BMJ Global Health

Co-learning during the co-creation of a dengue early warning system for the health sector in Barbados

Anna M Stewart-Ibarra ,[1] Leslie Rollock,[2] Sabu Best,[3] Tia Brown,[3] Avriel R Diaz,[4] Willy Dunbar,[5] Catherine A Lippi ,[6] Roché Mahon,[7] Sadie J Ryan ,[6] Adrian Trotman,[7] Cedric J Van Meerbeeck,[7] Rachel Lowe [8,9,10]

To cite: Stewart-Ibarra AM, Rollock L, Best S, *et al*. Co-learning during the co-creation of a dengue early warning system for the health sector in Barbados. *BMJ Global Health* 2022;**7**:e007842. doi:10.1136/bmjgh-2021-007842

Handling editor Seye Abimbola

Received 27 October 2021
Accepted 3 December 2021

For numbered affiliations see end of article.

Correspondence to
Dr Anna M Stewart-Ibarra; astewart@dir.iai.int

ABSTRACT

Over the past decade, the Caribbean region has been challenged by compound climate and health hazards, including tropical storms, extreme heat and droughts and overlapping epidemics of mosquito-borne diseases, including dengue, chikungunya and Zika. Early warning systems (EWS) are a key climate change adaptation strategy for the health sector. An EWS can integrate climate information in forecasting models to predict the risk of disease outbreaks several weeks or months in advance. In this article, we share our experiences of co-learning during the process of co-creating a dengue EWS for the health sector in Barbados, and we discuss barriers to implementation as well as key opportunities. This process has involved bringing together health and climate practitioners with transdisciplinary researchers to jointly identify needs and priorities, assess available data, co-create an early warning tool, gather feedback via national and regional consultations and conduct trainings. Implementation is ongoing and our team continues to be committed to a long-term process of collaboration. Developing strong partnerships, particularly between the climate and health sectors in Barbados, has been a critical part of the research and development. In many countries, the national climate and health sectors have not worked together in a sustained or formal manner. This collaborative process has purposefully pushed us out of our comfort zone, challenging us to venture beyond our institutional and disciplinary silos. Through the co-creation of the EWS, we anticipate that the Barbados health system will be better able to mainstream climate information into decision-making processes using tailored tools, such as epidemic forecast reports, risk maps and climate-health bulletins, ultimately increasing the resilience of the health system.

Summary box

- Through a co-learning and co-creation process, health systems are better able to mainstream climate information into decision-making processes through the use of tailored tools such epidemic forecast reports, climate risk maps or seasonal climate-health bulletins.
- Strategies to develop strong climate and health partnerships include buy-in from senior leadership and mandates for the health sector to address the threats posed by climate extremes and climate change, and for the climate sector to address health impacts.
- An epidemic early warning system (EWS) should be tailored to meet the needs of diverse end users, including actors that work across health policy, practice and research, disaster risk and water management, which may vary depending on their role (e.g., planning, resource allocation, policy, community outreach, research, operations).
- Key challenges to the sustainable implementation of a dengue EWS include lack of technological capacity and human resources in national climate and health institutions and lack of sustained funding to transition from a pilot system to an operational system.

INTRODUCTION

Over the past decade, the Caribbean region has been challenged by the co-circulation and overlapping epidemics of dengue, chikungunya and Zika viruses, which are transmitted to humans by the *Aedes aegypti* mosquito. A recent analysis found that the Caribbean region had the third highest burden of dengue fever globally (following South Asia and Southeast Asia),[1] although estimates may be skewed upwards in the Caribbean due to high healthcare-seeking behaviour and healthcare access, and low population estimates. The concurrent COVID-19 pandemic has both drained and diverted public health funding, resulting in declining resources to combat mosquito-borne diseases, despite global calls to sustain vector-borne disease control efforts.[2]

Small island developing states in the Caribbean are highly vulnerable to climate variability and climate change.[3–6] Extreme climate events, such as tropical storms and droughts, can increase the risk of mosquito-borne disease epidemics due to the impact of variations in temperature and rainfall on the mosquito life cycle, transmission of viruses and mosquito larval habitat.[7] The optimal temperature for dengue fever transmission by the *Ae. aegypti* mosquito, the primary vector in the Caribbean, is 29.1°C, with transmission rates declining in excessively cool or hot conditions above or below this optimum temperature.[8] As weather patterns continue to shift due to global heating, the epidemiology of these 'climate sensitive' diseases will also evolve, affecting when and where outbreaks occur, and the magnitude of the outbreaks.[9–13] Novel tools and sustained strategies are urgently needed to increase the capacity of the public health sector to combat mosquito-borne disease epidemics in the context of global environmental changes.[3] However, the capacity in Caribbean countries to develop these tools is currently low, with only one National Meteorological and Hydrological Service reported as offering specialised climate information services for the health sector.[14]

One promising adaptation strategy for the health sector is the development of epidemic early warning systems (EWS) that integrate climate information in forecasting models to predict the risk of disease outbreaks several weeks or months in advance.[3] Examples of climate information include rainfall or temperature measurements from local weather stations, data from satellite imagery (earth observations), gridded reanalysis or data from an ensemble of seasonal climate forecasts. An EWS is tailored to support the needs of the end user—in this case the public health sector—providing timely and accurate information that can guide decisions about early interventions to prevent an epidemic. An EWS is an example of a 'climate service for the health sector.' The Global Framework for Climate Services (GFCS) provides key global guidelines for their development.[15] Of note, potential health sector end users include diverse actors that work across health policy, practice and research, and whose needs may vary depending on their role (e.g., planning, resource allocation, policy, community outreach, research, operations).[15] Other end users of a dengue EWS may come from key sectors such as disaster risk management, water, education and tourism.

CO-LEARNING DURING THE CO-CREATION OF CLIMATE SERVICES

The co-creation of climate services, through a collaborative transdisciplinary approach, is a best practice to develop a climate service for health and other sectors.[15–18] Mauser *et al*[19] describe co-creation as a process that spans co-design, co-production and co-dissemination. A transdisciplinary science approach is problem driven and solution oriented,[20] integrating knowledge, tools and ways of thinking from multiple perspectives [21] through an interactive and participatory process involving researchers from diverse disciplines and relevant stakeholders from the public sector, private sector and/or civil society.[22]

The co-creation of an EWS can also be understood as a collaborative modelling process, as described by Voinov and Bousquet.[23] The process begins with the definition of the problem and identification of goals and decisions to be made, followed by identifying and engaging with stakeholders, choosing data analysis and modelling tools, collaboratively collecting and processing data, defining the system and developing conceptual models, running the model, discussing results, improving the design and finally, the implementation of actions. The modelling is supported by ongoing evaluation and feedback from participants, resulting in co-learning.[23,24] Through this collaborative approach, the final product is more likely to be relevant, credible and legitimate—increasing the potential for the climate service to be translated into action by the health sector.[19,25]

The Flagship report of the Alliance for Health Policy and Systems Research, *Learning health systems—pathways to progress,* emphasises that 'learning—at individual, team, organisational and cross-organisational levels—is fundamental to the strengthening of health systems and the achievement of health goals.' The authors emphasise that learning processes can drive broader changes at the organisational level and across multiple organisations or sectors in response to challenges, such as the health impacts of global heating. A focus on equitable co-learning allows for individuals, teams and institutions to learn from each other, ultimately increasing the resilience of health systems.[26] At the team level, co-learning facilitates a better understanding of roles, responsibilities and expectations.[15–17,26] However, at the health system level, learning occurs across multiple levels of an organisation and across organisations, thereby supporting adaptation and innovation, as in the case of a novel dengue EWS. Through this co-learning process, we anticipate that the health system will be better able to mainstream climate information into decision-making processes through the use of tailored tools such as epidemic forecast reports, climate risk maps or seasonal climate-health bulletins that form part of an EWS. We also anticipate that the climate system will be better able to support the operationalisation of climate-informed tools for the health sector. In the following, we share the experience of co-learning during the process of co-creating a dengue EWS for Barbados.

A DENGUE EARLY WARNING SYSTEM IN BARBADOS

Barbados is a small island developing state in the Eastern Caribbean. In 2017, Barbados had the highest age-standardised incidence rate of dengue worldwide.[1] Other countries from the Caribbean were also among the top 10 countries with the highest rates (Dominica, Trinidad and Tobago, Antigua and Barbuda, and Saint Lucia).[1] Barbados reported 4362 dengue cases from 2014 to 2020 (annual average of 21 cases per 10 000 population).[27] Outbreaks of chikungunya and Zika were reported for the first time in 2014 and 2015–2016, respectively.[28]

The economy of Barbados and many Caribbean islands is based on tourism and service industries; therefore, mosquito-borne diseases present a threat to the health of local residents, visitors and the economy.

In 2017, the Barbados Ministry of Health and Wellness (MHW) began partnering with the regional climate organisation and an international group of researchers to develop climate-informed disease forecast models to address the rising burden of mosquito-borne diseases. The project was initially coordinated by the Caribbean Institute for Meteorology and Hydrology (CIMH), which hosts the World Meteorological Organization-designated Regional Climate Centre for the Caribbean. The project was supported by the United States Agency for International Development-funded Programme for Building Regional Climate Capacity in the Caribbean.[29] Subsequent work has been supported by the Red Cross Red Crescent Climate Centre. This collaboration is ongoing, with team members from the MHW, the Barbados Meteorological Services (BMS), the CIMH (also based in Barbados), the Caribbean Public Health Agency (CARPHA) and academic researchers with diverse experience in mathematical modelling, geography, epidemiology, public health and policy research.

To manage dengue risk, the MWH in Barbados currently relies on the early recognition of increasing dengue incidence compared with seasonal averages from previous years and monitoring syndromic data.[7] The MHW anticipates an annual peak in dengue incidence during the warm and rainy season, although quantitative climate information and epidemiological data are not yet formally linked or analysed. When the collaboration began, the MHW had recognised the potential to harness collaborative data analysis given the existence of nearly two decades worth of dengue case data and limited capacity for in-house analysis (e.g., in terms of personnel, skills and issues related to time).

The process of co-creating the EWS is ongoing and has included engagement of practitioners to assess needs and priorities, identify key partners, an audit of available health and climate data, cleaning/collation of relevant data, co-development of the forecast model, feedback from practitioners via national and regional consultations, and webinar trainings for climate and health practitioners. Through the co-creation process, the team also identified a number of challenges to the implementation of a dengue EWS and solutions to address these challenges, which are described in the box below (box 1).

Box 1 Key implementation challenges for a dengue early warning system (EWS) in Barbados and the team's responses

Implementation challenges:

- Lack of sustained funding to transition from a pilot system to operational system.
- Lack of current technological/procedural capacity (eg, Geographic Information Systems (GIS), software engineers, statistical and/or modelling expertise) and financial/human resources in the Ministry of Health and Wellness (MHW) to implement an operational EWS.
- Lack of fine-scale climate data at a subnational level, linked to georeferenced epidemiological information, that would allow for spatially resolved probabilistic forecasts of diseased risk at the level of health districts.
- Lack of personnel dedicated to the curation and management of climate and health data, which limits effective data sharing in real-time.
- Lack of a specific mandate to address climate-health work in both the health and climate sectors, resulting in lack of dedicated personnel and resources.
- Lack of formalised partnerships (eg, Memoranda of Understanding (MOUs)) between national-level climate and health communities to facilitate a joint work plan, data sharing, and modelling.
- Challenges in translating probabilistic outbreak forecasts into impact alerts with response messages.

Solutions:

- Simplifying the modelling process, to use the most simple and parsimonious model to derive skilful dengue forecasts 3 months in advance. This was done by identifying optimum climate-disease case lags in the model and ensuring that the model did not have to rely on a live stream of health surveillance data, which can often be disrupted, particularly during a pandemic or other disaster.
- Convening of online spaces of dialogue and joint training with national and regional climate and health sectors to co-create the EWS, refine the model and visualisations according to stakeholder needs and ensure a sense of ownership of the product by partners.
- Leveraging of the existing online weather/climate hazard messaging platform operated by the Barbados Meteorological Services (BMS). The team is working to translate the probabilistic outbreak forecasts into impact-level warnings, using decision matrices, to combine level of certainty in the forecast with urgency for action based on other impact-based forecasting tools hosted by the BMS on their website. This has resulted in BMS and MHW working together and learning from each other to find solutions to host the online EWS and ensure its sustainability in partnership with the Caribbean Institute for Meteorology and Hydrology (CIMH) and the Caribbean Public Health Agency (CARPHA).
- In 2017 and 2020, CIMH and CARPHA signed a multi-year collaborative letter of agreement, thus acting as a model for national-level collaborations and playing a leadership role in the region. In partnership with the Pan American Health Organization (PAHO), these institutions have pioneered an interdisciplinary regional science agenda to advance climate-informed health EWSs at regional and national levels. By identifying climate services for health as a priority area and committing to jointly address gaps, they have sustained the engagement with the national health and climate stakeholders, despite short-term project funding cycles.

Learning about sectoral needs, priorities and perceptions

Through a series of stakeholder interviews and questionnaires, the team learnt about needs, priorities, existing mandates, capacity gaps and strengths, perceptions of climate-health linkages, existing use of climate information in the health sector, and strategies to strengthen the climate-health interface.[30] Through mapping of key stakeholders, the team identified a diverse web of institutions involved in dengue control, and institutions that could become more involved, such as local universities and the private sector. It was noted that there were no formal existing collaborations between the climate and health sectors, and that this needed to be remedied if the country wanted to develop sustainable climate services for the health sector. The team co-learnt about strategies to strengthen climate-health partnerships, including:

- Securing support from the senior leadership of the MHW early on to ensure that climate and health was a priority on the national health agenda.
- Creation of a mandate for the health sector to address climate impacts, and for the weather/climate sector to address health impacts.
- Formal institutional agreements, such as MOUs between climate and health sectors.
- National committees on climate and health with joint work plans with dedicated institutional and human resources.
- Data sharing agreements and protocols to ensure compatible scale and format of data.
- Regular meetings between the climate and health sectors to review climate and arbovirus forecasts.
- Joint trainings for climate and health sectors.
- Designation of institutions responsible for implementing and sustaining the EWS.

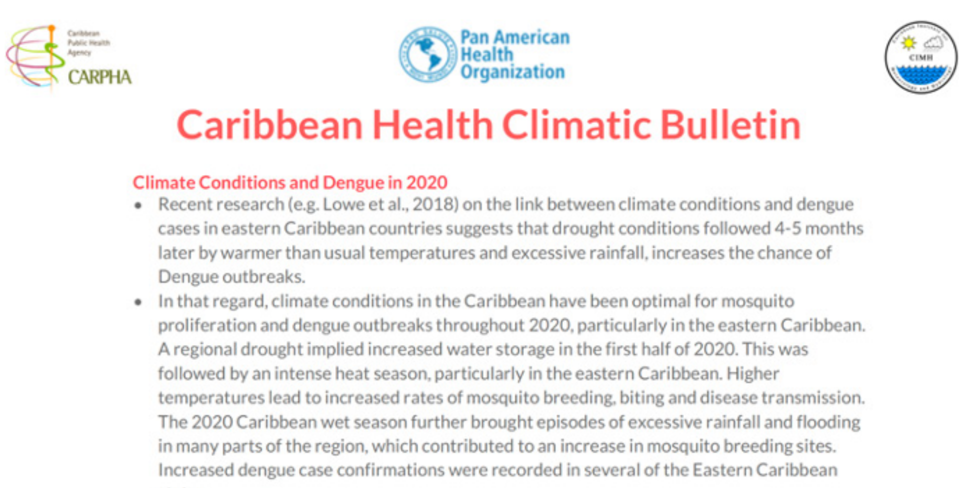
The team co-learnt about the ideal characteristics of a dengue EWS from the perspective of national climate and health stakeholders (e.g., the best time frame for forecasts and communication platforms). The climate sector learnt about the needs of the health sector with respect to climate information, and the health sector learnt about the capabilities of the climate sector to support their decision-making processes (e.g., the kinds of platforms and interfaces that could support an EWS, prior experience with developing climate services for other sectors and issuing climate alerts). The team also learnt about the training needs of health and climate sectors to enable an operational EWS, particularly the need for additional personnel trained in GIS, data management and data analysis in the health sector.

Learning about the potential use of climate information for a dengue EWS

The team was able to successfully create a pilot dengue prediction tool that incorporated climate information into a forecast model to predict the risk of outbreaks 3 months in advance.[7] This experience taught the team about the value of collaborative data analysis and how climate information could potentially be used by the health sector to inform decision-making in Barbados.

Through the modelling process, the team learnt that both excess rainfall and drought conditions could increase the risk of dengue outbreaks at different time-frames, thus providing critical local evidence of the effects of climate on dengue transmission.[7] It was found that wetter conditions could increase the likelihood of a disease outbreak up to 2 months later, likely due to the accumulation of rainwater in seasonal watercourses or other water receptacles, thereby increasing mosquito habitat. It was also found that drought conditions also increased the likelihood of a dengue outbreak 3–5 months later, likely due to water storage in uncovered containers around the home during periods of water scarcity. Water storage is a key issue to address in water scarce countries, like Barbados, where household water storage has been promoted as a climate change adaptation strategy. This finding taught the team about the need to collaborate with urban planners and other stakeholders involved with building ordinances.

These findings revealed the importance of public health messaging on proper water storage during drought periods in the Caribbean Health Climatic Bulletin.[29] The finding was cited in the monitoring section of the December 2020 edition of the Bulletin, advising public health stakeholders that climate conditions in the Caribbean were optimal for mosquito proliferation and dengue outbreaks throughout 2020, due to a widespread drought in the first half of 2020 followed by an intense heat season and excessive rainfall, particularly in the Eastern Caribbean[31] (figure 1). In


Caribbean Health Climatic Bulletin

Climate Conditions and Dengue in 2020

- Recent research (e.g. Lowe et al., 2018) on the link between climate conditions and dengue cases in eastern Caribbean countries suggests that drought conditions followed 4-5 months later by warmer than usual temperatures and excessive rainfall, increases the chance of Dengue outbreaks.
- In that regard, climate conditions in the Caribbean have been optimal for mosquito proliferation and dengue outbreaks throughout 2020, particularly in the eastern Caribbean. A regional drought implied increased water storage in the first half of 2020. This was followed by an intense heat season, particularly in the eastern Caribbean. Higher temperatures lead to increased rates of mosquito breeding, biting and disease transmission. The 2020 Caribbean wet season further brought episodes of excessive rainfall and flooding in many parts of the region, which contributed to an increase in mosquito breeding sites. Increased dengue case confirmations were recorded in several of the Eastern Caribbean states.

Figure 1 Image extracted from the December 2020 Health Climatic Bulletin linking the team's research findings to climate conditions and dengue risk in the Eastern Caribbean.[31]

Barbados, the MHW had already intensified monitoring for dengue outbreaks following the record increase in dengue cases in Latin America and the Caribbean, beginning in 2018 and continuing into 2019. Based on past experience, the MHW expected a similar increase in cases in Barbados and they were proactively issuing intermittent public messaging on avoidance of mosquito breeding, including on safe water storage. The recommendations issued in the December 2020 bulletin served to reinforce ongoing preventative actions.

The Barbados MWH has learnt how to use and interpret the regional Health Climatic Bulletin to inform quarterly planning, an important first step towards mainstreaming of climate information in health operations. They also receive information from the BMS Monthly Climate Outlook Newsletter, providing national-level weather and climate information. The team co-learnt about the potential to improve these products by incorporating quantitative information on dengue risk[7] or other climate-sensitive health issues.

The team co-learnt about effective messaging and alert systems for health hazards through the climate services online platform that is currently hosted by the BMS on their website. This platform provides warnings on a range of meteorological hazards. The team are exploring ways to translate probabilistic outbreak forecasts into impact level alerts, using decision matrices. This would allow the alert message to combine the level of certainty in the forecast with urgency for action, similar to other impact-based forecasting tools hosted by the BMS. The team also learnt that strong consideration must be given to the inclusion of success indicators of early detection and prevention, to avoid successful predictions that lead to preventative action being interpreted as false alarms from the EWS. The team discussed ways to automate the EWS and to minimise the human input needed to generate future forecasts, thus enhancing the sustainability of the system. For example, the team adapted the model so that it did not rely on a live stream of health surveillance data, which is vulnerable to disruptions such as during a pandemic or other disaster.

Simple automation—using an impact matrix with predefined and agreed upon language and thresholds for warning levels (e.g., low, medium, high risk)—is essential for the sustainability mentioned above. The BMS have adopted a similar approach for other meteorological hazards with different sectors in the country. During the warning generation process, there is little or no human input needed to specify the impacts expected during a particular hazard event. This has resulted in the BMS and MHW working together and learning from each other to find solutions to host the online EWS and ensure its sustainability in partnership with regional partners such as CIMH and CARPHA.

Learning about limits to spatial tools on small islands

During the development of the EWS, the team learnt about the potential use of georeferenced disease case data and spatial analysis, such as hotspot mapping, to inform public health policy and response. For example, dengue cases reported from health districts can be used as data inputs for hotspot analyses and risk mapping. The team learnt that there are limitations to consider when applying spatial statistics to epidemiological information on small islands. In an analysis of chikungunya data, an emerging disease, the data were simply too sparse to detect hotspots. Applying routine data preparations to account for variability in data structure (e.g., underlying population distribution) led to results that were still skewed.[32] The team learnt that hotspot mapping was a powerful tool for inform health agencies and guide further research; however, they must critically assess the applicability of the analyses when used with data from small islands, like Barbados, or data from small disease outbreaks.

Learning at the regional level informs practice at the national level

Learning at the national level was informed by strong, emerging partnerships between regional climate and health organisations.[29] In 2017, CARPHA signed onto a CIMH-led multi-institutional letter of agreement (LoA) promoting the co-development of climate services across several climate-sensitive sectors, including health.[33] More recently in 2020, CARPHA renewed its LoA commitment until 2022. Since 2017, these regional entities have engaged in an ongoing collaboration with the Pan American Health Organization (PAHO) to co-design, co-develop and co-deliver the quarterly Caribbean Health Climatic Bulletin, a climate service for the health sector. Each quarter, representatives from CARPHA, PAHO and CIMH come together to review the upcoming seasonal climate forecast and they jointly develop and issue expert statements on likely health impacts for the region. This Bulletin is shared with Ministries of Health and other interested stakeholders across the region, such as the tourism sectors. The Bulletin is also shared with Caribbean National Institutes of Meteorology and Hydrology, some of which adapt the information from the Bulletin for use in their own national bulletins. This experience established a precedent for operationalising climate-health collaborations in the Caribbean. This has informed subsequent efforts to issue national-level messages on climate and health in Barbados, Dominica, Saint Lucia, Grenada, St. Vincent and the Grenadines, Jamaica, and, more recently, in Guyana.

CONCLUSIONS

Equitable and effective collaboration, with an emphasis on co-learning, creates an environment that enables the translation of scientific knowledge to public health action. Prior authors established that a trusting relationship sets the foundation for sustained engagements between providers of climate services and end users—the health sector in this case.[14 16 17] As noted by Hewitt *et al*, significant time and effort are needed to build and sustain these trusting relationships.[34] Key strategies and best practices for the creation of climate-informed tools have guided this project[15 17 26 35] and this experience can serve to inform others. However, our collaborative process emerged and evolved in response to the unique local context and experiences of the team.

In the experience shared here, the team adopted a collaborative co-creation approach whereby team members worked together through a continuous and iterative process spanning the design and development of the EWS.[19] Team members were encouraged to be open to new ways of thinking. Decisions about the EWS were made through a deliberative consensus process that sought to balance the needs and capabilities of the team. The approach was inclusive, adaptable, reflective and flexible to changing conditions, following best practices for the co-creation of climate informed tools.[35] Team members continue to be committed to a long-term process of collaboration.

Co-learning was a key component of the collaborative process. Team members learnt from each other as equals and gained a better understanding of each other's roles, responsibilities and expectations. This focus on co-learning facilitated the team's comprehension of institutional contexts and the identifiation of solutions to EWS implementation (box 1). Through this process, the team co-learnt about the local social, environmental and climate factors influencing dengue transmission, resulting in more accurate interpretations of the model results and translation of the results to public health messages. Importantly, the team was better able to adapt and respond to the health sector's needs, which have evolved over the course of the project due to the COVID-19 pandemic and other factors.

Ongoing engagement over the last five years has built trusting relationships. By engaging with key partners from the beginning of the process, the team cultivated a shared sense of ownership of the EWS. This helped to ensure that the health sector perceived that their needs and priorities were being addressed, that the EWS had the potential to impact a health outcome that they considered to be important, and that the EWS could help them to better use their resources to reduce the burden of disease. This process aided in creating a sense of accountability of the joint commitments and outcomes of the collaboration by the national climate and health sectors. The team continues to work to ensure that the national climate and health organisations have the appropriate resources and capabilities to engage in the creation and implementation of the EWS.

Developing strong intersectoral partnerships, particularly between the national climate and health sectors, was a critical part of the research and development process. This process revealed differences in priorities, mandates, technical/academic training and language, pushing team members out of our comfort zones and challenging us to venture beyond institutional and disciplinary silos. The team learnt about the importance of harnessing the diverse experiences, perspectives and skills of the community of practice to provide the greatest opportunity to develop an EWS. Stakeholder engagement plans that foster inclusion, diversity, accessibility and equity can address this goal, allowing partners to maximally achieve the project goals while respecting values, beliefs and customs throughout the co-creation process.

The experience of co-learning in Barbados can inform critical efforts by health systems around the world to address the impact climate change, particularly in the Global South. This collaborative co-learning process and the EWS modelling framework is being shared with other Caribbean countries. However, one of the major challenges is the need for sustained institutional and financial support to operationalise an EWS. Global funding for climate change adaptation in small island developing states is needed urgently, coupled with efforts to increase national capacities and to create national mandates for the health sector to address the impacts of climate on health.

Author affiliations
[1]Inter-American Institute For Global Change Research, Montevideo, Uruguay
[2]Ministry of Health and Wellness, St. Michael, Barbados
[3]Barbados Meteorological Services, Christ Church, Barbados
[4]International Research Institute for Climate and Society (IRI), Columbia University's Climate School, New York, New York, USA
[5]Department of Health Promotion and Disease Prevention, Florida International University, Miami, Florida, USA
[6]Department of Geography and Emerging Pathogens Institute, University of Florida, Gainesville, Florida, USA
[7]Caribbean Institute for Meteorology and Hydrology, Bridgetown, Parish of Saint Michael, Barbados
[8]Centre on Climate Change & Planetary Health and Centre for Mathematical Modelling of Infectious Diseases, London School of Hygiene & Tropical Medicine, London, UK
[9]Earth Sciences Department, Barcelona Supercomputing Center, Barcelona, Spain
[10]Catalan Institution for Research and Advanced Studies (ICREA), Barcelona, Spain

Twitter Anna M Stewart-Ibarra @DrAnnaStewart and Rachel Lowe @drachellowe

Contributors RL, LR and AMS-I conceived of the article; AMS-I wrote the initial draft and is responsible for the overall content as the guarantor; all coauthors reviewed, edited and approved of the manuscript.

Funding The authors have not declared a specific grant for this research from any funding agency in the public, commercial or not-for-profit sectors.

Competing interests None declared.

Patient consent for publication Not applicable.

Ethics approval This study does not involve human participants.

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement There are no data in this work.

ORCID iDs
Anna M Stewart-Ibarra http://orcid.org/0000-0002-3383-4672
Catherine A Lippi http://orcid.org/0000-0002-7988-0324
Sadie J Ryan http://orcid.org/0000-0002-4308-6321
Rachel Lowe http://orcid.org/0000-0003-3939-7343

REFERENCES

1 Zeng Z, Zhan J, Chen L, *et al*. Global, regional, and national dengue burden from 1990 to 2017: a systematic analysis based on the global burden of disease study 2017. *EClinicalMedicine* 2021;32:100712.

2 Seelig F, Bezerra H, Cameron M, *et al*. The COVID-19 pandemic should not derail global vector control efforts. *PLoS Negl Trop Dis* 2020;14:e0008606.
3 Lowe R, Ryan SJ, Mahon R, *et al*. Building resilience to mosquito-borne diseases in the Caribbean. *PLoS Biol* 2020;18:e3000791.
4 Ebi KL, Lewis ND, Corvalan C. Climate variability and change and their potential health effects in small island states: information for adaptation planning in the health sector. *Environ Health Perspect* 2006;114:114.
5 Robinson Stacy-ann, Robinson S. Climate change adaptation in SIDS : A systematic review of the literature pre and post the IPCCFifth Assessment Report. *WIREs Clim Change* 2020;11:e653.
6 Pachauri RK, Meyer LA, eds. *IPCC, 2014: climate change 2014: synthesis report. contribution of working groups I, II and III to the fifth assessment report of the Intergovernmental panel on climate change*. Geneva, Switzerland: IPCC, 2014.
7 Lowe R, Gasparrini A, Van Meerbeeck CJ, *et al*. Nonlinear and delayed impacts of climate on dengue risk in Barbados: a modelling study. *PLoS Med* 2018;15:e1002613.
8 Mordecai EA, Cohen JM, Evans MV, *et al*. Detecting the impact of temperature on transmission of Zika, dengue, and Chikungunya using mechanistic models. *PLoS Negl Trop Dis* 2017;11:e0005568.
9 Colón-González FJ, Sewe MO, Tompkins AM, *et al*. Projecting the risk of mosquito-borne diseases in a warmer and more populated world: a multi-model, multi-scenario intercomparison modelling study. *Lancet Planet Health* 2021;5:e404–14.
10 Ryan SJ, Carlson CJ, Mordecai EA, *et al*. Global expansion and redistribution of Aedes-borne virus transmission risk with climate change. *PLoS Negl Trop Dis* 2019;13:e0007213.
11 Ryan SJ. Mapping thermal physiology of vector-borne diseases in a changing climate: shifts in geographic and demographic risk of suitability. *Curr Environ Health Rep* 2020:1–9.
12 Ryan SJ, Lippi CA, Zermoglio F. Shifting transmission risk for malaria in Africa with climate change: a framework for planning and intervention. *Malar J* 2020;19:170.
13 Ryan SJ, Carlson CJ, Tesla B, *et al*. Warming temperatures could expose more than 1.3 billion new people to Zika virus risk by 2050. *Glob Chang Biol* 2021;27:84–93.
14 Mahon R, Greene C, Cox S-A, *et al*. Fit for purpose? transforming national Meteorological and hydrological services into national climate service centers. *Clim Serv* 2019;13:14–23.
15 World Meteorological Association. *Health exemplar to the user interface platform of the global framework for climate services (GFCS*. Geneva, Switzerland: World Meteorological Association, 2014. https://gfcs.wmo.int/sites/default/files/Priority-Areas/Health/GFCS-HEALTH-EXEMPLAR-FINAL-14152_en.pdf
16 Kotova L, Terrado M, Krzic A. Lessons and practice of co-developing climate services with users, 2017. Available: https://www.climateurope.eu/wp-content/uploads/2018/03/Climateurope_D4.2_FINAL.pdf [Accessed 22 Jun 2020].
17 Lemos MC, Kirchhoff CJ, Ramprasad V. Narrowing the climate information usability gap. *Nat Clim Chang* 2012;2:789–94.
18 Borbor MJ, Ayala EB, Cárdenas WB. Chapter 5: Developing and delivering health-tailored climate products and services, Case study 5.C Vector-virus microclimate surveillance system for dengue control in Machala, Ecuador. In: *Climate services for health: global case studies of enhancing decision support for climate risk management and adaptation*. Geneva, Switzerland: World Health Organization/World Meteorological Organization, 2016: 106–9.
19 Mauser W, Klepper G, Rice M, *et al*. Transdisciplinary global change research: the co-creation of knowledge for sustainability. *Curr Opin Environ Sustain* 2013;5:420–31.
20 Klein JT, Grossenbacher-Mansuy W, Häberli R. *Transdisciplinarity: joint problem solving among science, technology, and society: an effective way for managing complexity*. Springer Science & Business Media, 2001.
21 Norgaard RB. The case for methodological pluralism. *Ecol Econ* 1989;1:37–57.
22 Regeer BJ, Bunders JF. Knowledge co-creation: Interaction between science and society. *Transdiscipl Approach Complex Soc Issues Den Haag Advis Counc Res Spat Plan Nat Environ Comm Sect Counc Neth RMNOCOS* 2009.
23 Voinov A, Bousquet F. Modelling with stakeholders☆. *Environ Model Softw* 2010;25:1268–81.
24 Voinov A, Kolagani N, McCall MK, *et al*. Modelling with stakeholders – next generation. *Environ Model Softw* 2016;77:196–220.
25 Cash DW, Clark WC, Alcock F, *et al*. Knowledge systems for sustainable development. *Proc Natl Acad Sci U S A* 2003;100:8086–91.
26 Foundation TR. Learning to support co-production. braced. Available: http://www.braced.org/resources/i/?id=f69880ae-f10f-4a51-adb5-fb2a9696b44d [Accessed 22 Jun 2020].
27 PAHO. Annual cases reported of dengue. data, maps, and statistics. PAHO/WHO, 2020. Available: http://www.paho.org/hq/index.php?option=com_topics&view=rdmore&cid=6290&Itemid=4 0734 [Accessed 24 Jul 2021].
28 Ryan SJ, Lippi CA, Carlson CJ, *et al*. Zika virus outbreak, Barbados, 2015-2016. *Am J Trop Med Hyg* 2018;98:1857–9.
29 Trotman AR, Mahon R, Shumake-Guillemot J. Strengthening climate services for the health sector in the Caribbean. *Bull World Meteorol Organ* 2018;67.
30 Stewart-Ibarra AM, Romero M, Hinds AQJ, *et al*. Co-developing climate services for public health: Stakeholder needs and perceptions for the prevention and control of Aedes-transmitted diseases in the Caribbean. *PLoS Negl Trop Dis* 2019;13:1–26.
31 CARPHA/PAHO/CIMH. Caribbean health climatic Bulletin, vol 4, issue 4, 2020. Available: https://rcc.cimh.edu.bb/files/2020/12/Caribbean-Health-Climatic-Bulletin-Vol4-Issue4-December-2020.pdf [Accessed 8 Apr 2021].
32 Lippi CA, Stewart-Ibarra AM, Romero M, *et al*. Spatiotemporal tools for emerging and endemic disease hotspots in small areas: an analysis of dengue and Chikungunya in Barbados, 2013-2016. *Am J Trop Med Hyg* 2020;103:149–56.
33 Mahon R, Farrell D, Cox S-A. Climate services and Caribbean resilience: a historical perspective. *Soc Econ Stud* 2018;67:239–324.
34 Hewitt CD, Stone RC, Tait AB. Improving the use of climate information in decision-making. *Nat Clim Chang* 2017;7:614–6.
35 Rouhaud E. Co-producing climate knowledge: great in theory, how about practice? 2018. Available: https://cdkn.org/2018/03/feature-co-production/ [Accessed 22 Jun 2020].