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A scoping review of the implementation of infectious disease early warning systems (IDEWS) for building health system climate change resilience

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Abstract

A scoping review and thematic synthesis are utilised to examine the contribution of infectious disease early warning systems (IDEWS) to climate change resilience, given the current dearth of critical evaluations. Three databases and relevant websites were searched, leaving 45 included references. Most systems were implemented in Africa or the Americas to predict outbreaks of malaria or dengue. IDEWS precipitated investment in institutions, data systems, and capacity building that strengthen climate resilience, but maintained northern, scientific hegemonies. IDEWS deployment needs to be more responsive to the communities implicated in responses; and more primary, qualitative studies are necessary in this field.

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Abbreviations

EPIDEMIA	Epidemic Prognosis Incorporating Disease and Environmental Monitoring for Integrated Assessment
ESA	Eastern and Southern Africa
EWARS	Early Warning and Response System
EWS	Early Warning System
FAO	Food and Agriculture Organization
FEWS NET	Famine Early Warning Systems Network
IDEWS	Infectious Disease Early Warning System
MSF	Médecins Sans Frontières
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
RVF	Rift Valley Fever
UK	United Kingdom
UNDP	United Nations Development Programme
UNFCCC	United Nations Framework Convention on Climate Change
UNISDR	United Nations International Strategy for Disaster Reduction
USAID	United States Agency for International Development
US	United States
WHO	World Health Organization
WMO	World Meteorological Organization

1. Introduction

Climate change is the biggest global health threat of the 21st century - projected to cause an additional quarter of a million deaths annually between 2030-2050 by the World Health Organization (WHO).[1,2] The incorporation of climate action into the Sustainable Development Goals (SDG 13) reflects the need to mainstream it into more established agendas in international development. When environmentalism first emerged in international discussions, promoted by the Global North, the Global South considered it incompatible with long-held developmental aspirations; however, the two domains are increasingly reconciled as the need to mitigate and adapt to climate change limits development prospects.[2] Environmental change poses a number of threats to health- including natural hazards, food and water insecurity, changing disease burdens and emerging infections- while testing health systems' capacity to respond.[1,3] Climate change will exacerbate inequalities along social, economic and political lines within borders and between states.[1] Infectious disease burdens are expected to shift as a result of the changing climate as populations are increasingly exposed to diseases not normally present in their environment due to the expansion of disease vectors into new territories, while natural disasters and forced displacements increase population susceptibility to outbreaks.[4] Malaria, dengue, cholera, and influenza are only some of the infectious diseases highlighted by WHO to be climate-sensitive, with an empirically demonstrated link between climatic variation and transmission patterns.[5] Climate change can thereby threaten recent gains in infectious disease control.

Health systems are therefore an integral part of climate change adaptation. To encourage health system climate action the WHO promotes the development of health national adaptation plans. In 2015, WHO published an operational framework to inform these, which urges states to pursue health system climate change resilience through the adoption of ten critical components.[6] One of these is integrated risk monitoring and early warning. Early warning systems (EWS) forecast and alert actors of impending climate events to initiate the deployment of a protective response.[6] Infectious disease early warning systems (IDEWS) use statistical models to evaluate input data in real-time to predict the occurrence of infectious disease outbreaks.[7] Input data can include one or a combination of indicators quantifying transmission risk (such as rainfall, temperature), vulnerability (such as immunity, malnutrition), and disease burden (from passive or active surveillance systems).[8] Because IDEWS compare input data in real-time against historical levels, data quality influences prediction confidence.[7] However, prediction is only one aspect of IDEWS- it is also necessary to establish a system of decision-making, communication, and response.[7] Due to their empirically-demonstrated relationship with climatic variation, 14 climate-sensitive infectious diseases were identified as candidates for IDEWS by WHO in 2005, although systems for malaria have been particularly prioritised.[5,9]

IDEWS are increasingly implemented globally. Of 78 respondent countries to the WHO's 2021 Health and Climate Change Global Survey, 39% reported having IDEWS for vector borne disease, 31% for airborne/respiratory illness and 31% for waterborne disease.[10] IDEWS were also the most common adaptation measure featured in health adaptation plans submitted to WHO.[10] Scientific literature reports on a range of models for infectious diseases and scoping reviews note their variable but largely good accuracy.[11,12] However, quantifying IDEWS' accuracy ex situ against curated datasets does not necessarily translate into protective outcomes in real-world settings because of the omission of alert interpretation, communication, and response, however no reviews are known to investigate how systems are operationalised in Southern contexts. Furthermore, given the impacts of climate change are increasingly felt globally, a better understanding of IDEWS implementation within the context of building climate change resilience is urgently needed. To address this gap, I will perform a scoping review and thematic synthesis focused on the Global South that expands upon previous works by asking:

A. Where and for which climate-sensitive infectious diseases have IDEWS been implemented?
B. How are IDEWS operationalised, particularly concerning input data, alert generation, and response?
C. What is the contribution of IDEWS to health system climate change resilience?

This work is structured as follows: the first section reviews existing literature to critically examine the use of resilience discourse in international development and global health, and maps what is currently known of IDEWS for climate-sensitive diseases; the second outlines the chosen methodology, including the search strategy and method of analysis; the third and fourth sections present results in line with the research questions, concluding with a final synthesis.

2. Literature review and theoretical framework

2.1 Examining resilience discourse in global health and development

Despite originating in the physical and ecological sciences, resilience discourse has proliferated in international development in recent years.[13] This has been attributed to a combination of its ideological compatibility with neoliberalism and the appeal of the implicated complex systems theory for excusing failed western interventions in the 1990s.[13,14] Due to its multiplicity of applications, resilience is difficult to define. The definition of the United Nations Framework Convention on Climate Change (UNFCCC) is considered most appropriate for this review: resilience is *"the ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organisation and the capacity to adapt to stress and change".*[15.]

Inherent in resilience discourse is the conception of the world as a complex ecological system which is unpredictable and non-linear; building resilience therefore implicates a need of individual preparedness against potential threats. Resilience discourse is closely linked to vulnerability, a term which is similarly ill-defined and can be politically deployed within the context of the UNFCCC.[16] In 2015, the publication of key frameworks and agreements saw resilience emerge as a core theme in the interrelated spheres of disaster risk reduction (the Sendai Framework), sustainable development (the Sustainable Development Goals), and climate change adaptation (the Paris Agreement).[17] The same year, resilience was the focus of the WHO's framework for building climate-resilient health systems, making resilience a policy item of growing importance in global health.[6] These agendas evolved separately, with each developing its own technical capacity and knowledge base. With its shared logic, resilience discourse offers a potentially unifying approach.[17,18]

Resilience discourse is not without its critics, who view it as a form of neoliberal governmentality.[19] Joseph (2013, 2016) highlights that resilience's ecological roots implies that the individual is a decision-making agent within a complex, unpredictable system; responsibilising the individual for their survival which can be achieved through awareness of- and preparedness against- system shocks.[14,19] Resilience policy is suggested to be imposed from the international to the national and local levels, and used to measure and shape the conduct of national actors upheld by soft law that makes compliance imperative to appear competitive for aid.[14] To Joseph (2016) resilience's emphasis on adaptation to contend with this complex system excuses failed western interventionism while shifting responsibility on to poorer states and communities themselves.[19] Where Joseph argues for the neoliberalism of resilience discourse, Chandler and Pugh suggest it is a post-liberal approach because its rejection of linear causality implicates the need of preventative approaches at the level of the object of governance – the individual or community- hence the predominance of 'empowerment' in resilience activities.[13,14,20] In the case of early warning systems (EWS), Gladfelter (2018) suggests a flood EWS in Nepal responsibilised community members while not necessarily building resilience.[21] However, this is a diverse policy space and critics may caricature this heterogeneity and ignore the potential programmatic benefits arising from this approach.[18,22] Proponents of resilience policy highlight that it provides individuals with agency in the face of impending crises and suggest that responsibilisation could flow upwards and encourage climate action from governments to protect communities.[19,21,23]

As resilience is symbiotic with vulnerability, resilience discourse has been further criticised for perpetuating a sense of crisis while promoting technical fix solutions that neglect the contribution of socioeconomic and political factors to vulnerability.[24,25] A study of resilience-building activities in the Philippines demonstrated how these replicated existing gender inequalities, despite being celebrated as empowering and presented as apolitical.[26] Meanwhile, these criticisms were echoed in global health as resilience discourse was critiqued for obscuring the socioeconomic factors that limited the Ebola response in West Africa.[27] It is therefore suggested that resilience approaches cannot disrupt the pre-existing power relations to which they elect to remain blind and that on a global level this reinforces neoliberal, capitalist hegemony.[28] However, international experts working in disaster resilience disagree with such criticisms, claiming that a focus on inclusion and empowerment of vulnerable groups is not lost in resilience-building activities.[18] Furthermore, proponents of resilience discourse suggest it is a desirable quality for health systems and provides a pragmatic approach to the challenges that health systems face.[29,30] However, there is some disagreement over whether resilience is compatible with – or seeks to replace- long-held goals in global health such as health systems strengthening and universal health coverage. While Kutzin and Sparkes (2016) suggest that resilience is compatible such goals, Abimbola and Topp are more critical in their indication that resilience may refocus resources away from the everyday functioning of health systems towards times of acute crisis and therefore undermine health systems strengthening.[30,31] Van de Pas further advocates that the capitalism and neoliberalism which resilience discourses represent undermines the achievement of global health goals.[32] In response to criticisms, Biddle *et al.* suggest that resilience discourse in global health has evolved to incorporate a greater focus on local power inequalities, building legitimacy of health actors, and improving everyday health system functioning in and between times of crisis.[27]

Several frameworks of health system resilience are proposed in the literature. A review of how resilience is operationalised in public health research suggests that the framework of Blanchet is most widely used, this describes four interlinked qualities of resilient health systems, namely the capacity to: [27,33]

1. Collect, integrate, and analyse different forms of knowledge and information (Knowledge).
2. Anticipate and cope with uncertainties and surprises (Uncertainty).
3. Engage effectively across scales and institutional silos (Interdependence).
4. Develop legitimate institutions that are socially accepted and contextually adapted (Legitimacy).

This research elects to use this framework to critically examine the impact of IDEWS on health system resilience, while not remaining blind to criticisms of resilience discourses.

2.2 Early warning systems (EWS) for building resilience

The United Nations International Strategy for Disaster Reduction (UNISDR) defines early warning systems as *"the set of capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities and organisations threatened by a hazard to prepare and act appropriately and in sufficient time to reduce the possibility of harm or loss".*[34] This comprehensive definition reflects the diversity of EWS, which can be based both on scientific and indigenous knowledge systems, although the latter are marginalised.[35] EWS have been implemented using both top-down and bottom-up approaches, in many global regions, and may be deployed on the global, national, regional or community level. For example, there are a number of successful EWS over global regions that warn the agricultural sector of drought and famine and are operated by international organisations with warnings communicated down to affected regions and communities.[36,37] In contrast, community-based EWS enable the deployment of a system operated by community members and suited to local knowledge systems and contexts, but these are generally poorly-linked to national and global levels.[37]

The ability of EWS to supplement the limitations of existing surveillance systems and reduce disaster-related deaths is increasingly demonstrated.[38,39] Implementation therefore constitutes a key part of international climate change policy due to their promotion by the UNFCCC under Article 7 of the Paris Agreement as well as the World Meteorological Organization (WMO) and United Nations Office for Disaster Risk Reduction under the "early warnings for all" mandate.[40,41] However, it will be necessary to iteratively revise systems to ensure they remain responsive to the changing climate.[42]

2.3 IDEWS for building health system resilience

Despite being recommended by WHO as a complement to malaria surveillance systems as early as 2001, IDEWS are less established than those for events more typically considered natural disasters because few research projects were translated into operationalisable systems during this period.[9,36] IDEWS were later reframed as tools for a broader range of diseases and environmental data were increasingly incorporated into models when WHO highlighted fourteen candidate diseases for IDEWS that had an empirical link between climate and epidemic.[5] This was reinforced in 2015 when IDEWS were incorporated into the WHO's framework for climate resilient health systems, which renewed interest in the systems as part of climate change adaptation.[6]

Preliminary searches identified a range of models for diseases such as malaria, dengue, meningitis, and cholera that were developed for both Global Northern and Southern contexts.[43–46] For instance, a prototype IDEWS for vector-borne diseases in Europe has been successfully utilised to assess environmental suitability for malaria transmission in Greece in the wake of a cluster of locally-acquired cases, and to control West Nile virus outbreaks linked to elevated ambient temperatures in southeastern Europe.[47] Review articles also suggest IDEWS' varied but promising accuracy.[11,12,48] A systematic review of dengue models identified acceptable predictive accuracy ranging from 50-100% sensitivity and 74-94.7% specificity, although performance varied with the type of model and the quality of the input data.[48] However, reviews predominantly report on the development of IDEWS models. Only the work of Hussain-Alkhateeb *et al.* attempts to discuss deployment, highlighting a number of challenges including: poor or unreliable case reporting, lack of geotagged data, inaccessible or lacking climate information, sole availability of remotely sensed data, no incorporation of other data affecting disease risk (such as land use or population mobility) and the necessity of advanced statistical skills to use systems.[11] Other discussion in the literature hypothesised that lacking capacity, weak institutional linkages, poor surveillance systems and necessity to develop decision-support mechanisms would limit the implementation of malaria IDEWS in Africa.[8,49]

Therefore, the current body of evidence jointly highlights the potential performance of IDEWS if deployed in the Global South and the numerous barriers to doing so. No identified reviews incorporated grey literature nor had an exclusive focus on climate-sensitive systems, despite noting the value of environmental variables for prediction accuracy.[11] Given that a number of Global Southern countries have reportedly deployed climate-sensitive IDEWS, discussion needs to advance beyond model development to real-world operationalisation; meanwhile the increasingly-apparent impacts of climate change mean this is a timely opportunity to initiate conversation on the contribution of IDEWS to health system resilience.[10]

3. Methodology

Munn *et al.* highlight scoping reviews as a suitable method for identifying knowledge gaps, mapping a body of literature, and clarifying concepts; therefore a scoping review methodology was elected for the purposes of this research.[50] Arksey and O'Malley identify five key steps to a transparent scoping review; 1) identification of the research question(s); 2) identification of relevant studies; 3) study selection; 4) data charting; 5) collating, summarizing and reporting of results.[51]

3.1 Search strategy

This review incorporates both academic and grey literature. The decision to incorporate grey literature was taken because of the failure of others to do so and its potential to provide supplementary information regarding how systems are operationalised in context. Meanwhile, the decision was made to focus on the Global South due to both the vulnerability of these health systems to the impacts of climate change and the likelihood that different factors affect IDEWS implementation compared to the North.

Academic literature was identified by searching three electronic databases – Ovid Medline, Embase, and Web of Science Core Collection- in June 2023. These databases were chosen for their ability to achieve a high recall rate, with Web of Science Core Collection specifically selected because of the interdisciplinary nature of this topic.[52] A search strategy was developed which combined synonymic terms relating to climate change or environmental variability; climate-sensitive infectious diseases; early warning; and implementation (Annex 1). A Cochrane expert search filter was used to focus results on the Global South.[53] These were combined with appropriate Boolean operators and results were filtered to only include references in English from 2005-onwards. This year aligns with the WHO publication outlining candidate climate-sensitive infectious diseases for IDEWS and was chosen to maintain both relevance and feasibility. Multiple search strategies were tested against a list of relevant publications- identified in preliminary searches- and optimized into the final strategy. For instance, a "NOT" operator was subsequently utilised to reduce the occurrence of COVID-19-related results. Databases were searched based on the title and abstract fields to produce a feasible scope.

In parallel, grey literature was identified by searching the websites of key organisations- the Foreign, Commonwealth and Development Office, the Intergovernmental Panel on Climate Change, Médecins sans Frontières (MSF), National Aeronautics and Space Administration (NASA), United States Agency for International Development (USAID), United Nations Development Programme (UNDP), United Nations Environment Programme, UNFCCC, WHO and WMO- and databases- Reliefweb and ClimaHealth- with terms such as "early warning system".[54,55] Reference lists of relevant review articles were also searched to maximize findings.

Inclusion and exclusion criteria were developed to identify references that discussed implementation of IDEWS for a climate-sensitive infectious disease in the Global South (Annex 2). References from the database search were uploaded into a review management software (Rayyan.ai), de-duplicated and screened, initially by title and abstract, then by full text. The same criteria were used to screen grey literature which was compiled in excel. References in English of any type (opinion, primary research, report, grey literature; pre- and post-print) that adhered to these criteria were eligible, except for reviews. Reviews were not included to avoid re-creating the focus of existing literature on model development. Included references were imported into a referencing software (Zotero) and compiled in excel. All authors were contacted where a full text was not publicly accessible and a contact address available.

3.2 Data analysis

Development of data extraction template

A data extraction template was inductively developed (Annex 3) to capture core information pertaining to the research questions, including:

- Country/region of implementation, target disease(s), scale of implementation, partners and donors.
- IDEWS input data and sources, alert generation method, communication strategy, description of (planned) response, if any.

This template was iteratively refined, and modifications made after trialling on a subset of included references. Extracted information was later standardised and used to inform the narrative and in the development of a summary table.

Thematic synthesis

Thematic synthesis- as outlined by Thomas and Harden (2008)- was the chosen method of analysis.[56] This applies the principles of thematic analysis to synthesise the results of included references and instruct the identification of themes of analytic depth.

Included texts were uploaded to NVivo (version 12) and coded using a combination (inductive-deductive) approach to provide both a rigorous and open-minded basis for thematic analysis.[57] A codebook was developed and pre-populated with codes pertaining to the four core aspects of Blanchet's framework for health system resilience.[33] New codes were inductively added and defined in the codebook throughout the coding process. Coding was closely informed by the text. NVivo was used to define cases by WHO region, World Bank income level and disease.[55,59] After the first round of coding, codes were revised and synthesized in an iterative process until first order themes organically arose. Data, codes, and first-order themes then informed the development of second-order themes pertaining to the core components of Blanchet's framework that provided greater analytical depth (see example in Table 1). Queries were generated in NVivo to explore how cases impacted coding frequency, with results noted to inform the narrative.

Studies were not evaluated for quality as this does not typically fall within the remit of scoping reviews. No ethical approval was required as no human subjects were involved.

Table 1. Example of coding process

Reference	Text	Code	Primary Theme	Secondary Theme	Framework Correspondence
Climate Services for Health[60]	*'…since the start of the project, meteorological and malaria services have worked together to begin installation of 16 new rain gauges located next to health centres in the project areas.'*	Meteorological data	Investment in data system	IDEWS expand health system ability to utilise different data types but require significant investment to be operationalisable.	Knowledge

3.3 Limitations

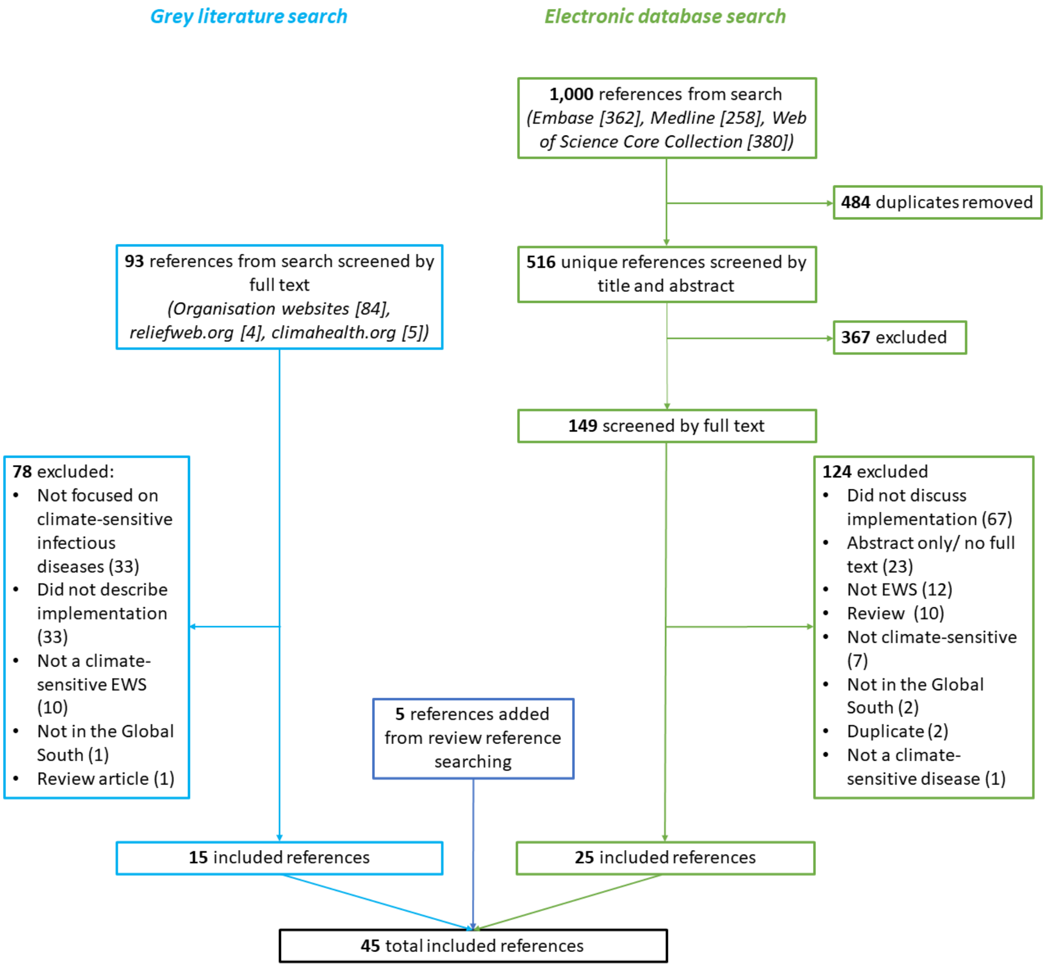
There are a few inherent limitations in this method. Firstly, compromises were made to ensure the feasibility of this project such as the inclusion of only three databases, not supplementing with regional databases, and searching based on title and abstract. These could result in references being missed. Secondly, only results in English could be included as per the language limitation of the author which will bias included references towards anglophone regions. Thirdly, thematic synthesis will be conducted by only one researcher from the Global North. This results in some intrinsic bias in theme identification which would be mitigated if multiple perspectives of varied expertise and background were involved. National and local level expertise from the Global South are important complementary perspectives that can therefore not be authentically represented. Finally, no quality assessment will be conducted so this paper is unable to make recommendations regarding the performance of IDEWS, however this has already been achieved in other scoping and systematic reviews that offer a complementary account.[11,12,49] As a scoping review, any conclusions made will be limited by the existing body of literature.

4. Results

4.1 Overview of search results

Searching electronic databases yielded a total of 1,000 initial results that included 516 unique references after de-duplication (Figure 1). These were screened by title and abstract and the majority (over 70%) excluded. 149 full texts were examined, most were irrelevant leaving 25 included references from the database search. Searching grey literature identified 93 references for full text screening, 90% of which came from organisations' websites, predominantly from WHO. However, most were excluded because they did not focus on climate-sensitive infectious diseases or did not describe implementation (both, n=33, 42%). Only 15 references were eligible from the grey literature search. An additional five references were included from reference lists of excluded reviews, leaving 45 references included in total.

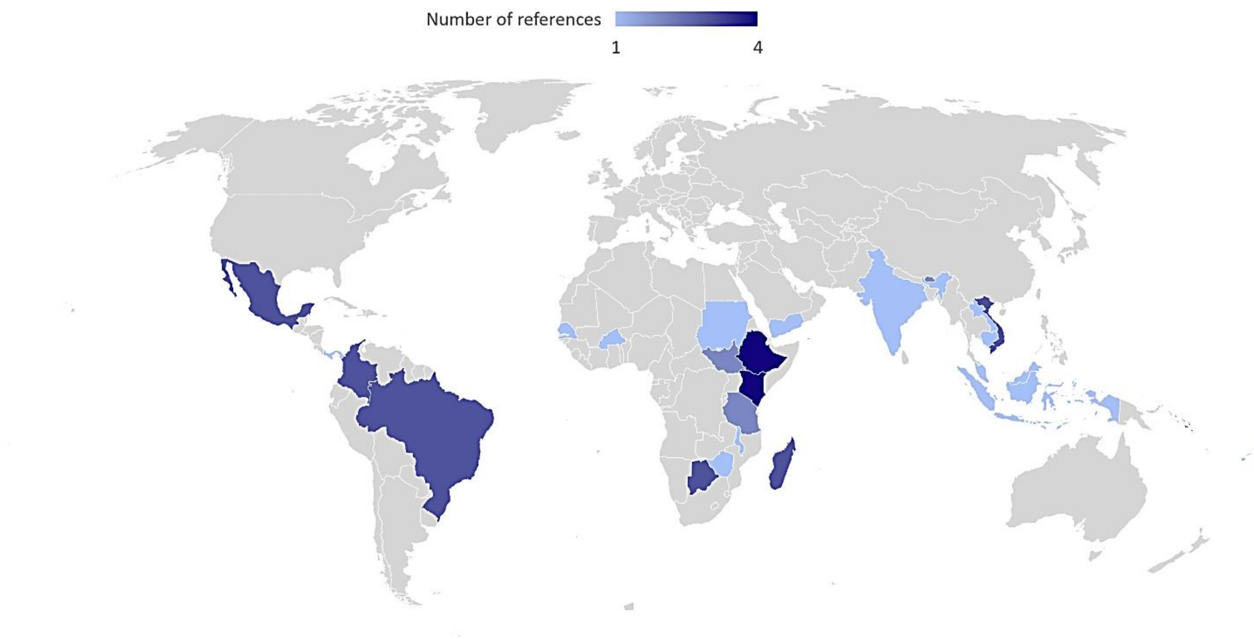
Figure 1: Flow chart summarising included literature.



4.2 Where and for which diseases have IDEWS been implemented?

The 45 included references spanned the last 20 years from 2003-2023: 38 described uses of IDEWS in one or more national contexts and eight discussed implementations in global regions (one described both). Implementation was noted in 28 countries, predominantly Ethiopia and Kenya (both, n=4); Brazil, Botswana, Colombia, Madagascar, Mexico, Solomon Islands, and Vietnam (all n=3) (Figure 2). Consequently, implementation was predominantly in Africa (n=22/38 (58%)), the Americas (n=12 (32%)) and the Western Pacific (n=11 (29%)). Only five references described systems in Southeast Asia and only two were noted in the Eastern Mediterranean. Around half of references discussed implementation in a lower-middle income country (LMIC), after this upper-middle income and low-income countries were most common (39% and 34%, respectively). References discussing high income countries made up 10% of the final inclusions. See Annex 4 for a summary of results.

Figure 2. A map of countries where references identified IDEWS implementation (n=38).



IDEWS were mostly used within states at a regional (n=23/45, 51%) or national level (n=11, 24%). Implementation at smaller scales was limited by the availability of data at this resolution (n=7, 16%). Eight references described systems covering larger scales, including East and Southern Africa (ESA), West Africa, continental Africa, and global scope. Two references did not specify the scale of implementation.

IDEWS in 41 references described targeting one or more climate-sensitive diseases: the other four referred to broader categories such as 'climate-sensitive diseases'. More than half targeted malaria and over a third focused on dengue; after these Rift Valley fever (RVF) (n=7), meningitis and chikungunya (both n=3) were most common. One reference each discussed systems for cholera and trypanosomiasis; while six discussed other diseases in addition to the those highlighted by WHO, including diarrhoeal diseases, zika, and plague. While the majority of IDEWS were un-named, two commonly referred to systems were Ethiopia's EPIDEMIA for malaria and the EWARS/EWARS-R system used in Brazil, Colombia, Malaysia, and Mexico, developed by WHO for dengue.

4.3 How are IDEWS operationalised?

Of 45 references, 37 detailed one or more input variables that informed epidemic prediction. Meteorological or environmental data was used by all of these, sometimes combined with surveillance (n=29/37, 78%) and/or entomological data (n=10, 27%). Demographic, public health intervention, cartographic, and socioeconomic data was used less frequently. Indigenous indicators were only utilised in one IDEWS, without integration of any other data.[61] Meteorological data came from national meteorological services, global data sources such as NASA and the National Oceanic and Atmospheric Administration (NOAA), and/or regional sources such as the African Data Dissemination Service.

Surveillance data was generally from the Ministry of Health/ relevant disease control programme. Only the minority of IDEWS were described as integrated with national information systems, these were in Bhutan, Burkina Faso, Madagascar, Mexico, Singapore, the Solomon Islands, and planned in Ethiopia.[60,62–67]

In the 22 references describing alert generation, a binary system (featuring an indication of ‘epidemic/no epidemic’) was most common (n=11/22, 50%), followed by a categorical system (featuring an indication of low, medium, high risk, for example, n=9, 41%) and then by visualisations of risk (such as heatmaps; n=7, 32%). These were not mutually exclusive as visualisations were sometimes used to complement other methods. Various statistical methods informed alert generation including percentiles, C-SUM, mean + two standard deviation, and composite risk indexes. Only the reference describing a community-based IDEWS did not fall into these categories as prediction was based on community observation and consensus.[61]

A similar number of references described alert communication, which was largely through bulletin/email (n=20/21, 95%) and/or a website/software (n=13/21, 62%). National health authorities were the most notified actor, after this were regional/district health authorities. International partners and non-governmental organisations sometimes received alerts, but national environmental agencies, donors, hospitals, universities/researchers, and military actors were less frequently included. Alerts were communicated to the general population in a handful of cases. For instance, in Brazil when a dengue IDEWS was established in preparation for the 2014 World Cup, the predicted outbreak risk of Brazilian cities was communicated to both the Brazilian population, to instigate the removal of breeding sites and individual protective measures, and to international visitors using foreign media and health authorities.[60]

Only 17 references discussed alert response, which varied as appropriate for the disease, lead time (how far in advance the warning was issued), and predicted scale of the epidemic. Community information, education, and communication was the most common measure (n=12/17, 71%), sometimes involving mass media. For example, in Singapore, IDEWS’ predictions informed the launch of a dengue public health campaign two months earlier than planned in 2013.[64] Other common responses included stocking up on vaccines/drugs (n=7), establishing outbreak plans (n=6), and strengthening surveillance and diagnostic capacities (both, n=3). Rarely noted measures included investigation of potential epidemic areas, providing chemoprophylaxis for risk groups, health worker recruitment, and facility preparation. Longer term forecasts were used in six references to inform health planning including resource and financial allocation. Some responses were only appropriate for specific diseases. Vector control measures were common due to references’ focus on malaria, dengue, and other vector-borne diseases. Similarly, references focused on RVF highlighted mass livestock vaccination and other controls including quarantine and movement restrictions, since human cases are often preceded by cattle outbreaks. Human vaccination campaigns, meanwhile, were discussed predominantly within the context of meningitis as most others do not have an available vaccine. For example, in response to a red-level alert from the meningitis IDEWS in West Africa, local health actors are advised to request vaccine dose allocations from the International Coordinating Group on Vaccine Provision.[45] In 2021, campaigns in Niger and Ghana were suggested to have prevented the projected epidemic.[45] Several other references reported instances where IDEWS had prompted an effective response. In Mexico, a dengue IDEWS- called EWARS- has been integrated into the national surveillance system since 2018, with districts that respond to alarms shown to experience fewer outbreaks.[62,68] Implementers of the same system from Brazil and Malaysia concur that the tool is useful for dengue control.[69] IDEWS also provided early warning in time to mitigate epidemics of dengue in Singapore and malaria in Madagascar; while in Kenya, the adjusted burden of malaria cases fell to less than 10% after implementation in pilot districts.[64,67,70]

4.4 What is the contribution of IDEWS to health system climate resilience?

Theme 1: IDEWS expand health system ability to utilise different data types but require significant investment to be operationalisable.

IDEWS need to incorporate meteorological or environmental data to be climate sensitive, but optimum performance is reserved for systems that integrate high-quality, real-time data from a combination of sources. This incentivises the development of IDEWS with substantial data requirements, which many contexts faced significant barriers and high initial costs to implementing. Difficulties accessing data affected almost all references but was particularly prominent in those discussing IDEWS in the Eastern Mediterranean, and low-income contexts.

The availability of weather stations to provide local climate data for IDEWS was noted to be scarce and this prevented predictions from being made at finer spatial scales, such as the sub-district or village level.[45,63,70–73] Use of remotely sensed satellite data was recommended to circumvent this since such data is increasingly freely available.[60,69,74] Satellite data was used for the prediction of outbreaks of dengue in Vietnam, RVF in Senegal and ESA, meningitis in West Africa, malaria in Ethiopia and trypanosomiasis in Tanzania.[74–80] However, reliance on external space agencies could threaten project sustainability when satellites are de-commissioned or output data format modified and there is little local capacity to make the necessary modifications to IDEWS.[66] A combination of local and satellite data is preferable, but may not be feasible due to the cost of accessing and processing raw data and the scarcity of weather stations.[66,81] IDEWS deployment attracted funding for meteorological services in the Global South. In Kenya, a joint project by WHO and UNDP installed weather stations to overcome these limitations; while in Bhutan, equipment for weather stations was procured as part of an IDEWS project.[70,82] The involvement of health actors is important to ensure stations are installed at points epidemiologically valuable for IDEWS predictions, such as close to settlements. Over time, this investment may improve data accessibility and reduce the initial barriers for subsequent projects. For example, since 2002 the Famine Early Warning Systems Network (FEWS NET) has provided freely available rainfall data across Africa to inform EWS for famine, but this data since been integrated into a web-based malaria IDEWS.[83]

References noted similar challenges when integrating data from health surveillance systems. Echoing previous research, health data was often missing, incomplete, heterogeneous, not reported in a timely manner, or missing altogether.[66,69,82,84–86] It was particularly challenging to integrate data from paper-based health information systems in Fiji, India, and Madagascar, although this is suggested to be possible for some systems like EWARS.[67,84,87] IDEWS projects sometimes had to make compromises as a result. In South Sudan, MSF adopted an alternative model that required only eight weeks of previous data, although other models are potentially more accurate.[11,86] Other projects had to abandon live integration with clinical data altogether.[71] The establishment of a reliable health surveillance system is therefore a necessary first step when implementing IDEWS in Southern contexts or lacking data quality and timeliness could be a barrier for implementation and scale-up.[66] IDEWS deployment could attract investment for strengthening surveillance systems.

References highlighted the need of capacity building to facilitate the use of diverse input data types. While this was previously noted in the literature within the context of malaria IDEWS in Africa, this was noted across regions and income groups.[8] Expertise in the relationship between climate change and health, meteorology, data analysis, statistical modelling, risk communication and epidemic response were all highlighted to be lacking but necessary for IDEWS operation. For example, in 2003, a national malaria IDEWS in Sudan did not warn of several small epidemics because managers failed to analyse data closely.[88] Although capacity building was often part of initial project phases, this was stressed to be an ongoing need by implementers in Brazil, Cambodia Ethiopia, Kenya, and Laos, especially because of high staff turnover in health systems.[60,66,69,70,89,90] Northern expert knowledge and automation were stopgap measures used to circumvent this skill shortage, particularly in LMICs and low-income countries, but neither offer autonomy to implementers and could threaten IDEWS sustainability. Although automated data acquisition and analysis reduces the opportunity costs of IDEWS implementation for busy operators, and limits the opportunity for human error, this increases the opaqueness of systems which could threaten sustainability where there is no local capacity and when a system modification is necessary, or a fault encountered.

Investment in health and meteorological data systems alongside health worker climate change capacity building prompted by IDEWS implementation will benefit health system climate resilience. However, in the absence of such investment, IDEWS implementation is likely to involve the long-term use of stopgap measures or be prioritised only in sites with a conducive data ecosystem. IDEWS development necessitates a significant body of foundational local research which could further exacerbate this bias as systems developed for one region are not necessarily transplantable to the next.

Theme 2: IDEWS privilege knowledge deemed scientifically valuable over alternative systems.

Despite the holistic definition of UNISDR, IDEWS are generally conceived of as scientific systems that are developed in answer to a suite of empirically proven relationships between disease transmission and environmental factors. This narrow definition necessitates the reproduction of local knowledge in a form that is acceptable to scientific authorities, with local knowledge considered anecdotal without such proof. Indigenous indicators were incorporated into IDEWS in only one reference, although an additional two deployed it for community education.[60,61,84] In Gwanda District, Zimbabwe, a community-based malaria IDEWS was implemented by South African researchers with local communities.[61] Community members selected predictive environmental indicators of malaria outbreaks and elected research assistants to monitor these alongside community health workers. Analysis was then discussed in routinely held village meetings prior to the typical malaria season, and with district health authorities when necessary. Meaningfully utilising indigenous knowledge in this way could offer a solution to the lack of data available at smaller scales and increase acceptability.

Socioeconomic data was also almost never incorporated into predictions, with only one instance noted in Brazil.[60] However, in their framework the WHO highlights indicators of vulnerability as a key input for predictions, while references themselves noted the importance of socioeconomic factors such as land use, urbanisation, livelihood, and migration for determining potential outbreaks.[6,73,76,77,91,93] The neglect of socioeconomic data in model development reflects not just that such data may be difficult to acquire, but the broader privileging of biological over social determinants of health. A similarly missed opportunity, highlighted in the case of RVF, is the inclusion of a One Health perspective by strengthening and incorporating livestock surveillance systems that could potentially provide a greater lead time ahead of human epidemics.[93]

IDEWS strengthen health system ability to parse data deemed scientifically valuable but in doing so contribute to the marginalisation of alternatives. This reflects the inherently scientific way that IDEWS, vulnerability, and resilience are understood as well as the ethos of evidence-based policy in global health. However, incorporating other knowledge could contribute to health system resilience and constitutes a missed opportunity in IDEWS development.

Theme 3: IDEWS' predictions internalise climate change associated uncertainty but put the onus of informed decision making and response on under resourced health systems.

IDEWS internalise the uncertainty of a complex ecological system- a climate changed world- into a prediction probability, that itself contains a level of uncertainty affected by the input data. Operators must consider this to decide if, when, and how to respond to a predicted epidemic. If uncertainty is too high, operators may choose not to act. NASA researchers developing a cholera IDEWS for Yemen in 2017 did not share their model's prediction with Yemeni actors because they had such low confidence in the prediction due to challenges accessing data.[91] That summer Yemen experienced one of its worst cholera outbreaks. How the IDEWS operator contends with prediction uncertainty is therefore not only an operational question, but a moral one. Prediction uncertainty may be elevated due to limitations in the model such as a lacking ability to predict the magnitude of epidemics, forecast outbreaks at smaller geographic scales, and in low-endemic areas.[45,66–68] Several references also described instances of false alerts from IDEWS.[46,69,78,94]

To aid in internalising this uncertainty many references deployed decision making, communication, and response guidelines.[45,62,70,71,84,89,90,95] This was a necessary step due to the insufficiency of existing emergency response protocols, although IDEWS guidelines should align with existing policy where possible.[69,70,84] For instance, in Barbados decision matrices are being developed that incorporate the prediction confidence and urgency for action into an appropriate communication and response plan for dengue outbreak alerts; this replicates an existing system used by the national meteorological services.[71] Other measures to contend with prediction uncertainty included further investigation in affected areas and the deployment of a staged response.[45,62,67,69,94]

A core sentiment in references was that responses are ultimately limited by existing resources, suggesting that IDEWS do not necessarily attract additional investment into disease control.[60,69,70,72,92,96] Under the guise of epidemic predictability, IDEWS may also justify not maintaining emergency resource capacity for diseases that occur infrequently, as described earlier in the case of meningitis epidemics in West Africa.[45] In general, rather than deploying additional resources, IDEWS were instead suggested as a tool to enable the more cost-effective use of existing (scarce) resources.[69,75,85,87,97,98] The choice of an alert threshold- the value above which IDEWS indicates an epidemic to be likely- particularly enabled this sentiment as a threshold can be chosen in line with current response capacity.[73] The deployment of IDEWS in this way perpetuates health system under resourcing which ultimately increases climate fragility.

Theme 4: IDEWS need to continue evolving in response to climate change uncertainty.

IDEWS were often deployed in the wake of unexpected climate-sensitive disease outbreaks; examples included the establishment of dengue in Bhutan in 2004; the spread of malaria to highland communities in Kenya and Ethiopia; chikungunya and zika outbreaks in Barbados between 2014 and 2015-2016, respectively; RVF outbreaks in ESA in the 1990s; and the re-establishment of cholera in Yemen.[60,70,71,78,82,91,99] The necessity of significant research prior to IDEWS deployment and of long-term datasets for model development mean that IDEWS cannot be developed proactively nor quickly and therefore that IDEWS will need to continue evolving in response to changing disease burdens.

This was demonstrated in two notable instances in references. Firstly, as climatic changes occur epidemics may happen in areas that do not typically experience them, so may not be covered by IDEWS. During the development of NASA's Predictive Surveillance System for RVF in ESA, the initial coverage was determined based on a literature survey identifying sites of prior outbreaks and by assessing the climatic suitability of areas.[93] This resulted in the system missing several outbreaks in coastal Kenya (2006-2007), South Africa (2008), Gezira, Sudan, and Madagascar, because they fell outside of the area previously thought vulnerable.[93] Secondly, as IDEWS are developed to be particular to a specific disease, when new disease threats emerge they will have to either be incorporated into existing IDEWS or be the subject of a separate system. The potential to incorporate multiple diseases into one platform was discussed particularly in dengue references because its *Aedes* mosquito vector transmits other infections like zika, chikungunya and RVF. This will require modifications to existing systems- for example, an IDEWS used for dengue in Colombia was not nearly as accurate at predicting zika outbreaks.[68]

IDEWS will therefore need to be iteratively revised in response to climate change associated uncertainty, further highlighting the need of building local capacity to develop and implement IDEWS for systems to be sustainable.

Theme 5: Implementing IDEWS strengthens linkages between institutional silos, but not a multi-level perspective, necessary for a climate changed world.

Due to their interdisciplinary nature, IDEWS are implemented by a combination of partners generally constituting at least national health authorities and meteorological services. Co-production emerged as an important concept in several included references, facilitating the development of IDEWS in Barbados, Ethiopia, and West Africa.[45,71,79] Co-production blurs the boundaries between developer and user to ensure the production of a system responsive to all actors' needs and has facilitated other climate change adaptation activities in the Global South.[100] In the context of IDEWS, it enabled collaboration between health and meteorology authorities despite differences in priorities, mandates, expertise, and technical language.[45,71,79] The formalization of collaborative efforts– such as through Memorandum of Understandings or data sharing agreements, depending on the nature of the relationship- was another important facilitator for delineating the roles and responsibilities of partners and creating a joint sense of accountability. The creation of new institutions with a mandate centred on climate change and health occurred alongside many IDEWS projects.[70,82,84,89,95,99,101] These provide a venue for multisectoral collaboration and variably included regional health staff, university researchers, donors and international organisations, alongside national health and environmental authorities and meteorological services.

These approaches strengthen institutional linkages across sectors to provide a basis for collaboration on a range of climate change and health issues and thus climate change adaptation in the health system more broadly. However, references did not demonstrate an equivalent emphasis on strengthening linkages across local, regional, national, and international scales. For example, despite the existence of the above structures in Ethiopia, the WHO country office described the breakdown of communication between focal points as monthly and quarterly reports produced by local experts using the EPIDEMIA system were not communicated to nor discussed at district, regional, and national levels, meaning the IDEWS is not perceived as part of the health system.[60] This is a noteworthy example given the system is relatively established- research began in 2009- and the intention of USAID to achieve national scale up.[66] Therefore, while implementing IDEWS catalysed collaboration between institutional silos, it does not necessarily enable co-operation across scales, although both are necessary for health system resilience.

Theme 6: IDEWS implementation reflects international agendas, threatening project sustainability.

International actors play numerous roles in IDEWS implementation and were referred to in a range of capacities: as sources of data and technical expertise, donors, and implementers. Due to the multisectoral nature of IDEWS and lack of Southern capacity, meteorological and space agencies from the United Kingdom (UK), United States (US), France, and Australia emerged as collaborators in projects. Data from agencies including NASA, NOAA, and FEWS NET were also often used by IDEWS, while NASA also developed and operated IDEWS for RVF in ESA, cholera in Yemen, and chikungunya globally.[77,91] Such organisations are an unusual actor in global health; their predominance reflects Northern, scientific hegemony in projects. Meanwhile, the majority of IDEWS in references were funded bilaterally by Australia, Canada, the European Union, France, the UK, or the US. Southern governments funded a minority of projects in comparison, and most were domestic.[60,64,87] International organisations were also prominent donors, with the Global Environmental Facility being the most common, funding seven WHO and UNDP projects.[70,82,84,89,90,95,101]

International actors therefore have significant power over IDEWS implementation. This was reflected by their involvement in establishing and participating in national climate change and health institutions, coordinating responses to IDEWS alerts, and institutionalising the use of IDEWS in national policy. International actors were often part of the national institutions created to steer IDEWS implementation alongside climate change health policy more broadly. For instance, when establishing the first IDEWS for dengue in Panama, the presence of the WMO was considered necessary to catalyse cross-sectoral collaboration between government authorities.[60] Involvement can also be long term- in Ethiopia, there has been protracted participation from USAID since research began on the EPIDEMIA system in 2009.[60,66] EPIDEMIA began producing weekly forecasts six years later, has since been tested in two regions (Amhara and Oromia) and is planned for national scale-up. Yet, as part of their scale-up roadmap USAID endorses the continued involvement of the US President's Malaria Initiative in a joint steering committee with Ethiopian authorities. This suggests a vision for ongoing involvement in the country despite USAID's stated vision for national owernship.[66] International participation in climate change and health institutions may provide a venue for agenda-setting. References describing projects in Barbados, Bhutan, Fiji, and Kenya highlighted the necessity of high-level advocacy among national policymakers to institutionalize IDEWS and mainstream health sector climate change adaptation more broadly.[71,82,84,94] Without such advocacy, project sustainability was threatened as references noted lacking national financial resources for pilot projects and scale-up, inability to sustain capacity building, and a lack of enthusiasm.[60,66,71,84]

International actors can also control IDEWS implementation, potentially for their own gain. This level of involvement was particularly prominent where IDEWS cover global regions. One example is the RVF IDEWS established by the US Department of Defence Global Emerging Infections Surveillance and Response System with NASA that predicts RVF outbreaks over ESA.[77,78] Alerts are publicly available online and are communicated through international organisations (WHO and the Food and Agriculture Organisation [FAO]) to national governments, non-governmental organisations, and US military units in the region.[77,78] Although some references described how this system helped to control the 2006 outbreak in Kenya, others suggested the warning issued by the FAO in November 2006 was too late because the input data used led to an alert after the conditions were already conducive to an outbreak.[91,93,96] Community observation was suggested to be a timelier warning system, calling into question how valuable the warnings were for affected communities.[96] In such cases, IDEWS may serve the agenda of international actors. References highlighted the potential contribution of this RVF IDEWS to US security, emphasizing the potentially disruptive economic impacts of RVF epidemics in the region.[77,91] A similar global system was later developed for chikungunya, partly funded by the US Defence Threat Reduction Agency.[91] As IDEWS shift into the domain of the UNFCCC and the Global North becomes increasingly habitable to new disease vectors, securitization discourses may take on a different tone. For example, in preparation for international visitors during the 2014 World Cup, Brazilian authorities deployed an IDEWS to project dengue risk for cities across the country so vector control could be instigated, meanwhile an international media campaign was organised to inform visitors to take precautions.[60] These measures were considered necessary despite the projected risk being generally low as the event was held in the winter when transmission is reduced.

It would therefore be amiss not to note the power of international actors over IDEWS implementation, which is facilitated by the lack of capacity in the Global South compared to the data, technical, and financial resources held by international actors. International actors may collaborate based on their own agenda, which calls into question the legitimacy of IDEWS projects and results in varied enthusiasm among Southern policymakers. Implementation in this way undermines IDEWS' potential to build climate resilience in the Global South due to the unsustainability of projects without national leadership.

Theme 7: There has been a lack of meaningful attempts to build the legitimacy of IDEWS among communities and climate-vulnerable groups in the Global South.

Given their interdisciplinary nature and opaque prediction process, there is a need to build the legitimacy of IDEWS among health actors and policymakers in the Global South. References pursued several processes with this intention: co-production, consultation, participation, and feedback exercises. These activities were important for highlighting several needs to ensure IDEWS were adapted for resource-limited contexts including offline access (particularly noted in the context of low and lower-middle income countries), use of open-source software, automation or minimized human input, interactive user interfaces (where internet bandwidth is strong enough), translation into local languages, compatibility with inexpensive/existing hardware and current storage capacities. Demonstrating accuracy was another important step in accruing legitimacy among Southern policymakers as was integration with existing structures, such as surveillance systems, national strategies, and communication channels. However, references typically described limited windows for feedback, such as circulating a survey or holding a stakeholder meeting, rather than continuous bidirectional communication. Only a minority further described how solicited feedback was incorporated into IDEWS. One notable example included the development of EWARS-R by WHO based on feedback received from users in Brazil, Malaysia, and Mexico.[69] Following a 7-10 month trial between 2016-2017, Hussain-Alkhateeb *et al* sought feedback via questionnaire, with respondents suggesting a range of front- and back- end modifications, including the use of open-source software (R) to improve accessibility, expanding the number of potential data inputs, modifying the prediction model to allow one or more variables to trigger an alarm, and developing a user interface.[69]

However, communities were largely not incorporated into these feedback processes. While the community were generally not operators of IDEWS, they were subject to communication and response strategies. Demonstrating this, community education was the most common response in references. It is therefore important that alerts from IDEWS are communicated in a way that is understandable and acceptable to local communities, especially since, by definition, early warning systems may prompt such measures to be taken before the community notes any signs of disease epidemics. This oversight could undermine the effectiveness of IDEWS for building climate change resilience and protecting population health because ultimately this depends on an effective response to alerts.

5. Synthesis and Conclusion

This scoping review provides the first timely synthesis of IDEWS implementation in the Global South and a critical discussion of these increasingly recommended- and aspired to- systems for building health system resilience.

IDEWS implementation was identified to have occurred in some capacity in 28 countries, although many were in the early stages or research projects. The skew of IDEWS towards malaria and the African region reflects the initial promotion of early warning systems as part of the WHO Global Malaria Programme.[9] Notably, this paper identified few references in Southeast Asia or the Eastern Mediterranean despite a predicted increase in dengue transmission in the former and the potential re-emergence of malaria in areas where it is currently eradicated, the expansion of *Aedes* vectors to new areas, and the lengthening of both transmission seasons in the latter.[4,102] Implemented IDEWS were only identified for half of the fourteen candidate diseases highlighted by WHO in 2005; with diseases such as influenza, leishmaniasis, and yellow fever absent. The disproportionate number of references discussing malaria reflects the political attention and funding given to this disease in global health. In addition, references discussed IDEWS for other diseases such as zika, diarrhoeal disease and plague. Although IDEWS fall into the intersection of climate change and global health, most references did not discuss systems in the context of the adaptation plans called for by the WHO and UNFCCC, potentially indicating that in the literature they are still conceived of in terms of their ability to strengthen disease control programmes as opposed to climate change resilience.

The impact of IDEWS on health system resilience depends on how they are deployed. To contribute to health system resilience, Blanchet's framework highlights that IDEWS should strengthen health system capacity to use different forms of knowledge; enable response to uncertainty; strengthen effective collaboration across sectors and scales; and build legitimate institutions.[33] These contribute to the absorptive, adaptive and/or transformative capacity of health systems.

Regarding knowledge, this review highlighted how IDEWS projects provide an entry point into the intersection between climate change and health, contributing to the development of human, technological, and institutional resources to effectively utilise climate data and therefore that IDEWS facilitate health system climate change adaptation and resilience as a result. However, the IDEWS identified in this review were generally statistical modelling systems, despite the diversity accounted for in the definition of the UNISDR.[34] Such systems are data-hungry, resulting in significant obstacles to implementation in the Global South. This results in IDEWS implementation that is biased towards areas with conducive data ecosystems and could therefore reinforce local and global inequalities as socioeconomic and political factors invisibalise some of the most climate-vulnerable populations in data systems. For example, a meningitis IDEWS covering West Africa that averted epidemics in Benin, Ghana and Niger cannot be extended to regions in Central Africa due to difficulty accessing data, despite some locales reporting cases annually.[45] IDEWS should be conceived of more broadly to include the deployment of community-based systems and those based on indigenous indicators in areas where there is a dearth of available data. Implementation of community-based IDEWS for other climate hazards has already been successful, but was only identified once in this study in

Zimbabwe.[36,61,103] Furthermore, because IDEWS are understood narrowly as scientific systems, deployment generally strengthened the ability of health systems to utilise forms of knowledge conceived of as scientifically valuable, resulting in a neglect of indigenous knowledge and socioeconomic variables in IDEWS systems. Conflicting with the suggestion of Biddle *et al.* that resilience discourse in global health has shifted to be more holistic, this instead reflects the narrow, scientific way that vulnerability is conceived of when deploying IDEWS and reflects criticisms of resilience discourses as overly scientific and deceptively apolitical.[24,27]

IDEWS strengthened health system ability to contend with climate change associated disease outbreaks as systems were used in several instances to deploy effective responses to predicted epidemics. However, in contrast to the suggestion by critics that resilience discourse skews resources towards emergency periods, IDEWS did not appear to attract significant additional resources for outbreak response.[30] Systems were instead deployed to be compatible with health systems' current resources, which was a limiting factor in responses. This echoes critics' suggestion that resilience is framed as coping despite weaknesses, such as resource limitation, rather than building strength.[30] This undermines the potential of IDEWS to deploy effective protective responses to alerts and therefore their wider contribution to health system resilience. In addition, under resourcing limits the system's responsiveness to changing disease burdens as IDEWS need to evolve to manage the emergence or reintroduction of disease threats, changing disease seasonality and expansion of diseases to new areas. While IDEWS are currently deployed to be focused on a particular climate sensitive disease – mirroring vertical approaches to disease control in global health- to better contribute to climate change resilience these will need to evolve into multi-disease platforms that can reinforce the health system multilaterally. Hess and Ebi (2016) note the need to iteratively manage heat early warning systems in response to a changing climate, however the ability to do this for IDEWS will be constrained by resource capacities and the strength of surveillance and diagnostic networks, particularly.[42] Deploying IDEWS with a wider framework of health systems strengthening could better enable the systems to protect population health in the face of climate change and ensure they do not detract from everyday health system operation.

The interdisciplinary nature of IDEWS challenges the health system to work outside of its institutional silo with meteorological services and related authorities. Doing so catalyses the establishment of formal partnerships and institutions dedicated to the emerging intersection between climate change and health that go beyond IDEWS to contribute positively to health system climate change adaptation and resilience more broadly. However, there was a significant role of international actors in administering IDEWS projects because of the relative lack of capacity in the Global South to do so, and this provided an opportunity for international actors to position themselves within national climate change and health institutions and thereby influence national policy. Although doing so could facilitate climate change adaptation, short-term donor funding cycles coupled with a lack of national leadership threatens the sustainability of resilience-building activities as a result. The substantial involvement of the international level may also have consequences on how legitimate IDEWS, and their related institutions, are perceived to be. Efforts to build legitimacy concentrated on Southern policymakers but neglected communities and climate-vulnerable groups despite their suggested role in responses to IDEWS alerts. Building community trust in IDEWS is especially important for effective responses since communities must buy-in to the prediction to respond. Furthermore, given IDEWS' neglect of indigenous indicators there could be a mismatch between the indicators of epidemic risk incorporated into IDEWS and those that are perceived by the community, this has already been noted to prevent responses to early warning systems in the Global South for other natural hazards.[104] Deployment of almost all IDEWS in this study was top down, which agrees with previous literature that highlighted the dearth of community-based and participatory approaches to early warning systems for infectious diseases compared to other natural hazards.[36] This could result from the predominance of top-down approaches in global health. However, this is a missed opportunity since participatory approaches to early warning systems for other hazards has been advantageous for expanding data networks, improving public awareness and risk knowledge, and providing a supplementary source of information, especially where official data sources are insufficient or non-existent.[103]

This review therefore highlights several opportunities to improve IDEWS implementation to fully realise the potential of these systems in the Global South. Firstly, there is a need to explore the incorporation of indigenous indicators of disease outbreaks and community-based approaches to IDEWS as a complement to data-driven predictions and with potential to supplement in locations where data is scarce. Secondly, the incorporation of social science approaches to IDEWS implementation - such as through the integration of socioeconomic data into models and assessing communication and response strategies along axes such as ethnicity, gender, race, age, and income level - could enable IDEWS to be more inclusive and responsive to the needs of affected communities and vulnerable groups. The necessity of tailoring communication and response strategies to climate vulnerable groups has previously been highlighted by studies on EWS in both the Global North and South.[105–107] Thirdly, both this study and the WHO's Climate Change and Health Survey suggest an emerging group of implementers in the Global South who have technical expertise in IDEWS development and implementation. South-South collaboration could therefore provide an avenue to foster partnership, build capacity, and encourage innovation between Southern implementers while improving the legitimacy of IDEWS among Southern policymakers. Finally, there is a need to develop IDEWS that incorporate multiple climate-sensitive diseases to build health system resilience multilaterally and to periodically revise systems in the changing climate.

This scoping review also identified notable gaps in the IDEWS literature, affecting the conclusions of this review. Firstly, because IDEWS are largely conceived of as prediction systems most included references deployed quantitative approaches that were ill-equipped to parse important aspects such as acceptability, suitability, and feasibility. Primary studies taking a qualitative approach that is better able to appraise such aspects are urgently needed. Secondly, most references did not describe IDEWS as an end-to-end system, focusing on model development and deployment over alert communication and response, despite these constituting an important aspect for protecting populations. The generalisability of the conclusions of this review on these aspects could therefore be limited by this smaller sample. Thirdly, this review knowingly sacrificed depth for breadth because of its goal to map existing IDEWS projects, summarise system deployment, and critically examine IDEWS' contribution to resilience. This was also the most feasible approach given the lacking availability of varied research approaches and detailed information on individual cases of IDEWS deployment. The conclusions of this report are also impacted by biases intrinsic to the method, as discussed previously. For instance, the limitation of the search to English could contribute to the lack of literature identified from China and the few studies identified from francophone West Africa, while searching regional databases could have assisted in identifying more references from Southeast Asia and the Eastern Mediterranean. Furthermore, the focus of the search strategy on WHO climate-sensitive diseases could contribute to the lack of literature on IDEWS for zika and other such diseases with a recently demonstrated climate link.

Despite these limitations, this review offers novel insight into how IDEWS have been implemented in the Global South. To better protect vulnerable populations from climate change, IDEWS implementation could learn from the bottom-up approaches more established in spheres like disaster risk reduction. However, not only were IDEWS demonstrated to prompt effective proactive responses to climate-sensitive infectious diseases in the Global South, but they provided an entry point into the intersection of climate change and health for disease control programmes. A significant part of IDEWS' contribution to building climate change resilience was therefore in the ability of projects to mobilise resources to strengthen existing meteorological and disease surveillance systems, facilitate the use of climate data in health programming, catalyse collaboration between institutional silos, and initiate capacity building at the intersection between climate change and health. While strengthening the resilience of health systems against climate-sensitive infectious disease outbreaks, these measures also facilitate broader health system climate change adaptation.

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7. Annexes

7.1 Annex 1: Search strategy for Embase.

#	Query	Results from 9 Jun 2023
1	exp Climate Change/ or exp Greenhouse Effect/	70,775
2	(climat* or environment* or el nino or la nina or ENSO or meteorolog* or biolog* or weather or precipitation or heat or temperature or rain* or atmospher*).ti,ab.	4,122,576
3	1 or 2	4,136,567
4	exp Population Surveillance/ or exp Disease Outbreaks/ or (transmi* or infect* or epidemic or outbreak or prevent* or control*).ti,ab.	10,192,086
5	3 and 4	1,211,310
6	(Early warning* or EWS or alert or alarm or MEWS or HEWS or DEWS or EWARS).ti,ab.	79,492
7	(vector-borne or water-born* or malaria or cholera or dengue or yellow fever or YFV or trypanosomiasis or encephalitis or leishmaniasis or mening* or murray valley or rift valley or ross river or west nile or influenza).ti,ab.	528,952
8	(Intervention* or respons* or adapt* or measur* or program* or mitigat* or test* or experiment* or pilot* or scale-up or prepar* or strength* or plan* or implement* or effective* or performance or acceptab* or feasib* or valid* or experience or evaluat* or assess* or trial* or investigat* or accuracy).ti,ab.	24,940,382
9	(afghan* or africa* or albania* or algeria* or angola* or antigua* or barbuda* or argentin* or armenia* or aruba* or azerbaijan* or bahrain* or bangladesh* or bengal* or bangal* or barbados* or barbadian* or bajan or bajans or belarus* or belorus* or byelarus* or byelorus* or belize* or benin* or dahomey or bhutan* or bolivia* or bosnia* or herzegovin* or botswan* or batswan* or bechuanaland* or brazil* or brasil* or bulgaria* or burkina* or burkinese* or upper volta* or burundi* or urundi* or cabo verde* or cape verde* or cambodia* or kampuchea* or khmer* or cameroon* or cameroun* or ubangi shari* or chad* or chile* or china* or chinese or colombia* or comoro* or comore* or comorian* or mayotte* or congo* or zaire* or costa rica* or "cote d'ivoir*" or "cote d' ivoir*" or cote divoir* or cote d ivoir* or ivory coast* or ivorian* or croatia* or cuba or cuban or cubans or "cuba's" or cyprus* or cypriot* or czech* or djibouti* or french somaliland* or dominica* or ecuador* or egypt* or united arab republic* or el salvador* or salvadoran* or guinea* or equatoguinea* or eritrea* or estonia* or eswatini* or swaziland* or swazi* or swati* or ethiopia* or fiji* or gabon* or gabonese* or gabonaise* or gambia* or ((georgia or georgian or georgians) not (atlanta or california or florida)) or ghana* or gibraltar* or greece* or greek* or grecian* or grenada* or grenadian* or guam* or guatemala* or guyana* or guiana* or guyanese* or haiti* or hispaniola* or hondura* or hungary* or hungarian* or india* or indonesia* or iran* or iraq* or isle of man* or jamaica* or jordan* or kazakh* or kenya* or karabati* or korea* or kosovo* or kosova* or kyrgyz* or kirgiz* or kirghiz* or laos or lao or laotian* or latvia* or lebanon* or lebanese* or lesotho* or lesothan* or lesothonian* or basutoland* or mosotho* or basotho* or liberia* or libya* or jamahiriya* or lithuania* or macedonia* or madagasca* or malagasy* or malawi* or nyasaland* or malaysia* or malay* federation or maldives* or maldivian* or indian ocean or mali or malian* or "mali's" or malta or maltese* or "malta's" or micronesia* or marshallese* or kiribati* or marshall island* or nauru or nauran or nauruans or "naurian's" or mariana or marianas or palau or paluan* or tuvalu* or mauritania* or mauritan* or mauritius* or mexico* or mexican* or moldova* or moldovia* or mongol* or montenegr* or morocco* or moroccan* or ifni or mozambique* or mozambican* or myanmar* or burma* or burmese or namibia* or nepal* or new caledonia* or netherlands antill* or nicaragua* or niger* or oman or omani or omanis or "oman's" or pakistan* or palestin* or gaza* or west bank* or panama* or paraguay* or peru or peruvian* or "peru's" or philippine* or philipine* or phillipine* or phillippine* or filipino* or filipina* or poland* or polish or pole or poles or portugal* or portuguese or puerto ric* or romania* or russia* or ussr* or soviet* or rwanda* or rwandese or ruanda* or ruandese or samoa* or navigator island* or pacific island* or polynesia* or "sao tome and principe*" or sao tomean* or santomean* or saudi arabia* or saudi or saudis or senegal* or serbia* or seychell* or sierra leone* or slovak* or sloven* or melanesia* or solomon island* or norfolk island* or somali* or sri lanka* or ceylon* or "saint kitts and nevis*" or "st kitts and nevis*" or kittian* or nevisian* or saint lucia* or st lucia* or saint vincent* or st vincent* or vincentian* or grenadine* or sudan* or surinam* or syria* or tajik* or tadjik* or tadzhik* or tanzania* or tanganyika* or thai* or timor leste* or east timor* or timorese* or togo or togoles* or "togo's" or tonga* or trinidad* or tobago* or tunisia* or turkiy* or turkey* or turk or turks or turkish or turkmen* or uganda* or ukrain* or uruguay* or uzbek* or vanuatu* or new hebrides* or venezuela* or vietnam* or viet nam* or yemen* or yugoslav* or zambia* or zimbabwe* or rhodesia* or arab* countr* or middle east* or global south or sahara* or subsahara* or magreb* or maghrib* or west indies* or caribbean* or central america* or latin america* or south america* or central asia* or north asia* or northern asia* or southeastern asia* or south eastern asia* or southeast asia* or south east asia* or west asia* or western asia* or east europe* or eastern europe* or developing countr* or developing nation* or developing population* or developing world or less developed countr* or less developed nation* or less developed world or lesser developed countr* or lesser developed nation* or lesser developed world or under developed countr* or under developed nation* or under developed world or underdeveloped countr* or underdeveloped nation* or underdeveloped world or middle income countr* or middle income nation* or middle income population* or low income countr* or low income nation* or low income population* or lower income countr* or lower income nation* or lower income population* or underserved countr* or underserved nation* or underserved population* or under served population* or under served nation* or under served population* or deprived countr* or deprived population* or high	3,289,994

	burden countr* or high burden nation* or countdown countr* or countdown nation* or poor countr* or poor nation* or poor population* or poor world or poorer countr* or poorer nation* or poorer population* or poorer world or developing econom* or less developed econom* or underdeveloped econom* or under developed econom* or middle income econom* or low income econom* or lower income econom* or low gdp or low gnp or low gross domestic or low gross national or lower gdp or lower gnp or lower gross domestic or lower gross national or lmic or lmics or third world or lami countr* or transitional countr* or emerging econom* or emerging nation*).ti,ab.	
10	5 and 6 and 7 and 8 and 9	396
11	limit 10 to yr="2005 -Current"	378
12	limit 11 to english language	369
13	12 not (covid-19 or coronavirus).ti,ab.	362

7.2 Annex 2: Inclusion and exclusion criteria

Inclusion criteria	**Exclusion criteria**
Features a climate sensitive IDEWS for public health use.	Does not feature IDEWS that incorporates an environmental/meteorological/climate variable in the prediction. IDEWS for use in clinical settings were not eligible.
Target a WHO CSD (Table 1).	Non-communicable, emerging/zoonotic, and mental health diseases alongside EWS for natural disasters were not included.
Discuss IDEWS pilot, implementation, or scale-up within a context.	Model development/validation studies and references quantifying correlations between climate variables and disease were excluded.
Focus on a Global Southern context.	General discussion or Global Northern references were excluded.

7.3. Annex 3: Data extraction template

DATA TO BE EXTRACTED	
Reference information	
Year	
Title	
Authors	
Article Type	
Case information	
Climate-sensitive disease(s)	
Country of implementation	
Scale of implementation	*Local / regional / national / global region*
Details (if any)	
Name of system (if any)	
Details of system	
Input data type(s)	*Meteorological / surveillance / entomological / socioeconomic / other (detail)*
Input data sources (if given)	
Integration with national health information system	*Y / N / NA*
Alert format	*Binary / categorical / other (detail)*
Method of alert generation	
Mode of alert communication	
Details (if any)	
Description of response	
Actors involved	
Implementing partners	
Donor(s)	

7.4 Annex 4: Summary table

Country	Climate-sensitive infectious disease	Name of IDEWS, project dates, level of implementation	Prediction data types and sources	How is an alert generated and communicated, to whom	Description of response and/or outcome	Implementation partners and donor	Reference number
WHO African Region							
Botswana	Malaria	NA	Climate and weather predictions from the Southern African Regional Climate Outlook forum.	Made available through National Meteorological and Hydrological Services websites.	In 2006, malaria incidence levels were maintained at levels far below those in previous years, partially attributable to this new strategy.	WHO Global Malaria Programme in partnership with WMO, MoH, National Ministries of Meteorological and Hydrological Services	92; 108; 109
Burkina Faso	Meningitis	National level	Climate data from national weather stations and from re-analysis data from National Centres for Environmental Prediction. Epidemiological data from the WHO and national MoH. The system is integrated with national health information system.	Predictions are routinely made in December, before the onset of outbreak season. Forecasts and verifications are communicated to the public via bulletin and distributed to national authorities in charge of health and environment as well as non-governmental organizations, financial and technical partners.	Includes financial mobilization for vaccines, resource (including health staff) targeting to potential epidemic areas, educational campaigns.	The MoH implements the system, supported by the Laboratory of Ocean and Climate Sciences and the National Oceanic and Atmospheric Administration's (NOAA) Climate Prediction Center.	60
Ethiopia	Malaria	Research began in 2009. EPIDEMIA began to produce weekly forecasting reports in September 2015. Testing is ongoing in Oromia after an initial pilot in the Amhara region. National scale up is planned.	Surveillance data from the Public Health Emergency System. Each week the user manually queries the system to download surveillance data. Climate data is from a network of meteorological stations and is manually downloaded. The EPIDEMIA tool includes automated data screening and cleaning and scripts to automate data processing, modelling, and reporting.	EPIDEMIA generates forecasts up to 12 weeks in advance. Two types of alerts are generated and communicated to public health stakeholders; early detection alerts (compares recent malaria case observations to alert threshold based on historical patterns); early warning alerts (compared EPIDEMIA forecasts of malaria cases out to 12 weeks to the alert thresholds for this future period). The National Malaria Control Programme shares a monthly bulletin with regional health bureaus for planning. These are also posted on various institutions websites.	At the national level, long-term forecasts (3-6 months) will support planning. Supply distribution at the woreda level can be made with a lead time of one to three months. Emergency/outbreak capacity will be needed at the sub-district level. Responses include: anti-malarial distribution, indoor residual spraying, ITN distribution, vector control, increased surveillance, communication of prevention messages..	The MoH originally worked with the Roll Back Malaria Partnership. The project is USAID funded and implemented with regional public health agencies, the national meteorology agency, universities, and NGOs.	60; 66; 79; 99
Kenya	Malaria	In 2010, the Kenyan malaria early warning system (KMEWS) was implemented in pilot districts by the WHO/UNDP.	Meteorological data from installed weather stations. Malaria surveillance data collected by health staff from the surveillance system.	District-level health officers are the end-users. The system is operationalized through an e-data prediction and decision-making software. Alerts are communicated through a risk communication network.	NA	The project was implemented by the Department of Environmental Health, the Malaria Control Program and the Ministry of Environment, Water and Natural Resources. Kenya Meteorological Services were also involved in implementation. Part of a joint initiative of WHO and UNDP, funded by the Global Environment Facility Special Climate Change fund.	70

		The system was launched by the Kenya Meteorological Department in 2011 to cover three counties- Kericho, Kisii and Kakamega- in the Western Kenyan highlands.	Malara surveillance data from national health information system. Meteorological data from Kericho, Kisii and Kakamega stations and transmitted to Kenya Meterological data center in Nairobi. Entomological data From the Ecology of African Highland Malaria project database.	Alerts generated based on surpassing a threshold outbreak probability. Different thresholds necessary for different states: Kakamega model (30%), Kisii and Kericho/Nandi (20%). Meteorologists communicate the results at the end of every month for assessment by malaria control division of the Ministry of Health.	Used to mobilize extra drugs, diagnostic supplies are restocked. Extra supply of ITNs.	Lead by the Kenya Meteorological Department and the MoH, in collaboration with the WHO Country Office, Kenya Medical Research Institute, National Institute for Medical Research (Tanzania), MoH (Uganda), and the International Centre for Insect Physiology and Ecology. Funded by NIH, IDRC, FCDO.	94
		The Highland Malaria Project (HIMAL) tested predictive early warning systems in the East African highlands	Rainfall data.	NA	District health management teams need to provide evidence for exceptional seasonal epidemics to mobilise resources.	Division of Malaria Control with UNICEF	72
	Malaria and diarrhoeal diseases.	Implementation in Nyando Province.	Data from national meteorological services was used to provide seasonal and short-term climate predictions – "climate-based disease anticipation".		Educational materials that also utilised indigenous early warning signs were used for community mobilisation. Establishment of health contingency plans for outbreak occurrence. Pre-peak season activities included strengthening flood gates, cleaning water channels, de-silting rivers, stockpiling water purifiers, treating drinking water, cleaning mosquito breeding grounds, disposing of waste, fortifying latrines and homes, hand washing campaigns. In the peak season, water channels and ponds should be opened, and disaster responses reviewed.	Implemented by the International Red Cross and Red Crescent Movement. Funded by the Rockefeller Foundation. Provincial governments, local committees and meteorological departments were key partners.	60
Madagascar	Malaria	WMO-funded pilot project began in 2008.	Surveillance data from sentinel surveillance sites (primary health centers). Satellite data on temperature, rainfall, normalized difference vegetation index (NDVI) provided by the International Research Institute for Climate and Society. Time-space data on malaria	An alert is generated when the 90th percentile value of malaria cases is exceeded for three consecutive weeks. Alert is available through a free, open-source, automated and interactive interface using R Shiny. The system is available to Roll Back Malaria Partners.	NA	The MoH, Institut Pasteur de Madagascar and Meteo Madagascar. Project supported at various stages by the WHO Roll Back Malaria Initiative, WMO and funded by USAID.	60; 67

			interventions from the President's Malaria Initiative and National Malaria Control Programme.				
	Malaria, Rift Valley Fever, Plague	NA	Climate and weather predictions from the Southern African Regional Climate Outlook forum. Data also comes from meteorological satellites installed in the country and the International Research Institute for Climate and Society.	An epidemiological risk map is generated for the highlands of Madagascar- areas are classified as very weak, weak, medium, high or very high risk. Made available through National Meteorological and Hydrological Services websites. An online tool for febrile syndromes is also available.	The Directorate of Public Health and Epidemiological Surveillance receives the alerts. A monthly bulletin is generated by for the health sector ahead of the rainy season. The Pasteur Institute uses the projected risk maps to prioritise areas in the highlands for IRS.	WHO Global Malaria Programme in partnership with WMO, National Ministries of Health, National Meteorological and Hydrological Services, Pasteur Institute, UNCIEF and USAID.	1
Malawi	Vector-borne diseases	IDEWS was implemented in four districts in 2014 as part of the 'Adaptation for Africa' project.			A communication strategy was developed.	Implemented by a Health and Climate Change Core Team which constituted staff from government ministries, WHO, academic, media and civil society organisations. Climate change and health program was set up with support from the Global Framework for Climate Services (GFCS).	95
Senegal	Rift Valley Fever	A monitoring system, contributing to an EWS for RVF was piloted in Senegal as part of the AdaptFVR project in 2008, it was tested locally in the Barkediji village, Ferlo region.	Zones potentially occupied by mosquitoes were characterised using meteorological and environmental data from the real time monitoring of water bodies (storage/ponds) and rainfall events. Data from the German Aerospace Center satellite is combined with entomological and pastoral data (animal distribution).	Bulletins are distributed to the AdaptFVR partners, including the Centre de Suivi de l'Environnement, Direction des Services Veterinaires, and Pasteur Institute.	A coordinated response of either livestock vaccination or displacement from risk areas is recommended.	A joint effort between the Centre National d'Etudes Spatiales (Meteo France) and Columbia University (US). Funded by the French Ministere de l'Ecologie, de l'Energie, du Developpmenet durable et de la Mer (MEEDM)	80
South Sudan	Malaria	Launched as part of the Malaria Anticipation Project (MAP) in 2021, currently being piloted locally in Lankien, Jonglei State.	Routinely collected malaria data and climatic indicators (rainfall, temperature, humidity, wind speed)	NA	The end user is MSF health teams to inform resource allocation. Possible to extend use to the MoH if successful.	MSF and the South Sudanese MoH. LuxOR funded MSF to test linear regression model.	86; 98
Tanzania	Trypanosomiasis	An EWS was piloted among the Masai community in Northern Tanzania.	Remotely sensed data from satellites (precipitation, temperatures, vegetation and waterbodies) and Google Earth Engine data, integrated in a smartphone	Risk mapping and time series data is available through the smartphone app.		Under the WHO – TDR International Development Research Centre Research Initiative on Vector-Borne Diseases and Climate Change, with Columbia University	74

			app with local data on tsetse fly and trypanosomiasis distribution.				
	Malaria and diarrhoeal disease	Pilot sites were in the coastal Tanga province.	Data from national meteorological services was used to provide seasonal and short-term climate predictions as part of climate-based disease anticipation".		Educational materials and health contingency plans were designed for outbreak response. Cleaning of the local environment, distributing treated bed nets and water purifiers alongside sanitation campaigns were key activities before the beginning of the rainy season.	Implemented by the International Red Cross and Red Crescent Movement. Funded by the Rockefeller Foundation. Meteorological service and local health department highlighted as important partners.	60
Zimbabwe	Malaria	Community-based IDEWS established as part of a research project in Matabeleland South Province, Gwanda District.	Indigenous environmental indicators (plant phenology, behaviours and movement of birds, insects and animals), meteorological indicators (wind patterns, direction) were monitoring indicators for malaria that were collected by community-elected volunteers.	Monitoring from community volunteers was compiled and analysed in community meetings and documented in a record book, kept by the councilor. Village meetings were held to allow input of indicators from other villagers who were not formal volunteers. In October, information obtained from the analysis was disseminated to the general community and DHE.	Ward health team members agreed on an alert response strategy, with community health workers and research assistants involved in the response. Health education, identification of potential breeding places and covering the places, as well as case finding were highlighted response strategies.	A research project conducted by the National University of Science and Technology, Zimbabwe, and University of KwaZulu-Natal, South Africa. It was funded by UNICEF, UNDP, the World Bank, WHO-TDR and the Canadian International Development Research Centre.	61
Americas region							
Barbados	Dengue	Prediction tool piloted in 2021.	The current model relies on the early recognition of increasing dengue incidence, compared with seasonal averages from previous years. Climate information is incorporated into the pilot forecast model.	Alerts use an existing online climate hazard platform managed by the Barbados Meteorological Services (BMS). Thresholds for warning levels (low, medium, high) are being established.	Communication through bulletin to MoH and other industries (tourism) and through online platform. Response is based on decision matrices that consider the certainty of the forecast and the urgency for action. One highlighted need is proper water storage by households during drought periods which will be the subject of a messaging campaign.	The 2010 project was part of a joint initiative of WHO and UNDP, co-funded by the Global Environment Facility Special Climate Change Fund. Since 2017, there is ongoing collaboration between the MoH, Barbados Meteorological Services, the Caribbean Public Health Agency and academic experts which has also been funded by USAID and the Red Cross Red Crescent Climate Change Centre.	71; 101
Brazil	Dengue	The new predictive model was developed as part of the Leverhulme network project EUROBRISA. This was applied during the 2014 FIFA World Cup in Brazil, but now	Data types used include dengue surveillance, climate, cartographic, demographic, and socioeconomic.	Alert thresholds for scenarios of medium risk and high risk of dengue, defined by MoH	Audience is the public and authorities. City-specific mitigation and control actions were set up three months ahead of the World Cup, financial resources were increased for mosquito control, multilingual information campaign launched to inform visitors about dengue protection. The national dengue control programme launched	Originally led by University of Exeter with the Brazilian Centre for Weather Forecast and Climate Studies as part of the Leverhulme network project EUROBRISA. Now - Brazilian Climate and Health Observatory in collaboration with the Brazilian Institute for Space Research, European and Brazilian climate services, universities and the UK MET office.	60

		has national coverage of 553 microregions.			control measures such as house-to-house visits to destroy potential mosquito breeding sites. campaigns to inform and educate local communities in higher risk areas to reduce breeding sites and protect themselves. International warnings facilitated by publication in international press and through foreign health authorities.		
		EWARS-R was tested from December 2016-February 2017 in ten districts.	Meteorological data (outdoor mean air temperature, outdoor mean humidity, total rainfall); epidemiological data (mean age of hospitalized cases, serotypes, probable and lab confirmed and hospitalized dengue cases); entomological data.	Threshold based system. An 'outbreak week' was triggered once dengue incidence crossed the upper threshold (z*SD); an alarm signal was then triggered when the outbreak probability crossed the alarm threshold.	Response involves district health managers and national authorities. National guidelines issued for a staged response (initial, early, late and emergency).	Implemented by WHO-TDR with national dengue control services and academia, supported by the EU-funded IDAMS consortium.	69
		This dengue prediction system was developed for Southeast Brazil, where it will be piloted as part of a newly established Climate and Health Observatory	The prediction uses climate and non-climate covariates (dengue case data; demographic and cartographic data); climate data (precipitation, ONI, temperature) retrieved from the Brazilian passive surveillance system, the Brazilian Institute for Geography and Statistics and relevant government agencies. Climate data is from the Global Precipitation Climatology Project, NCEP/NCAR Re-analysis project and the NOAAA Climate Prediction Center.	An alert is generated when dengue cases are projected to surpass a pre-defined alert threshold (e.g., greater than 50% chance of exceeding 300 cases per 100,000 inhabitants). To communicate the probabilistic forecasts, three risk categories could be used to classify microregions as low, medium, high.	Heatmaps of microregion classification used for resource targeting, preparation of health facilities for increased numbers of dengue cases and education of populations to reduce vector breeding sites.	The model was developed by the University of Exeter, Centre for Theoretical Physics, the Met Office (UK), with the Oswaldo Cruz Foundation in Rio. Funding came from the Leverhulme trust.	73
Colombia	Malaria	Part of the Integrated National Adaptation Pilot (INAP) project IDEWS models are being piloted at four sites (Montelibano,	Details of model not yet published but are suggested to includes- malaria case data from the passive public health surveillance system and lab-confirmed cases, entomological data from the MoH, literature, field collections and lab	An operational platform is being developed by the INAP, Colombia’s NIH and SIVIGILA (current surveillance system) for the IDEWS.	Response is devolved to local authorities: bed nets, IRS in endemic areas, control of mosquito breeding sites, updating and improving drug stocks, enhancing diagnostic network capacity, using mass-media campaigns, developing chemoprophylaxis for target	Led by the Colombian National Institute of Health and Colombian Ministry of Social Protection, funded by Conservation International Colombia.	85; 97

		Puerto Libertador, San Jose del Guaviare, Buenaventura).	experiments; climate data (temperature, precipitation and ENSO) from the Colombian Institute of Hydrology, Meteorology and Environmental studies. The system will integrate with national surveillance systems.		groups in high malaria season, effective case management.		
	Dengue, Chikunguny a, Zika	EWARS (WHO-TDR) tool for dengue is piloted for dengue in Colombia in the city of Cucuta, this paper tests its applicability to Zika and Chikungunya.	Epidemiological, meteorological, and entomological data from national epidemiological surveillance systems and meteorological institutes.	Alarms are triggered when the outbreak probability surpasses a user defined threshold.	A response plan is recommended using the online system depending on the lag time. Response plan is staged.		68
Mexico	Dengue	WHO-TDR EWARS was implemented in 2015-2017 in 20 health districts, the tool was later integrated into the national surveillance system in 2018.	A mixture of outbreak records, epidemiological, entomological, and meteorological data available from National Epidemiological Surveillance systems and National Meteorological Institutes.	Endemic channel statistical model is used in alarm generation. Alarms occur when the probability of an outbreak surpasses the alarm threshold set by the user. Alarms may be 'initial' (two consecutive weeks past the threshold); early (three consecutive weeks) or late (more than three weeks of alarms). Alarms are then communicated to local authorities and dengue committees, outbreak management teams at hospitals. Additional stakeholders may also be engaged depending on the level of the alarm – an 'early' alarm is shared with emergency operations committees, communities, mass media partnerships and IEC, as well as national and international authorities.	Depending on the level of the alarm (initial, early, late). Initial response: communicating risk to relevant stakeholders, preparing facilities (updating necessary background information [cartography, demographics, inventory]) and targeted vector control. Early response: the above, as well as convening local dengue/emergency operations committees, social mobilization, public health and media communications, vector control for adult mosquitoes with limited spatial fogging. Late response: full application of all contingency plans.	Joint effort of WHO-TDR, Center for Vector Control (MoH, Mexico) with European research institutions.	62; 69
	Dengue, Zika	Tests the utility of WHO-TDR's EWARS dengue tool for Zika.	Epidemiological, meteorological, and entomological data from national surveillance systems from national epidemiological surveillance systems and meteorological institutes.	Alarms are triggered when the outbreak probability surpasses a user defined threshold. A response plan is recommended using the online system depending on the lag time. Response plan is staged.	NA	NA	68

Panama	Dengue	Piloted regionally in district of Panama.	Uses meteorological data from the department of hydrometeorology of ETESA and entomological and epidemiological data from the MoH department of vector control	A monthly bulletin co-produced by GMIHS and ETESA which shows predicted vector densities and geographic distributions 2 months in advance. This is sent to decisionmakers- MoH, city mayors, academics, environmental authorities, and researchers.	NA	Gorgas Memorial Institute of Health Studies (GMIHS) with the Cuban Institute of Meteorology, Panamanian Electricity Company, School of Statistics of the University of Panama; funded by state financing and Cuban INSMET.	60
Eastern Mediterranean region							
Sudan	Malaria	In July 2001 a weekly malaria warning system was established for each state in Sudan. This research project proposes an alternative system, trialed on data from Gezira district.	Variable inputs are unknown for the 2001 system, beyond incorporating both climate and surveillance data. The proposed system incorporates environmental variables (rainfall, humidity, temperature) and case data. Malaria cases are reported to the federal ministry of health from hospitals/units; monthly climate data is from Sudan's meteorological service, water levels are obtained from ministry of water resources, irrigation, electricity.	An alert is generated if the number of cases exceed the epidemic thresholds, based on statistical difference from historical average. The 2001 system saw epidemic thresholds established for each state.	The 2001 system failed to detect small outbreaks in 2003 because malaria managers at the state level did not carefully assess the data. Under the proposed system a graph is generated by the system, sent to the health unit director who should plot it against the actual monthly cases and inform the regional director if threshold is exceeded.	The research project is run by a Saudi University in partnership with the Sudanese government	88
Yemen	Cholera	The Cholera Prediction Modelling system's first real-world test was in 2017.	Health data, satellite and ground-based data on air temperatures, ocean temperatures, salinity, precipitation, water phytoplankton concentration. NASA SeaWiFS, NASA precipitation data from the Global Precipitation Measurement mission, air and ocean temperatures from Moderate Resolution Imaging Spectroradiometer (MODIS) instruments on satellites	Cholera risk prediction is shown as a heat map.	In 2017, weekly reports of potential outbreaks were generated and shared with UNICEF and FCDO. Reports continue to be generated each week and the cholera risk assessment is shared with more than 100 colleagues in public health and remote sensing sectors. Response included promoting good hygiene practices, distributing hygiene kits and cholera treatment.	The model was developed by NASA and the University of Florida, partnering with UNICEF, the FCDO, UK Met Office.	91
South-East Asia region							

Bhutan	Climate sensitive diseases with initial focus on diarrhoeal diseases	Bhutan has adopted a 6-point plan to implementing an early warning system; validation of the pilot model for diarrhoeal diseases is ongoing in six basic health units in a high-risk riverine area.	Disease surveillance data; meteorological data (daily and monthly rainfall, temperature, humidity); monthly entomological data from vector surveillance. The EWS is suggested to be integrated with the national surveillance system.	Alerts are generated based on the calculation of a health risk index-predicted number of cases over the average number of cases. Once the threshold value has been surpassed an alert is issued.	Health professionals will be encouraged to prepare response plans.	The Department of Public Health of the MoH led the project, with the Environmental Health Programme coordinating implementation. Part of a joint initiative of WHO and UNDP, funded by the Global Environment Facility Special Climate Change Fund.	82;110
India	Dengue	Research project piloted MOSapp and DISapp (for android smartphones) in Kerala (Fort Cochin and Aluva) in December 2015 for MOSapp, and January 2017 for DISapp. These will be integrated into an EWS after user pilot.	MOSapp is designed for health workers to enter entomological and environmental data. DISapp is designed for the general public to upload geotagged surveillance data (e.g., mosquito bites) and to provide an individualized risk score based on the user's current location (ranging from very low- very high) based on MOSapp and DISapp data. Data is used by the systems to calculate the MPI (mosquito perception index) which is used to predict potential outbreaks.	The system is not known to be integrated into wider public health system.	NA	The apps were created by researchers from Indian Universities, funded by the Government of India.	87
Indonesia	Dengue	Pilot project.	Data from national meteorological services was used to provide seasonal and short-term climate predictions – "climate-based disease anticipation".		Educational materials and health contingency plans were designed to inform when and where disease prevention activities should be concentrated.	Implemented by the International Red Cross and Red Crescent Movement. Funded by the Rockefeller Foundation.	60
Sri Lanka	Dengue	Mo-Buzz, an integrated mobile- and desktop-based communication system was piloted in Colombo.	Predictive surveillance component uses algorithms based on entomological, weather, and human data to predict dengue outbreaks.	Predicted outbreaks are presented in the form of hotspot maps to health officials and the public. Health alerts and tailored messages are disseminated based on predictions to health authorities and individuals/communities living in hotspot zones.	Citizens inform health authorities of breeding sites, symptoms, and mosquito bites through forms on websites and social media.	NA	87
Western Pacific region							

Cambodia	Dengue, Chikungunya	IDEWS implementation is part of the '*Building resilience of health systems in Asian LDCs to climate change'* project which began in 2019.	NA	NA	Responses are determined by a rapid response plan	Implemented by the Ministry of Health with WHO and UNDP, funded by the Global Environmental Facility	89
Fiji	Climate-sensitive diseases (initial focus on diarrhoeal disease)	Pilot communities in Ba and Suva.	Uses surveillance and climatic data.		Training and education occurred in villages. Community response plans were established for pilot villages. Incorporation of indigenous indicators of climate change into seasonal calendars.	The project was managed by the Fijian Ministry of Health, Division of Public Health. Part of a joint initiative of WHO and UNDP, co-funded by the Global Environment Facility Special Climate Change Fund. Community engagement by the Fiji Red Cross Society.	84
Lao People's Democratic Republic	Dengue	IDEWS implementation is part of the '*Building resilience of health systems in Asian LDCs to climate change'* project which began in 2019.	NA	NA	Guidelines are being developed for dengue vector management.	Ministry of Health of Laos with WHO and UNDP, funded by the Global Environmental Facility	90
Malaysia	Dengue	WHO-TDR's EWARS-R was tested from December 2016-February 2017 in ten districts.	Meteorological variables (outdoor mean air temperature, outdoor mean humidity, total rainfall); epidemiological variables (mean age of hospitalized cases, serotypes, probable and lab confirmed and hospitalized dengue cases); entomological variables.	Threshold based system, an 'outbreak week' was triggered once dengue incidence crossed the upper threshold (z*SD); an alarm signal was triggered when the outbreak probability crossed the alarm threshold.	District health managers, national authorities. National guidelines for a staged response (initial, early, late and emergency) as described earlier.	Implemented by WHO/TDR with national dengue control services and academia, supported by the EU-funded IDAMS consortium.	69
Singapore	Dengue	National EWS	Prediction is based on dengue case data, weather data (temperature, humidity), demographic data (population) and vector surveillance data (weekly breeding percentage). Model data is updated weekly from the Ministry of Health (weekly infectious diseases bulletin), National Environment Agency.	Predictions provide a 3-month lead time and are shared with operational partners, including the Ministry of Health and the Environmental Public Health Operations Department of the NEA.	During a 2013 epidemic, forecasts informed hospital bed management and public health interventions (pre-emptive source reduction measures, recruitment of ground staff and education campaigns), early risk communication to the public through the advanced launch of a dengue public health campaign.	Implemented by the National Environment Agency and Communicable Disease Division, Ministry of Health. Project funded by Government of Singapore.	64

			Meteorological Services Singapore, Department of Statistics,				
The Solomon Islands	Malaria	Piloted the MalaClim model in September 2014 in the region of Northern Guadalcanal. Officially launched in 2015 after successful pilot, with expansion to cover Guadalcanal and Central Provinces.	OND rainfall provided by the Solomon Islands Meteorological Service. Rainfall gauges are being installed at EWS locations.	The warning system is based on three categories of alert levels based on level of rainfall– below normal, normal, and above normal- which aligns with the methodology used by local meteorological services. Monthly outlooks are communicated throughout the malaria season.	Currently communicated as a malaria outlook produced by meteorological services and communicated to the national vector borne disease control programme. Predictions are made up to 4 months ahead of the malaria season inform preparation activities. Response includes raising community awareness, preparedness in terms of diagnostics and treatment allocations, and vector control measures.	Implemented by the National Vector-Borne Disease Control programme with the Solomon Islands Meteorological Service and the Australian Bureau of Meteorology. Funded by the Australian Department of Foreign Affairs and Trade, Climate and Oceans Support Program in the Pacific.	60; 63; 111
Vietnam	Dengue	D-MOSS system developed and implemented between 2018-2021 in Ha Noi, Dak Lak, Dong Nai and Khanh Hoa Provinces.	D-MOSS uses Earth-observation data from satellites (land cover), weather forecasts (precipitation, temperature), a hydrological model of water availability and case data on dengue to make its prediction.	Forecasts are available up to 8 months in advance.	Expected to alert people in high-risk areas with warning several months in advance who will receive direction on where to focus their efforts to reduce mosquito-breeding sites to prevent dengue outbreaks.	The system was implemented by the MoH in collaboration with the WHO, UNDP, HR Wallingford and funded by the UK Space Agency.	75; 76 ,
		Pilot project.	Data from national meteorological services was used to provide seasonal and short-term climate predictions as part of "climate-based disease anticipation".	NA	Educational materials and health contingency plans were designed to inform when and where disease prevention activities should be concentrated.	Implemented by the International Red Cross and Red Crescent Movement. Funded by the Rockefeller Foundation.	60
Global regional surveillance systems							
East and Southern Africa and the Arabian Peninsula.	Rift Valley Fever	Following RFV outbreak in 1997-1998, US agencies initiated a partnership to forecast RVF outbreaks in Africa-	Climatic variables include sea surface temperature, estimated rainfall, outgoing longwave radiation, NVDI and indicators of ENSO; all are retrieved from NASA and the NOAA and are supplemented with ground-based data collection.	Analysis is by NASA. Forecasts and notifications are available through a designated website and are also communicated to public health authorities and international organisations in at-risk areas (including WHO, FAO, CDC; in Kenya the International Emerging Infections Program and the US Army Medical Research Unit in Nairobi; for the Arabian Peninsula, the US Naval medical Research Unit in Cairo).	When the system detected an RVF outbreak in East Africa (2006-2007) alerts were sent to WHO and FAO, who communicated them to at-risk countries, calling for enhanced surveillance and community awareness. USAMRU-K, KMRI and CDC Kenya deployed a field team to investigate high risk areas in Garissa district (mosquito testing, reports of	The US Department of Defense-Global Emerging Infections Surveillance and Response System (DOD-GEIS) (also called the Armed Forces Health Surveillance Center) with other US government entities, international organisations (FAO and WHO), African governments and NGOs.	77; 78; 91; 93; 96

				For the 2006-2007 epidemic over East Africa, forecasts were published online in December 2006.	animal and human cases). After confirmation, Kenyan MoH initiated a social mobilization campaign, vector control measures, a ban on animal slaughtering, animal movement controlled and quarantining, as well as a mass cattle vaccination campaign.		
West Africa	Meningitis		The system uses expert reanalysis of atmospheric conditions - temperature, relative humidity- provided by the National Center for Environmental Predictions and dust projections are from the Barcelona Supercomputer Centre. Sub-seasonal forecasts are from the European Centre for Medium-Range Weather Forecasts (ECMWF).	ACMAD produces the forecast with a two-week lead time. WHO defined two thresholds to monitor meningitis outbreaks: alert threshold when three suspected meningitis cases are reported in a week for every 100,000 inhabitants in an area. An epidemic threshold when then suspected cases of meningitis are reported in a week for every 100,000 inhabitants in a given areas. WHO defines four vigilance levels for countries (red, orange, yellow and white) - red means that meningitis outbreaks are expected.	WHO Afro coordinates prevention, preparedness, and response in countries of the meningitis belt. EWS is checked every Monday during the meningitis season and WHO staff share a bulletin with technical partners and national health authorities. WHO Afro organizes fortnightly coordination meetings to follow up on epidemiological situations in countries. When a red vigilance level is associated with reported meningitis cases, local health services submit a request to MenAfriNet to provide high quality case-based surveillance. Local health services transportation of samples and vaccine doses, manage available supports to improve performance and reinforce the surveillance system for upcoming weeks. A request is submitted to the International Coordinating Group on Vaccine Provision to secure doses.	Implemented as part of the Science for Weather Information and Forecasting Techniques (SWIFT) project. The system was a collaborative effort between the African Centre of Meteorological Applications for Development (ACMAD), the WHO Afro West Africa intercountry support team and national health systems. Other partners included in planning include the CDC and MSF. Funding from UK Research and Innovation.	45
Africa (continent)	Malaria	The risk maps have been available since June 2002	Dekadal rainfall anomalies (maps updated approximately every 10 days) and malaria risk. Data is from FEWS NET's African Data Dissemination Services.	It is suggested that regional support centers prepare bulletins for e-mail or courier distribution to district health teams in epidemic-prone areas based on the available data.		Famine Early Warning System Network (FEWS NET) created the original maps. A new monitoring interface was developed by the International Research Institute for Climate Prediction. The map is maintained by the US Geological Society and funded by USAID.	83
Global	Chikunguny a	CHIKRisk was developed in 2016 and provides a global forecast	Temperature and rainfall data from NOAA, land surface temperature from NASA, humidity and soil	CHIKRisk provides monthly outlooks of where risk is highest around the world. The calculated chikungunya risk		The model was developed by NASA and is used by the US Department of Defense GEIS and PAHO. Funding from the US Defense Threat	91

			moisture data from NASA's Global Land Data Assimilation System, Human Population density data from NASA's socioeconomic data and applications center. Chikungunya vector distributions from the Walter Reed Biosystematics Unit VectorMap. Ground-based surveillance from ProMED	forecast is displayed as a global heat map.		Reduction Agency and the NOAA Climate Program.	

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