediated by a multitude of climatic and environmental factors operating at multiple geographic and temporal scales and are further impacted by human activities and development. Numerous studies have examined the changes in the range and transmission risk of mosquito-borne diseases under current and future climatic conditions. Collectively, the results suggest that climate change, particularly rising temperatures, may cause the future range of disease vectors to expand from its present boundaries. Future studies are needed to ascertain the dependence of vectorial capacity parameters on temperature and also their sensitivity to diurnal temperature variations and further improve our currently limited understanding of these relationships. Such understanding is particularly important for *Ae. albopictus,* which is a competent vector for arboviruses. This vector has expanded its geographic range drastically over the past decade, including temperate areas in Europe, and is associated with dengue and chikungunya outbreaks in areas previously free of disease [20]. In relationship to temperature, studies that specifically incorporate urban heat islands are also needed. As a matter of fact, urban heat islands can be several degrees warmer than surrounding areas, and this increase in temperature may have profound effects on vector survival. For instance, in the case of urban dwelling of *Ae. aegypti*, urban heat islands can facilitate its spread to fringe areas in the United States, Europe, and China [16]. The effects of rising temperatures on vector population dynamics are generally robust across studies; however, the effects of rainfall fluctuations and shifts are less certain. Besides temperature and rainfall, there are other climatic factors, such as relative humidity and wind, that are known to affect vector development and survival and hence vectorial capacity. Future studies on these factors are also warranted to improve disease transmission models. Studies should also seek to better estimate and include vector densities that are field tested in the estimation of vectorial capacity. Vector density estimates should not only depend on climatic factors, such as rainfall, water temperature, and air temperature, but also consider land use, land cover, and local health system capacity to suppress the proliferation of vectors by modifying and eliminating their breeding habitats. Predictions for vector abundance under current and future climate conditions have been inconsistent across studies [16]. While manual elimination of containers that serve as breeding habitats may negatively affect the proliferation of *Ae. aegypti*, water storage practices because of drier conditions may favor it. It is important to bear in mind that disease models incorporating few biological and environmental factors may produce spurious estimates of vector abundance. Several of these factors are also likely to be affected by local socioeconomic and environmental conditions as well as vector control interventions in place.

One of the most challenging aspects of vector-borne disease prevention and control is the interdisciplinary nature of disease transmission and its drivers. Collaborations between researchers in physical science, epidemiology, and social science to better understand disease transmission dynamics have advanced considerably in recent years. These interdisciplinary collaborations have been encouraged by funding opportunities supported by the United States and European funding agencies and have substantially improved integrated assessments of disease transmission, predictability, and prevention. For the most part, these collaborations have involved diverse experts bringing their traditional analytical tools and study designs to the problem of vector-borne diseases, with minimal feedback across disciplines that limit more effective integration of techniques. For example, the epidemiological triangle of disease causation (agent–host–environment) often characterizes disease risk as discrete events between agents and hosts. Environment, often a distant third wheel, is usually considered as the place where agent–host interactions occur. This is where a large disconnect lies between epidemiology and land/climate scientists. In epidemiology, environment is a discrete space (e.g., community, political/administrative boundary, etc.) and is statistically modeled as a predictive variable of infection. However, land/climate scientists recognize that environmental characteristics are derived from modeled products (e.g., satellite imagery), and their use in epidemiology as input variables is actually continuous in space and time. The severing of a continuous ecological biome to examine discrete events can result in ecological fallacies or at least spurious relationships between environment and disease outcomes.

Overall, the application of satellite imagery to vector-borne diseases represents a unique opportunity. While multiple sources of information from satellite imagery and sensors are of interest to vector-borne disease risk monitoring and prediction, these satellite imagery sources and sensors are not designed with any specific consideration for what measurement characteristics would be most useful for vector-borne disease research or surveillance. Similarly, climate models are rarely optimized for vector-borne disease applications in their resolution, in periods of analysis, or even in the process simulations and model outputs. Of course, some limitations in these physical science techniques are difficult to overcome—high-resolution satellite-derived soil moisture measurements are expensive and sometimes impossible to obtain, and climate models are computationally intensive and are plagued by possibly irreducible uncertainties for both seasonal prediction and future climate change projections. Recognizing this, epidemiologists might need to alter the study designs and/or the surveillance networks to take full advantage of model results and satellite observations that are available.

In small research teams, there are opportunities for epidemiologists and land/climate scientists to collaborate during a given epidemic or during an eradication/elimination campaign. Epidemiologists might develop a model to test the effectiveness of focal screening for infection and treating individuals living near any given location [81]. However, in a resource-limited setting, there might not be enough public health resources to justify enacting this active surveillance and treatment public health campaign. Into the model, land/climate scientists might add the predicted climate and land use patterns. Satellite imagery and climate measures might be combined with epidemiologic surveillance and treatment protocols. The combined model would be a valuable tool for deciding upon public health strategies and priorities. Moreover, by modeling these factors together, we would increase our understanding of both climatic and non-climatic factors that impact vector-borne pathogens and the diseases they cause.

This suggests that collaborations that currently occur primarily at the scale of small research teams need to be moved upstream into satellite mission design, climate model development, and planning for health monitoring systems, so that the interdisciplinary nature of vector-borne disease problems is recognized in the design of the required research tools as well as in their application.

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