Research for Action on Climate Change and Health in the Caribbean:
A Public, Private, People's and Planetary Agenda

Caroline F. Allen[1], Renée M. West[1], Georgiana Gordon-Strachan[2], Saria Hassan[3], Shelly McFarlane[2], Karen Polson-Edwards[4], Audreyanna Thomas[4], C. James Hospedales[5*], Robert Dubrow[6*]

[1]Blue Sky Development Consulting
[2]Caribbean Institute for Health Research, The University of the West Indies
[3]Rollins School of Public Health, Emory University
[4]Pan American Health Organization
[5]EarthMedic and EarthNurse Foundation for Planetary Health
[6]Yale Center on Climate Change and Health, Yale School of Public Health
[*]Co-chair

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DOMAIN 1: CLIMATE CHANGE HEALTH IMPACTS, EXPOSURES AND VULNERABILITY

2. VULNERABILITY TO VECTOR-BORNE DISEASES

2.1. WHAT IS HAPPENING?

Vectors are living organisms that can transmit disease-causing microorganisms between humans or from animals to humans (WHO, 2022). Mosquitoes are the most significant vectors for transmitting diseases to humans in the Caribbean. On a global scale, mosquitoes cause more human deaths than any other animals, including humans themselves (Wilkerson et al., 2021). Higher temperatures speed up the development and maturation of larvae; therefore, global warming brings larger numbers of vectors and greater chances of infection. Mosquitoes also tend to feed more frequently in warmer weather (Hemme et al., 2010; Mavian et al., 2018; Méndez-Lázaro et al., 2014; Schnitter et al., 2019; Taylor et al., 2010; Yearwood and Polson-Edwards, 2017). Finally, changes in precipitation patterns due to climate change can affect mosquito breeding in complex ways (Dubrow, 2021; Gharbi et al., 2011; Jury, 2008; Méndez-Lázaro et al., 2014).

Mosquitoes require standing water to breed. Therefore, there tend to be more mosquito-borne disease cases in the rainy season (Douglas, 2021; Francis, 2021; Jury, 2008; PAHO, 2022a; Schnitter et al., 2019). Tropical storms and hurricanes associated with climate change increase the amount of debris and discarded items that collect water. Floods and sea level rise can increase the quantity of pools of water for breeding (CARPHA, 2017, 2018; Mavian et al., 2018; Medlock, 2021; Méndez-Lázaro et al., 2014). Unless properly monitored and covered, water storage drums and underground drains and septic tanks can provide additional sites for mosquito breeding (CARPHA, 2014; Chadee et al., 2006; Clauzel and Forbes-Robertson, 2017; Medlock, 2021; Ortiz et al., 2015). Thus, harmful behavioural practices and a lack of availability of water and sanitation services combine with climate change to create vulnerabilities throughout most of the year (Medlock, 2021; Ortiz et al., 2015).

Since at least 2008, increasing numbers of vector-borne disease (VBD) outbreaks have been registered in Small Island Developing States (SIDS), with importation of some new diseases from endemic areas. SIDS have been identified as hotspots for emerging mosquito-borne viruses, with their characteristics facilitating the emergence and dispersal of these viruses to the mainland, fuelling global epidemics. These characteristics include tropical climatic conditions that are becoming ever more suitable for vector reproduction as temperatures rise and hurricanes increase in intensity; rapid urbanisation and high population density; the high cost and poor quality of sanitation and water infrastructure and vector control systems; and the intense movement of humans and goods owing to SIDS' remoteness and size and thus strong reliance on international trade, including tourism. These conditions have set the stage for the global dispersal of dengue, chikungunya and Zika, and may promote novel, unknown and unexpected threats to public health from mosquito-borne diseases (Mavian et al., 2018).

The challenge of addressing a VBD relates not only to the disease itself but also to controlling the vector and its habitats (CARPHA, 2017; Lichtveld and Wahid, 2017; Rawlins et al., 2006a). Vector control requires community mobilisation, environmental management and tailored disaster preparedness measures. Public health measures are needed to prevent and treat imported cases.

VBDs affect vulnerable populations most severely, including people with the poorest access to health services, people with disabilities, pregnant women, impoverished people, and women and children living in remote rural areas and informal urban settlements (Diaz-Quijano and Waldman, 2012; Medlock, 2021; Sommerfeld and Kroeger, 2015). The *Aedes aegypti* mosquito is the most common disease-transmitting mosquito in the Caribbean and is well adapted to urban settings where human-inhabited buildings are close together (CARPHA, 2017; Henry and Mendonça, 2020; Heslop-Thomas and Bailey, 2006; Mavian et al., 2018; Medlock, 2021; PAHO, 2022b).

Increased contact between infected and uninfected populations occurs through international travel, tourism and migration (Mavian et al., 2018). Caribbean people are relatively mobile, and tourism is a mainstay of Caribbean economies. Migration to the Caribbean from other parts of the world is also relatively common, especially from the South American mainland. It is challenging to implement infection control measures among informal migrants. This movement of people also facilitates the spread of VBDs beyond Caribbean shores. For instance, 50–80% of the imported cases of dengue, chikungunya and Zika found in Florida in 2008–2018 were reportedly introduced from the Caribbean (Mavian et al., 2018).

In recent years, three viruses spread by the *Aedes aegypti* mosquito (and secondarily by the *Aedes albopictus* mosquito) have caused many illnesses, disabilities and deaths, and outbreaks have incurred major economic and social costs (Dubrow, 2021).

Cases of dengue have risen in the region since the 1980s, with major outbreaks and a transition to a highly endemic state and annual outbreaks in multiple locations (CARPHA, 2017; Rawlins et al., 2006a; Schnitter et al., 2019). Typical dengue symptoms include fever, headaches, nausea, vomiting, a rash and pain in the eyes, joints and muscles. The World Health Organization (WHO) has classified dengue cases according to symptoms to help patients gain access to the appropriate care according to disease severity as follows: dengue without warning signs (D-W), dengue with warning signs (D+W) and severe dengue (also known as dengue haemorrhagic fever). D-W and D+W are classified as non-severe dengue fever (Ajlan et al., 2019; WHO, 2009). In addition, there are four dengue serotypes, each of which could cause either non-severe or severe dengue (WHO, 2009). Infection with one dengue virus subtype confers immunity from that subtype but can increase vulnerability to dengue haemorrhagic fever if a person is infected with another subtype. Caribbean countries have moved from a situation where only one subtype was circulating to one where subtypes 1 to 4 are circulating. This has increased the incidence of severe health outcomes. Cardiovascular complications have also been found to arise from dengue (Araiza-Garaygordobil et al., 2021).

In the 2013–2016 period, attention shifted from dengue control to the control of two VBDs that had not existed in the region before (Mavian et al., 2018). Chikungunya can cause high fever, a rash, headaches and joint and muscle pain that can culminate in arthritic symptoms and disabilities (La Rosa et al., 2017). Although the chikungunya virus is traditionally considered nonfatal, a study in Jamaica showed that 2499 excess deaths took place in Jamaica during the epidemic in 2014 (Freitas, 2019). Zika generally causes mild symptoms or can be asymptomatic, so incidence may be underestimated (Public Health England, 2017). Concern about Zika arises mainly because of its association with neurological birth defects, including microcephaly, a condition where babies are born with a small head and incomplete brain development (CDC, 2022), and Guillain–Barré syndrome, a condition that causes nerve damage (Krauer et al., 2017; Ryan et al., 2017, 2018). When the WHO declared the Zika epidemic a Public Health Emergency of International Concern (Krauer et al., 2017), there was a decrease in tourist arrivals to the Caribbean (CARPHA, 2017; R4ACCHC, 2022a). Cases of chikungunya and Zika increased work absenteeism and decreased worker productivity in the Caribbean (Ramrattan, 2015).

Yellow fever and malaria have been kept under control in the region by vaccination and a concerted eradication campaign, respectively. However, malaria continues to be endemic in the Dominican Republic, Belize, Haiti and Guyana (CARPHA, 2018). Caribbean countries remain at risk of outbreaks of yellow fever and malaria and VBDs transmitted by other vectors, which, in the Americas, primarily affect impoverished communities in Central and South America.

Caribbean research teams have been at the forefront of research showing links between climate and VBDs for about 30 years (Amarakoon et al., 2008; Chen et al., 2006a; Chen et al., 2006b; Ortiz Bulto and Linares Vega, 2021; Rise et al., 2022). Several Caribbean studies have established positive relationships between rising temperatures and the incidence of dengue fever (Amarakoon et al., 2008; Gharbi et al., 2011; Jury, 2008; Lowe et al., 2018; Méndez-Lázaro et al., 2014). Some studies have also found a positive association between levels of precipitation and dengue incidence, with others finding no or only a weak relationship between the two (Gharbi et al., 2011; Johansson et al., 2009; Méndez-Lázaro et al., 2014). Two studies have noted higher numbers of cases in years with El Niño activity (Ferreira, 2014; Johansson et al., 2009). Higher vulnerability to dengue in urban than in rural areas has been found, along with a tendency towards an expansion of dengue's geographical range to higher altitudes (Henry and Mendonça, 2020). In Barbados, geographical hotspots of dengue and chikungunya cases were identified (Lippi et al., 2020). In Puerto Rico, a study found an association between dengue and sea level rise, which may have resulted from the perimeter of an estuary expanding and shorelines moving inland, providing pools of brackish water for mosquito breeding. However, as mean sea level rise was found to correlate with both sea surface and air surface temperatures, the authors noted that rising temperatures were likely to be the most important explanatory factor (Méndez-Lázaro et al., 2014).

The Caribbean body of research has spearheaded the development of information products and communication known as climate services for health. Climate predictors of VBD outbreaks have been identified, facilitating the development of early warning systems (EWSs) (Linares-Vega and Ortiz-Bulto, 2021; Linares-Vega et al., 2020; Lowe et al., 2018; Lowe et al., 2020; Ortiz, 2021; Ortiz et al., 2015; Stewart-Ibarra, 2021; Stewart-Ibarra et al., 2017, 2019, 2022). However, action to address VBDs is constrained by the failure in most countries to link climate and health action, and a lack of specialised human resources. In addition, some of the approaches used do not sufficiently integrate metrics from medical, environmental, climatic and epidemiological sources (Ortiz Bulto and Linares Vega, 2021), highlighting the need to strengthen collaboration between agencies (see Chapter 10, "Collaboration between agencies"). In the research field, there is a need to build the skills of local staff in statistical modelling, geographic information systems (GISs) and data analysis, to increase self-sufficiency in the conduct of studies, and in building and using EWSs (Hussain-Alkhateeb et al., 2021; Stewart-Ibarra et al., 2019). While gaps remain, VBDs are one of the only areas where a substantial body of Caribbean research exists (Allen et al., 2021a,b; CARPHA, 2018).

2.2. WHAT SHOULD BE DONE?

Individual and community actions and how to support them

A major focus of individual and community action to prevent mosquito-borne diseases, especially those transmitted by *Aedes aegypti*, which spreads the most common VBDs in the Caribbean, should be reducing standing water that is accessible to mosquitoes for breeding. This highlights the importance of water management, such as covering water containers, and waste management, such as removing plastic litter and old tyres, where water can gather (R4ACCHC, 2023). For other VBDs, the reduction of breeding sites is also a major strategy. Proper waste management controls other vector populations such as rats, flies and fleas, and so can reduce the incidence of the diseases they spread. In Saint Lucia, a project was established where communities were encouraged to use old tyres and plastic to construct kitchen gardens, so that these communities had greater access to fresh food, thus contributing to a reduction in noncommunicable diseases (NCDs) (R4ACCHC, 2023). Personal protection and vector control measures complement these approaches.

At the individual citizen and community levels, these methods require small amounts of time and effort at regular intervals for environmental inspection and reducing breeding sites. Clearing drains and guttering and removing household waste are important. Small sums need to be spent on installing lids or fine netting on water containers and cistern openings so that mosquitoes cannot enter and lay their eggs.

There are also long-standing barrier methods such as installing bed nets and insect screens and wearing long-sleeved garments and insect repellent (R4ACCHC, 2022a). These can be adopted by visitors to the region as well as residents. Support for installing and using barrier methods is important given the difficulties in reducing breeding sites in the Caribbean (R4ACCHC, 2023). Individuals and communities can liaise and cooperate with environmental inspectors and implement other aspects of vector control, such as using technologies to kill adult mosquitoes or larvae. Educational institutions at all levels should be involved in sharing information on prevention and control strategies with their students. Communication should be tailored to populations at risk, such as pregnant women (R4ACCHC, 2023).

From an intervention perspective, Caribbean experience suggests that action involving communities is often more effective than communication to motivate individual behaviour change. It is difficult to change how people manage the spaces around them without involving them in some collective activity, such as clearing up items where rainwater has settled (R4ACCHC, 2023; Yearwood and Polson-Edwards, 2017). Community-based vector control interventions in several Latin American countries were tested in cluster randomised trials and found to be effective (Sommerfeld and Kroeger, 2015).

Tools and equipment are needed to facilitate individual and community action, such as bins, garbage trucks, gloves, spades, mosquito netting and specially adapted water containers. Adequate drainage and drain maintenance also facilitate prevention (R4ACCHC, 2023).

People in the Caribbean often do not take the actions necessary to protect themselves and keep vectors under control in their own households and communities. Research is needed to understand why such actions are taken or not, and to build and implement effective communication and behavioural interventions. As suggested above, it is also important to conduct studies on the efficacy of community-based interventions. Recommended research is described below.

Structural/governmental and private sector actions

Establish effective intersectoral and interagency collaboration mechanisms based on the One Health approach

Intersectoral and interagency collaboration to address climate-related health risks is addressed in detail in Chapter 10, "Collaboration between agencies". For research and action on VBDs, relevant government ministries and environmental health, medical and climate professionals should work together. Staff on the front line of service provision in public, private and nongovernmental organisations should be involved, as well as managerial staff and academics (Dubrow, 2021; Fontes-Filho et al., 2021).

The One Health approach is particularly relevant to collaboration relating to tackling VBDs (Benjamin, 2021; Dente et al., 2018).

> One Health recognizes that the health of humans, animals and ecosystems are interconnected. It involves applying a coordinated, collaborative, multidisciplinary and cross-sectoral approach to address potential or existing risks that originate at the animal-human-ecosystem interface.
>
> One Health Global Network (n.d.)

For instance, to prevent and address tick-borne diseases, in which wild and domestic animals infested by ticks play an integral role, it is important for veterinarians, medical and public health scientists and entomologists (specifically acarologists) to work together and provide advice to policymakers (Charles et al., 2021). This concept of interdisciplinary collaboration is fundamental to the integrated vector management (IVM) approach promoted by the WHO (2012, 2022a).

IVM uses a suite of complementary approaches involving governmental and community action across sectors, making use, based on evidence, of high and low technologies and environmental management approaches, and involving monitoring and evaluation, to ensure effectiveness and efficiency. It reduces the previous reliance on toxic chemical insecticides, which can be harmful to public health (WHO, 2012). In 2017 the WHO built on experiences with IVM with the issue of its "Global vector control response 2017–2030" strategy. Limited IVM uptake was attributed to limited human capacity to advocate, plan and implement, as well as fragmented global and national architectures unable to support a multi-disease approach. The strategy highlighted the need to increase human capacity at the national and subnational levels and to strengthen infrastructure and systems (e.g. access to potable water, adequate solid waste and excreta management), particularly in vulnerable communities. It called for strategic intersectoral and interdisciplinary action, linking efforts in environmental management and health education and reorienting relevant government programmes around proactive prevention and control strategies (WHO, 2017).

Implement vector control strategies with a special focus on poor and disadvantaged communities

The circumstances in which people live and work affect their vulnerability to VBDs, as is the case for other health conditions (Marmot, 2005). In low-income communities, vector control programmes tend to be inadequate; healthcare and sanitation infrastructure is suboptimal; and social and environmental conditions tend to promote mosquito breeding. Inequalities within and between countries affect responses to VBDs (Mavian et al., 2018).

Outreach strategies may be necessary to involve low-income and isolated communities and assist them in environmental action to clean up potential breeding sites (Sommerfeld and Kroeger, 2015). Special efforts are needed to meet the needs of geographically remote communities with weaker infrastructure, such as indigenous communities.

Poorer communities and those with an inadequate water supply can also be assisted through donations of supplies and equipment, such as insect screens, and guidance on how to store water safely by modifying storage

Figure 1: Health promotion poster in Dominica aimed at preventing the spread of mosquito-borne diseases

Source: photo of an Environmental Health Department of Dominica poster, taken by Caroline Allen.

drums (Mavian et al., 2018), such as the example in Figure 1. The distribution of products and community education should focus on women, since it is mostly women who manage water storage and harvest rainwater as part of their domestic responsibilities. Opportunities are available for the private sector to become involved in providing supplies and public education as part of corporate social responsibility.

Boost the capacity of public health departments responsible for vector control

Vector control in SIDS is constrained by a lack of dedicated personnel. Sometimes there are no specialist vector control staff; instead, vector control is one of the several environmental and public health responsibilities of small teams or individuals. Resources should be dedicated to building up the numbers and skills of staff with vector control expertise. If the cost of recruiting additional staff cannot be met, existing personnel should be selected for training and they should be allocated the responsibility of vector control. Teams should be supported with knowledge about the latest scientific developments in vector control and with equipment and supplies to pilot and implement the latest vector control strategies (Medlock, 2021). Teams should be provided with skills for vector and disease surveillance, and contribute to and be provided with information from EWSs. They should be given support to become “first responders” in addressing the environmental risks of VBD transmission (R4ACCHC, 2023).

Governments should determine the level of human resources and range of skills necessary to address vector control and compare current staffing and skills with these. Shortfalls may be addressed by recruiting additional staff or providing existing staff with new skills and revised responsibilities, and supportive supplies and infrastructure. Educational institutions should be involved in identifying the skills needed for vector control and training new cohorts of students as well as existing health sector staff (see Chapter 13, “Awareness- and skills-building”).

Vector control teams should be provided with opportunities for networking and collaboration (Ortiz Bulto and Linares Vega, 2021; Ortiz, 2021). In Barbados, Cuba and Dominica, government and international partners have enabled team members to collaborate with meteorologists and scientists to co-create VBD EWSs and determine how information from them will be used. VBD experts at the regional and international levels should actively include staff working in the field in discussions on how to translate the results of research and the development of EWSs into practical and useful action on the ground (Lowe et al., 2020; Stewart-Ibarra, 2021; Stewart-Ibarra et al., 2019, 2022).

Vector control teams should be trained in/have the following characteristics (Medlock, 2021):

- Strong links with the community and understanding of factors promoting compliance;
- Good knowledge of mosquito ecology and disease risks in the context of climate change;
- Mosquito surveillance;
- Knowledge of how to seek and destroy breeding sites and reduce infestations;
- Knowledge of how to monitor and evaluate vector control interventions;

- Appropriate use of insecticides given evidence on resistance;
- Resources and infrastructure for mobilisation;
- Strong leadership and supportive work environments.

Strengthen water, sanitation and hygiene infrastructure and services

Building climate-resilient water, sanitation and hygiene (WASH) systems is a general recommendation for addressing climate-related health risks (R4ACCHC, 2023) and is detailed in Chapter 3, "Water, sanitation and hygiene". It is critical for the elimination of vector breeding sites, especially in vulnerable communities and urban settings (Henry and Mendonça, 2020; Medlock, 2021). Guidelines on vector control should be expanded to include underground breeding sites (such as cisterns and pipes) and brackish water (Mavian et al., 2018; Méndez-Lázaro et al., 2014). Public health regulations on water storage should be revised, updated and enforced (Lowe et al., 2020).

Waste management before the wet or hurricane season is a key intervention for disaster resilience. If potential water receptacles are covered or adequately disposed of, the potential for mosquito proliferation in the event of flooding or a hurricane will be lower (Medlock, 2021). Community clean-up drives can assist with this (Sommerfeld and Kroeger, 2015). Bodies responsible for solid waste management should ensure that their equipment, such as garbage trucks, can access remote communities in the event of a landslide, flood or hurricane (Allen et al., 2019a; CARPHA, 2018).

Build skills in complementary disciplines

The training of healthcare workers and laboratory staff is also needed. Further and higher education institutions can build skills in areas such as clinical care, communication, entomology, environmental health, laboratory testing and vector control. The development of short courses and online training modules, through collaboration with regional institutions of higher learning, can assist. See also Chapter 13, "Awareness- and skills-building".

Support the tourist sector and ports of entry in preventing and controlling vector-borne diseases

Some VBDs, such as yellow fever, can be prevented through vaccination. A malaria vaccine has also been launched. Caribbean governments should continue to be vigilant in requiring visitors to be vaccinated against VBDs for which effective vaccines have been developed, depending on VBDs predicted to be of concern (CARPHA, 2017). Airlines and cruise ship companies should continue with practices such as spraying aircraft cabins prior to take-off and inspecting ships for infestations, particularly in water containers.

The Caribbean Community (CARICOM) Regional Coordinating Mechanism on Health Security was developed in 2014 partly in response to the chikungunya epidemic and focuses on measures to protect local populations from imported diseases. The Global Health Security Cooperative Agreement with the Centers for Disease Control and Prevention (CDC) included funding to address Zika starting in 2016. This has focused on enhanced surveillance using GISs and laboratory and insectary facilities, and building a Caribbean network of VBD experts (CariVecNet).

Some tourist establishments have installed barrier methods such as bed nets, conduct regular exercises to remove breeding sites and have advised their visitors to adopt prevention methods. The Caribbean Public Health Agency (CARPHA) has collaborated with tourism ministries, the Caribbean Tourism Organization and the Caribbean Hotel and Tourism Association (CHTA) to develop strategies on mosquito-borne diseases. The Caribbean Alliance for Sustainable Tourism, which was formed by two board members of the CHTA, has conducted educational sessions and webinars on Zika and other mosquito-borne diseases (R4ACCHC, 2022b). Such initiatives should be continued and promoted. Tourist premises should be subject to more regular public health inspections, with an increase in the number of inspectors if necessary.

Include vector-borne diseases in disaster preparedness and resilience strategies

Extreme weather events associated with climate change may disrupt vector control activities, highlighting the need to put systems in place to strengthen the resilience of community infrastructure (Medlock, 2021). Resilience strategies relevant to vector control in extreme events such as hurricanes and flooding should be put in place (Allen et al., 2019a; CARPHA, 2018; Medlock, 2021):

- Strengthen the climate resilience of buildings housing laboratories and vector control departments and their communications and other equipment and supplies.
- Provide air conditioning in buildings and shipping containers used for remote laboratories or equipment storage.
- Provide robust vehicles and parking spaces for vector control staff that will withstand flooding or high winds in the surrounding area.
- Prepare temporary office accommodation and establish rapid repair processes.
- Provide staff with real-time information on geographical communities at risk, through collaboration with sentinel stations and meteorological services.
- Establish rapid procurement/sourcing of vector control products and equipment.
- Establish systems for the rapid removal and proper disposal of bulky waste and debris.
- Establish systems for checking and fixing gauze on outlet pipes and screens on windows and for ensuring rainwater drums are covered.
- Ensure access to first aid for vector control staff and vulnerable communities.
- Maintain and stockpile resources such as traps with charged batteries, mesh for securing cisterns, covers for temporary water-capture receptacles, larvicide and where necessary adulticide (for fogging), and public communication material for rapid dissemination.
- Compile lists of available stocks and create procedural manuals.

Research gaps and how to address them

Improved prediction models for vector-borne diseases

Research is needed to determine how meteorological factors interact with nonclimate drivers in the spread, distribution and incidence of vector-borne infections. Nonclimate drivers include pathogen evolution, human susceptibility to infection, ecosystem change, level of economic development, water and land use (e.g. dams, deforestation), urbanisation, human behavioural factors, international travel and trade, level of public health infrastructure, vector control measures and migration. It is reasonable to hypothesise that meteorological factors interact with nonclimate drivers with a high degree of specificity, with marked variation by disease and geographical location, meaning that this research needs to be conducted on a disease-specific and SIDS-specific basis (Dubrow, 2021; Ortiz Bulto and Linares Vega, 2021). An important reason for conducting this research is to inform the development of accurate EWSs, but it should be noted that this type of activity is research, not surveillance. It can help to inform national, regional and international prevention and control policies; inform adaptation and mitigation measures; and target resources where most needed.

The development of prediction models depends on the existence of strong surveillance data from the field and from laboratories, however (R4ACCHC, 2023). See the subsection “Surveillance gaps and how to address them” below.

Communication of information from early warning systems

It is important to research the best ways to communicate information from EWSs to key stakeholders. Knowledge and communication products should be simple to use and accessible to decision-makers, especially those responsible for public health, health service management and disaster preparedness (Stewart-Ibarra, 2021). Knowledge products and communication methods designed for the general public based on EWS data may be helpful, particularly in motivating action to prevent outbreaks (Lowe et al., 2020). Simplified modelling and automation of thresholds for warnings can enhance uptake (Lowe et al., 2018; Stewart-Ibarra et al., 2022). Forecasts of disease risk could be used to inform hospitals about staffing needs and which medicines and laboratory diagnostic reagents to stock (Allen et al., 2021a; Lowe et al., 2020; Stewart-Ibarra et al., 2019).

Studies on knowledge, attitudes, beliefs and practices on vector-borne diseases

Studies on knowledge, attitudes, beliefs and practices (KABP) can reveal motivations for and constraints on individual action to control VBDs, but very few have been conducted in the Caribbean. Only one study was identified in the current review, published in 2006 (Rawlins et al., 2006b). Since the chikungunya and Zika epidemics, the CDC has provided funds to CARPHA for further KABP surveys, but conducting these surveys was challenging during the COVID-19 pandemic. Studies should be conducted to measure public knowledge about vectors, their breeding practices, how they transmit diseases and whether diseases such as dengue are believed to be spread in ways other than by vectors. Attitudes and behaviours relating to evidence-based VBD prevention and control recommendations also need to be more closely examined to inform future interventions (Allen, 2021).

KABP studies are needed to inform the development of effective communication and behavioural interventions to achieve the major objectives of vector control programmes, i.e. reducing vector breeding sites and adopting personal protection and vector control measures.

Research on effective behavioural and communications interventions

Approaches to promoting vector control in the general population should be tested using intervention studies, the outcomes of which are the adoption of behavioural recommendations and, ultimately, changes in vector numbers and disease outbreaks (Dubrow, 2021).

Research based on behavioural theory can help in the development of interventions. For example, Anderson et al. (2020) applied protection motivation theory in a study of personal protective behaviours to prevent chikungunya (appropriate clothing and repellent use) among travellers from the United States of America to the Caribbean. The perceived severity of the disease and perceived vulnerability were found to be significant predictors. This type of research can help to inform communication in the tourism sector.

The general application of research on how to strengthen community action on public health can also assist. A CARPHA evidence brief reviewed behaviour change strategies that can help to strengthen household and community action for the prevention and control of mosquito-borne diseases. Findings included the following (Yearwood and Polson-Edwards, 2017):

- Participation in environmental enhancement and conservation activities produces personal, social, physical and psychological benefits, and these foster individual change to benefit the community.
- Digital health promotion interventions, presented via electronic devices and social and other media, help to modify behaviour, especially if combined with text messaging, online support and decision support tools.
- Financial incentives, both positive and negative, have been successfully used to modify behaviour related to risks such as smoking and alcohol use and the use of vaccination services, and these incentives could be applied successfully to prevention of viral VBDs.

The implementation of recommendations from behavioural research should be monitored and evaluated to improve the effectiveness of interventions.

It is important when conducting such research to enable participants to explain in their own words the factors that may prevent them from adopting the appropriate preventive behaviour. Individuals and communities may regard other concerns as more immediate or important than VBD prevention, such as retaining employment, maintaining relationships and other health concerns.

Studies in Latin American countries looked at strategies to involve communities in removing discarded containers, cleaning backyard areas, covering large water containers, covering windows and large containers with insecticide-treated material, elementary school education and practical skills development. These interventions all led to a reduction in mosquito populations compared with control communities (Sommerfeld and Kroeger, 2015). Similar studies involving vulnerable communities in research and intervention design should be conducted in the Caribbean, while assessing the human resources and other resources available for the sustained support of these efforts.

Identification of vulnerable communities in need of vector control interventions

As highlighted in the situational analysis on VBDs and in Chapter 9, "Distribution, equity and justice in climate change and health", the risks of VBDs are unevenly distributed such that identification of vulnerable communities is critical (R4ACCHC, 2023). The starting point for this research should be identifying the key facets of communities' vulnerability to VBDs, including:

- Poor or unreliable access to water;
- Poor or inadequate access to solid waste removal;
- High prevalence of open containers;
- High risk of flooding;
- High risk of being isolated following severe weather events;
- Low income;
- History of marginalisation and discrimination.

Sentinel stations, VBD surveillance and meteorological services can help to provide real-time information on vulnerable communities and their needs.

Further vulnerabilities within communities should be identified, such as among women, children, older people, people with disabilities and people with NCDs. Research along these lines can assist in the efficient and equitable allocation of vector control and healthcare resources (Allen, 2021; R4ACCHC, 2023).

Surveillance gaps and how to address them

Strengthened field and laboratory surveillance

Field-based staff, such as vector control, environmental, public health and laboratory personnel require further skills, equipment and supplies, so that they can collect, enter and analyse data on a systematic basis. Their ability to collect data on environmental conditions, vector numbers and distribution, and disease incidence and prevalence must be improved so that data coverage and quality can be improved. Time series and location-based data are critically needed. Strengthening capacity among front-line staff is critical to the ability of researchers and policymakers to develop and use the evidence base (R4ACCHC, 2023). There is also a role for "citizen science" in providing reports on breeding sites and environmental hazards. Tools such as smart phone apps can be used to facilitate data collection (Poon, 2022; Walsh et al., 2018).

Rapid availability of relevant data on public health and weather risks

Electronic information systems should be developed to enable the establishment of EWSs and responses to evolving risks. Weather forecasting capacities should be strengthened and early warnings provided directly to healthcare providers. Public health inspectors and vector control teams should be trained in and provided with computer hardware and tailored software to record their monitoring data on environmental conditions relating to VBDs, such as drainage; solid and liquid waste management and disposal; water storage; adult and larval vector counts; and inspection of public and commercial buildings and facilities, especially hotels, ports, cargo, healthcare facilities and workplaces. Data from EWSs should be presented in bulletins to stakeholders, including policymakers, healthcare managers and the general public.

Assess current and required equipment and supplies

Inventory and procurement information systems are needed to keep track of equipment and supplies for vector control and enable a flexible response to emerging environmental threats.

Mapping the movement of vectors, vector-borne diseases and viral strains geographically and over time

Mapping and predicting the distribution of vectors, cases of disease and viral strains can sharpen the design of control strategies and optimise the use of limited public health resources. With four dengue virus serotypes circulating in the Caribbean, and given the vulnerability of individuals to severe forms of the disease if they are exposed to a serotype they have not been infected with before, it is critical to map how serotypes and strains are circulating within the region and in other areas connected through travel. Routine sequencing of dengue virus strains can identify which part of the world they came from, helping to prevent further imported cases (Douglas et al., 2020). Awareness of the spread of existing strains and the introduction of new strains is also needed. Mapping the spread of vectors, which may move into new environments and even adapt to new places and conditions, is needed as well. For instance, Yang et al. (2018) mapped the spread of the snails that cause schistosomiasis and found that a combination of human behavioural and climatic factors has led to the enlargement of their habitat from tropical to some subtropical regions. Prioritising surveillance and control efforts in high-traffic regions with highly suitable vector habitats may be the most effective approach.

Excess deaths and seroprevalence surveys as tools of epidemiological surveillance

Many cases of VBDs are not reported to healthcare practitioners or onwards to surveillance systems. This means that the true extent of illness and death from VBDs is not known. In the Jamaica Health and Lifestyle Survey 2016–17, the population prevalence of self-reported chikungunya was 48.8%, but 80.4% of the population had a positive serum (blood) test for the disease (Ministry of Health Jamaica, 2018). This highlights the importance of utilising available diagnostic tests to establish seroprevalence in the context of major outbreaks.

Freitas et al. (2019) looked at excess mortality in Jamaica in 2014, the year of a major outbreak of chikungunya. Excess deaths were estimated by calculating the difference between observed deaths and the expected number of deaths based on the average age-specific mortality rate in 2012–13. They found that there was an excess of 2499 deaths during the epidemic (91.9/100 000 population) and a strong positive correlation between the monthly incidence of chikungunya and excess deaths. Similar methods could be used in future to investigate whether outbreaks are associated with increased mortality.

Research and surveillance capacity-strengthening needs

Improved prediction models for vector-borne diseases

Collecting good longitudinal data on nonclimate drivers is needed to enable research that will lead to improved prediction models for VBDs. Researchers in several academic disciplines, including medical science, environmental science, economics, behavioural science and international relations, should contribute their expertise by strengthening their collection, analysis and communication of data on nonclimate drivers of climate change and health risks, and informing policy.

Establish links, networks, working relationships, data-sharing and methodological agreements between research and surveillance professionals in the meteorological and health fields

This is linked to the recommendation on intersectoral and interagency collaboration and is covered in more detail in Chapter 11, "Research and surveillance on climate change and health". With regard to research on VBDs, time periods for the integration of longitudinal data on weather patterns, vector densities and VBDs, and spatial boundaries for data collection should be agreed on (Linares-Vega and Ortiz-Bulto, 2021; Ortiz, 2021; Ortiz et al., 2015). There are some methodological challenges, since data on vector densities and VBD cases tend to be collected less frequently than data on weather. For instance, at the regional level, cases of dengue, chikungunya and Zika are reported in four-week blocks in communicable disease surveillance reports to CARPHA and confirmed by laboratory testing of samples (Allen et al., 2019a). The relative infrequency of aggregated regional VBD data collection means that, to get a picture of climate–VBD associations at the regional level and to compare countries, datasets may need to cover periods of years (Allen et al., 2021a; CARPHA, 2017). These types of methodological challenges will need to be discussed between agencies collecting data, to agree on ways to integrate climate/weather and health data to analyse associations.

As mentioned above, the One Health approach is particularly relevant to the prevention and treatment of VBDs; therefore, research collaborations between meteorologists, environmental health and medical professionals, veterinarians and entomologists would be fruitful.

An excellent example of integrated science for health is that of the approach taken in Cuba. In this country, research has been conducted on climate variability and change and its impact on health over the last 30 years. This was facilitated by establishing a multi-agency group on climate and health based at the Instituto de Meteorología de la República de Cuba (INSMET), resulting in research projects and publications combining climate and health data. INSMET communicates with the public when climate-related disease outbreaks and risks are predicted (Allen et al., 2021b). In the past decade, efforts in Cuba have focused on understanding and attributing the effects of climate on changing patterns of viral and bacterial agents that cause infectious diseases. Cuban research teams have examined climatic data alongside the dynamics of the vectors and pathogens affecting changes in disease transmission; ecological changes such as biodiversity loss, residential location and nutrient cycle changes; and socioeconomic changes in areas such as demographics, migration, sanitation and nutrition (Ortiz Bulto and Linares Vega, 2021).

Strengthen early warning systems and embed them in public health decision-making

The Caribbean is a global leader in the development of EWSs for VBDs (Stewart-Ibarra, 2021), and these have helped decision-makers to take targeted action to prevent and address outbreaks. However, only some Caribbean countries have established these systems and are using them to help guide decision-making.

A scoping review found that almost all EWS models for VBDs require highly skilled users with knowledge of advanced statistics (Hussain-Alkhateeb et al., 2021). One of the challenges in the local development of EWSs in SIDS has been the lack of personnel with the requisite skills to combine health and climate datasets and to conceptualise and implement the complex statistical modelling required (Mavian et al., 2018). There is therefore a need to build expertise in statistical and epidemiological modelling in the region. Other areas where strengthening skills is required are GIS and computer programming (Stewart-Ibarra, 2021; Stewart-Ibarra et al., 2022). Cuba has developed its own institutional capacity in these areas (Linares-Vega and Ortiz-Bulto, 2021; Linares-Vega et al., 2020; Ortiz, 2021; Ortiz et al., 2015). In other Caribbean countries, the requisite expertise has generally been provided through collaboration with universities outside the region (Lippi et al., 2020; Lowe et al., 2018; Lowe et al., 2020; Stewart-Ibarra et al., 2022). These universities have engaged in collaboration and capacity-building with local staff, but specific efforts are needed throughout the region to build human resources through advanced training and scholarships as well as short courses.

Electronic information systems are generally weak in the Caribbean and it is particularly important to strengthen capacity for the monitoring of environmental conditions and diseases. Investment in electronic hardware and the development of specialised software is needed.

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