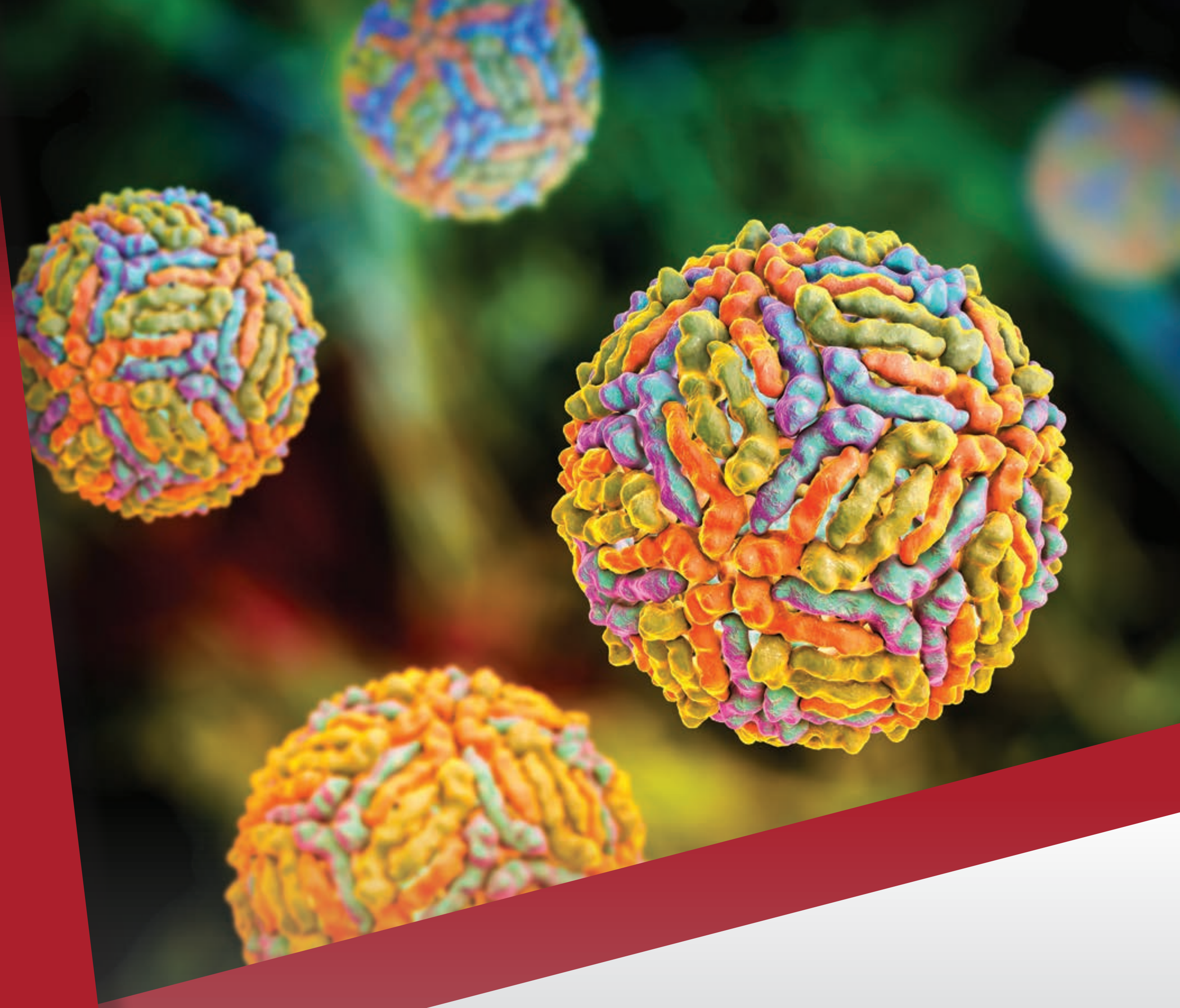
COLLOQUIUM REPORT



Role of Climate Change on Emerging and Reemerging Infectious Diseases

From Attribution to Action in Global Health Preparedness

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Role of Climate Change on Emerging and Reemerging Infectious Diseases: From Attribution to Action in Global Health Preparedness

Report on an American Academy of Microbiology and American Geophysical Union Colloquium held on October 9 & 10, 2025.

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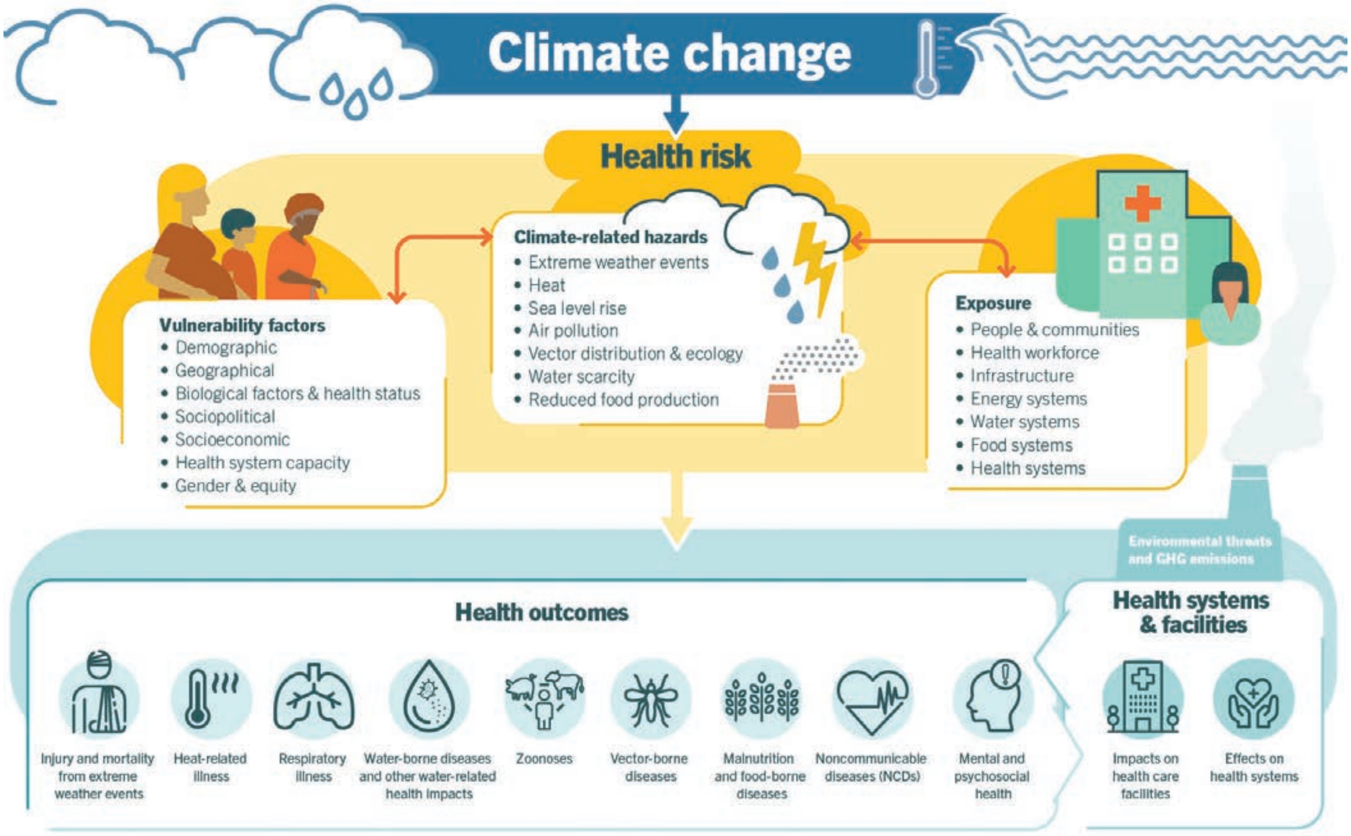
Executive Summary

Anthropogenic climate change is a fundamental threat to human health (WHO 2023). Altered temperature and precipitation levels, sea level rise, and more frequent and intense weather and climate events associated with climate change can negatively affect human health and health systems, especially with respect to infectious diseases. These changes impact the ecology, evolution, distribution, and prevalence of infectious disease reservoirs, hosts, vectors, and pathogens in ways that lead to the emergence of disease. Understanding and quantifying the relationship between climate change and infectious diseases are crucial for informing mitigation and adaptation strategies that strengthen public health responses.

This report is based on the deliberations of experts in epidemiology, microbial ecology, and evolution, infectious diseases, and climate science who participated in a colloquium on October 9 and 10, 2025, organized by the American Academy of Microbiology, the honorific leadership group and think tank within the American Society for Microbiology (ASM), and the American Geophysical Union (AGU). These experts came from diverse disciplines and sectors to articulate opportunities to build on climate, microbial, and attribution science to promote proactive public health preparedness and response. The participants highlighted the need for long-term attribution studies, proactive workforce training, development of novel diagnostics and treatments, and improved surveillance systems so that health systems are capable of rapidly responding to a changing infectious disease landscape.

Introduction

Global climate change is a fundamental threat to human health (WHO 2023). The effects of anthropogenic climate change have the potential to negatively impact human health in various ways (Fig. 1). For example, increasing temperatures lead to heat-related illnesses, and more frequent weather events lead to increased injuries and death. Altered temperature and precipitation levels, increased air pollution, and extreme natural disasters, such as hurricanes, cyclones, heatwaves, and floods, all associated with climate change, strain health care systems and other public services vital for public health, indirectly influencing health (WHO 2023). This report focuses on the effects of anthropogenic climate change, henceforth referred to as climate change, on human health.



Climate change greatly impacts infectious diseases. Hotter temperatures, altered precipitation, and rising sea levels all impact the ecology, evolution, distribution, and prevalence of infectious disease vectors and pathogens in ways that can lead to the emergence or expansion of disease. Extreme weather and droughts can also overwhelm sanitation systems and water infrastructure, potentially increasing exposure to pathogens, thereby indirectly impacting cases of infectious diseases (UNESCO 2020). Anticipating and preparing for the direct and indirect effects of climate change on pathogens in the near term and long term is critical to prevent disease emergence and spread.

Figure 1. Human health risks and outcomes affected by climate change. Source: WHO.

Climate Change and Infectious Disease

Infectious diseases pose a considerable global burden on human health, especially in low- and middle-income countries (LMICs) (WHO). Climate change can affect infectious diseases through multiple, interconnected pathways, including altering the survival, reproduction, and geographic distribution of pathogens, vectors, and hosts (Jayakumar et al. 2024; Wu et al. 2016). In addition, climate-driven environmental changes alter the physical and ecological conditions that facilitate pathogen transmission to human populations (Jayakumar et al. 2024; Wu et al. 2016). Zoonotic diseases are shaped in part by climate-driven shifts in distributions, abundance, and behavior of animal hosts or reservoirs (Eby et al. 2023; Plowright et al. 2024; Filho et al. 2025; Islam et al. 2025). Vector and host behavior, immune status, and spatial distribution can also be affected by climate change, leading to higher pathogen loads or increased contact between pathogens and humans that pose higher risks of infection.

The IPCC's Sixth Assessment Report notes that climate change and associated extreme weather events have led to an expanded temporal and spatial range of some human pathogens, including foodborne, waterborne, and vector-borne pathogens (Cissé et al. 2022). This expansion of range has led to the presence of diseases outside their usual or expected region as weather and climatic conditions shift to become more favorable to a pathogen or vector. For instance, long-term warning trends have shifted the geographic distribution and seasonality of disease outbreaks, such as Vibrio infections occurring at higher latitudes and for a longer part of the year (Messina et al. 2019; Semenza et al. 2017; Almagro-Moreno et al. 2023; Brumfield et al. 2025). Several arboviruses are appearing across different regions of the world, with their geographic distribution expanding both latitudinally and altitudinally in the past decade (Barcellos et al. 2025; Ortiz-Prado et al. 2026). These so-called emerging diseases are appearing in a new area or population for the first time (WHO 2026).

Previously rare diseases are reemerging in association with changing environmental conditions.

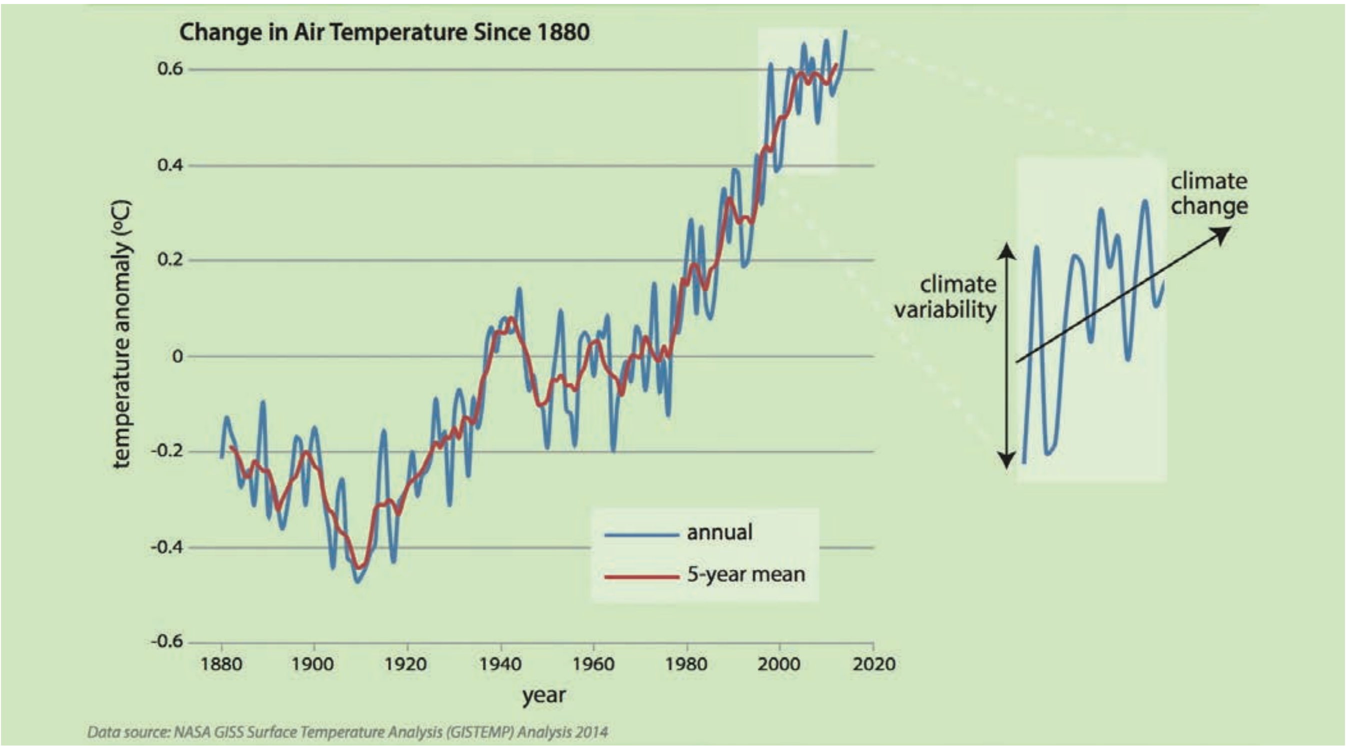
Previously rare diseases are reemerging in association with changing environmental conditions. Plague, which was responsible for one of the deadliest pandemics in human history, is now reemerging. Increased cases of human plague, which is caused by the bacterium Yersinia pestis carried by rodent fleas, have been associated with warmer and wetter seasons that cause rodents to expand their interactions with humans and lead to zoonotic transmission (Anyamba et al. 2019). The effects of climate change are also impacting how humans interact with their environment and how wild animals are interacting with humans and domestic animals, leading to more human-animal interactions that increase the risk for zoonotic transmission (Rupasinghe et al. 2022; Eby et al. 2023; Plowright et al. 2024).

Emerging and reemerging diseases pose a significant challenge to public health, as many clinicians and public health systems are unprepared to detect and treat diseases not within the historic transmission range (M. Ramon-Torrell 2023; De Gaetano et al. 2025). This scenario places cumulative strain on health systems, as it unfolds alongside other population health challenges, including the persistent high burden of noncommunicable diseases, which itself may also be influenced by climate change (Sesay and Osborne 2025; Sutanto 2024). Delineating how changing climatic patterns impact infectious diseases will help public health preparedness. Detection and attribution science can provide a formalized method to do just that (Ebi et al. 2025).

Infectious Diseases and Health Attribution

Many studies have demonstrated associations between climate variability and patterns of disease outbreaks or transmission, such as increased cases of Lyme disease because of warming temperatures or expanded spread of Valley fever associated with drought, but there are few studies directly linking and quantifying the effects of anthropogenic climate change with impacts on human health (Ogden et al. 2014; Head et al. 2022; Couper et al. 2021). This lack of data limits proactive public health actions, as developing health policy around statistical associations can lead to incorrect assumptions and erode public trust. Therefore, there is a growing and urgent need for robust and quantitative frameworks for directly connecting anthropogenic climate change and public health risks.

Formal statistical methods developed by climatologists and economists are beginning to be applied in the health sector to quantify the extent to which recent climate change altered the burden of climate-sensitive health outcomes in response to an extreme weather and climate event or to gradual increases in temperatures or changes in the hydrological cycle (Ebi et al. 2020; Ebi et al. 2025). A key to understanding the impact of climate change on health is the quantification of impacts arising from climate change vs natural climate variability (Fig. 2). **Detection** is the "process of demonstrating that an observed change is statistically different from natural variability" and **attribution** is the "process of establishing cause and effect with some defined level of confidence, including the assessment of competing hypotheses" (IPCC 2001). Detection and attribution studies (henceforth called attribution studies) provide robust evidence that move climate and health synthesis statements from describing associations between weather patterns and health outcomes to quantifying the magnitude and pattern of the current impacts of climate change on health and well-being.

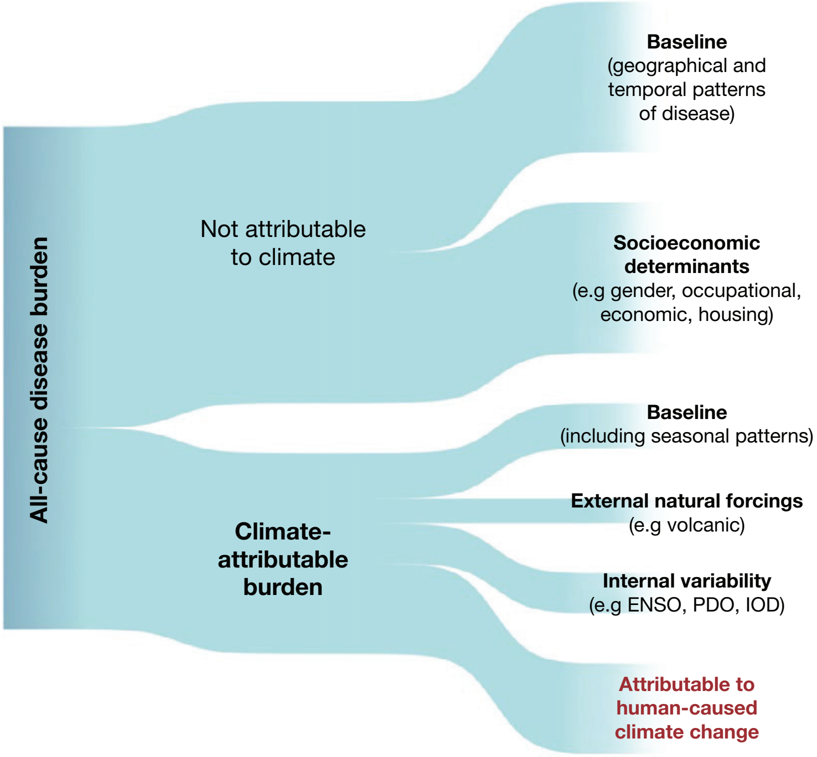


Data source: NASA GISS Surface Temperature Analysis (GISTEMP) Analysis 2014

Figure 2. Climate variability leads to different average temperatures each year, but climate change is responsible for the significant increase in global air temperature since the Industrial Revolution in the 1880s. Source: UCAR.

Health attribution studies quantify the contribution of anthropogenic climate change to a particular health outcome, such as mortality, displacement, or food insecurity, while **disease attribution** focuses specifically on impacts on disease burdens (Ebi et al. 2025; Carlson et al. 2025). Disease burdens, including infectious disease burdens, are influenced by a complex network of climatic, environmental, and social factors (Fig. 3). Not all increases or observed changes in cases of an infectious disease are the result of climate change. Thus, conducting infectious disease attribution studies is challenging, and only a handful of such studies exist to date, some of which are not yet published in the peer-reviewed literature (Erazo et al. 2024; Fay et al. 2025; Childs et al. 2025; Harris et al. 2026; Carlson et al. 2026).

Figure 3. Sources of disease burden. Source: Carlson et al. 2024.



(ENSO: El Niño-Southern Oscillation; PDO: Pacific Decadal Oscillation; IOD: Indian Ocean Dipole.)

A Framework for Infectious Disease Anticipation and Global Health Adaptation

As infectious disease attribution science progresses, microbiologists can work in transdisciplinary ways to bridge gaps and promote human health. Rigorous infectious disease attribution studies to understand and quantify the direct and indirect causal links among climate drivers, climate variability, and infectious diseases are essential for deepening scientific understanding, building public trust and confidence in scientific findings, guiding public health actions, and informing risk communication, public engagement, and climate litigation (Ebi et al. 2020; Stuart-Smith et al. 2021; Ebi et al. 2025). However, disease burdens often change faster than studies can be conducted, so the need for clinical and public health workers to address rising cases of infectious diseases is immediate. Building on studies that show correlation—but not direct causation—between climate change and infectious diseases can help health systems to prepare for emerging and reemerging diseases. This must be counterbalanced by concerns that associating too many diseases with climate change without rigorous evidence can erode public trust in scientific claims and can lead to predictions that are too broad or shift focus to climate change and away from effective prevention strategies (Reiter 2008; Cologna et al. 2024). Moreover, climate change may not always be the largest contributor to changes in disease burden, and understanding the relative impact of climate versus other drivers is critical for allocating public health, disease control, and biomedical research effort where it can be most beneficial (Carlson et al. 2024).

Experts in microbial sciences, infectious disease, and climate science have come together to build a framework that supports microbiologists to more effectively contribute to future research and public health strategies. These experts participated in a colloquium on October 9 and 10, 2025, organized by the American Academy of Microbiology, an honorific leadership group and think tank within the American Society for Microbiology, and the American Geophysical Union. The colloquium was also supported by the American Society of Tropical Medicine and Hygiene. This report is based on the deliberations of the colloquium participants.

The colloquium participants focused on balancing mechanistic studies and health attribution studies with public health preparedness to promote human health and well-being worldwide. Through their discussions, they outlined a framework for addressing infectious disease changes in response to a changing environment, identifying the following key issues:

- Improving infectious disease models and policies.
- Strengthening public health responses.
- Coordinating locally and globally.

The participants highlighted the need for long-term attribution studies, proactive training, development of novel diagnostics and treatments, and improved surveillance systems to prepare health systems so they are capable of rapidly responding to a changing infectious disease landscape.

Predicting the Future of Infectious Diseases in Response to a Changing Climate

A rapidly expanding body of research demonstrates that climate change is already reshaping the ecology, evolution, and geographic distribution of infectious diseases (Mahon et al. 2024; Rocklöv and Dubrow 2020; Rohr et al. 2011). Collectively, this work supports the conclusion that climate is not merely a background condition but a core driver of infectious disease dynamics.

Current State of Infectious Disease and Climate Change Research

Many infectious disease and climate change studies have focused on identifying mechanistic links between climate variables and transmission. Central concepts include thermal performance curves and hydric performance curves, which describe how traits such as pathogen growth, vector survival, biting rate, and host susceptibility vary across temperature or moisture gradients (Mordecai et al. 2019; Mordecai et al. 2017; Brown et al. 2023). Trait-based mechanistic models integrate these relationships into estimates of transmission potential (e.g., basic reproduction number R0), thereby enabling predictions of how warming and other climate-associated variables shift transmission potential (Fig. 4) (Nguyen et al. 2021; Ryan et al. 2019).

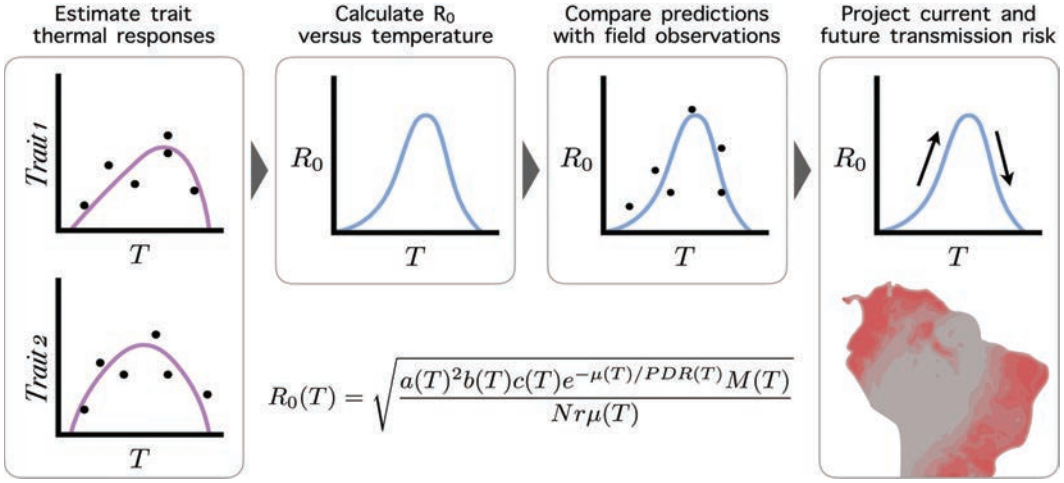


Figure 4. Example of trait-based approach to understand effects of temperature on vector-borne disease transmission. Source: Mordecai et al. 2019.

Other modeling efforts incorporate both mechanistic temperature sensitivity estimates and other estimated socioecological and public health drivers (Symons et al. 2026). Compared with purely correlative approaches such as species distribution models, these frameworks provide stronger causal interpretation and better extrapolation under novel climates (Mordecai et al. 2019; Rohr and Cohen 2020). However, these frameworks are often simplified to focus on single climatic drivers (such as average temperatures), without accounting for concurrent changes in factors like socioeconomics, mobility, and public health measures that might interact with climate. At the same time, large-scale statistical and geospatial analyses have improved prediction (Ryan et al. 2019; Symons et al. 2026). Integrating epidemiological surveillance with climate, land use, and socioeconomic data has enhanced early warning systems and risk mapping (Brett et al. 2017; Zhao et al. 2025). Increasingly, hybrid models combine mechanistic trait data with machine learning or spatial statistics to balance biological realism with predictive power (Kraemer et al. 2019; Kraemer et al. 2025). These advances are moving the field from retrospective description toward actionable forecasts that can inform preparedness and intervention.

Despite progress, major knowledge gaps remain. First, data limitations constrain inference. While methods to detect pathogens have dramatically improved over time, temporal inference must account for changes in disease surveillance, diagnostics, and reporting over time in historical data. Long-term harmonized datasets that link climate, pathogens, and human outcomes have historically been rare but are becoming increasingly available with large-scale data synthesis and harmonization efforts, especially in low- and middle-income regions where risks are highest (van Panhuis et al. 2015; Murray et al. 2024; Symons et al. 2026). Experimental trait data across multiple climate gradients are limited, and hydric performance curves are even rarer than thermal performance curves (Brown et al. 2023).

Second, most studies consider single stressors; yet secondary drivers, such as land use change, insecticides, and public health interventions, interact strongly with climate to alter transmission (Brown et al. 2023; Rohr and Cohen 2020; Pfenning-Butterworth et al. 2024; Eby et al. 2023). Few experiments or models have quantified these multidimensional interactions, reducing their relevance to real-world conditions.

Third, climate variability and organismal plasticity, where an organism adjusts its physiology or behavior in response to a change, are often overlooked (Rohr and Cohen 2020; Symons et al. 2026; Raffel et al. 2013; Paaijmans et al. 2010; Sgrò et al. 2016). Organisms experience diurnal and seasonal fluctuations rather than constant means, and acclimation or behavioral plasticity can substantially modify disease outcomes. Ignoring variability may misestimate risk.

Fourth, evolution and adaptation are insufficiently studied (Couper et al. 2025; Couper et al. 2021; Sternberg and Thomas 2014; Rohr et al. 2018; Cohen et al. 2020; Cohen et al. 2017). Rapid pathogen evolution may allow microbes to respond to climate faster than hosts, potentially amplifying disease burdens, but empirical tests thus far remain limited (Rohr and Cohen 2020; Rohr et al. 2018).

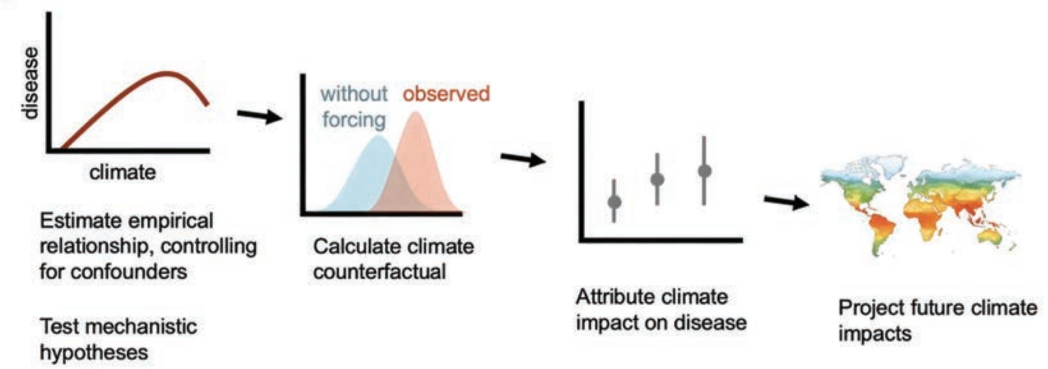
Finally, attribution science for infectious diseases is an emerging frontier with a limited number of existing case studies (Ebi et al. 2017; Childs et al. 2025). Strengthening attribution is critical because public health decisions increasingly depend on understanding whether risks are transient or climate-driven and persistent.

Climate Change and Infectious Disease Attribution Science

Infectious disease attribution studies quantify the extent to which an observed climatic change or event is attributable to anthropogenic forcings (e.g., changes in greenhouse gases, aerosols, and land cover) versus natural contributions in a methodical and formalized way (Carlson et al. 2025). End-to-end disease attribution involves the following general steps (Fig. 5):

1. Identifying and isolating a causal relationship between a specific climate driver and a disease outcome.
2. Estimating transmission under the observed climate (factual) and a counterfactual scenario without anthropogenic forcing.
3. Comparing disease outcome estimates under the factual and counterfactual climate to identify the proportion attributable to human-caused climate change.
4. (Optionally) Projecting disease outcomes under future climate scenarios.

Figure 5. Framework for climate attribution for infectious diseases. Map image created using Dall-E.



Thus, formal attribution typically builds upon an accumulation of empirical evidence establishing linkages between climate drivers and components of transmission, including both mechanistic (e.g., controlled laboratory experiments quantifying temperature impacts on pathogen replication rates) and observational (e.g., field-based analyses relating vector population expansion to climatic change) studies. Importantly, a quantitative relationship between climate and disease must be estimated in a large-scale real-world context given the multiple concurrent drivers that affect infectious diseases, to assess the magnitude of impacts of the focal climate variable. This typically requires observational disease data over a long time period. As a result, only a handful of formal infectious disease attribution studies currently exist, and all have been conducted in mosquito-borne disease systems, which have been relatively well-studied, particularly with regard to temperature (see case studies in Table 1). Several other studies have additionally estimated causal climate-disease relationships, forming a foundation for future attribution studies if the climate counterfactual is incorporated (e.g., Ogden et al. 2014; Head et al. 2022; Couper et al. 2021).

Table 1. Infectious Disease and Climate Attribution Studies Case Studies.

Disease Studied	**Study Finding**	Identifies and isolates a causal relationship between a specific climate driver and a disease outcome	Estimates transmission under factual and counterfactual scenario	Identifies proportion of disease outcome attributable to human-caused climate change	Projects disease outcomes under future climate scenarios	Study is a climate attribution study for infectious disease
Dengue	~18% of dengue burden is due to climate change in 21 countries in Asia and the Americas (1995-2014) (Childs et al. 2025)	Yes	Yes	Yes	Yes	Yes
	~60% of dengue cases reported over three months in northwestern Peru after Cyclone Yaku attributable to extreme precipitation driven by climate change (2023) (Harris et al. 2026)	Yes	Yes	Yes	No	Yes
Malaria	A small net increase in the prevalence of childhood malaria in sub-Saharan Africa, characterized by regional increases and decreases (1901-2014) (Carlson et al. 2026)*	Yes	Yes	Yes	Yes	Yes
West Nile virus	2- to 6-fold increase in population at risk from West Nile virus in Europe (1901-2019) (Erazo et al. 2024)	No, the relationship is observational	Yes	Yes	No	Partially. The inferred climate – disease relationship is observational and does not control for potentially confounding variation, but is based on mechanistic hypotheses
	~20 day longer West Nile virus transmission season in New York state over 25 years (1999-2024) (Fay et al. 2025)*	Yes	Yes	Yes	No	Yes
Lyme disease	Increase in cases in the Northeast U.S. by 2050 (Couper et al. 2020)	Yes	No	No	Yes	No, climate counterfactual scenario needed
Valley fever	Increase in drought-attributable cases of Valley fever in California (2000-2020) (Head et al. 2022)	Yes	No	No	No	No, climate counterfactual scenario needed

* At the time of this report, these studies are not yet peer-reviewed publications but exist as publicly available preprints.

The are currently only five existing climate attribution studies for infectious diseases, of which three are published and two are preprints. They examine the following mosquito-borne diseases:

Dengue: Childs et al. examined the impact of temperature and climate warming on dengue incidence by constructing a panel dataset—repeated measurements of disease and environmental covariates in many different spatial units over many time points—of subcountry (administrative levels 1 and 2), monthly dengue observations from 6,639 units in 21 countries in the Americas and Southeast Asia, with each time series averaging 11 years long (Childs et al. 2025). With this dataset, they performed a panel regression with a polynomial function of temperature (the effect of interest), covariate data on precipitation, and fixed effects for administrative unit, country and year, and country and month. This analytical strategy aims to isolate causal effects of temperature on dengue while controlling for observed and unobserved potentially confounding variation. The study found a large nonlinear effect of temperature on dengue incidence, with dengue doubling with every 1°C of temperature warming in the cool range of 17–20°C and incidence peaking at 27.8°C, closely aligning with previous mechanistic models parameterized from laboratory experimental data (Mordecai et al. 2017). Given climate counterfactuals from global circulation models (GCMs), they found that on average 18% of the global dengue burden in these 21 countries was attributable to climate change in the 1994–2015 period, with larger attributable burdens in historically cooler study regions. The study went on to project larger increases in dengue with future warming, ranging from 49–76% average increases by mid-century depending on the climate scenario.

Harris et al. focused on the effects of extreme precipitation caused by a tropical cyclone on dengue incidence (Harris et al. 2026). In March 2023, Cyclone Yaku hit the coast of Peru during a localized El Niño event that also brought warmer-than-usual temperatures. The storm caused widespread flooding, damage, displacement, and mortality. Subsequently, Peru experienced its largest dengue outbreak on record to that point, with 381 deaths and 10× higher than average caseloads. The study used district-level (admin-3) weekly dengue data from 2010 to 2023 and a generalized synthetic controls approach, pairing each unit designated as cyclone-affected (precipitation anomaly greater than 8.5 mm/day) with a weighted average of otherwise climatically similar “control” districts, using latent factors to control for shared spatial and temporal variation, and controlling for temperature and precipitation. By comparing the divergence of each affected unit from its synthetic control post-cyclone, the study estimated that extreme precipitation during Cyclone Yaku accounted for 60% of all dengue cases in affected districts, or a total of 21,014 cases. An analysis of GCMs during a pre-industrial baseline compared to a contemporary period estimated that the extreme warm and wet conditions observed during Cyclone Yaku were 189% more likely due to anthropogenic forcing.

Malaria: Carlson et al. examined the effect of a century of climate warming on malaria in sub-Saharan Africa (preprint Carlson et al. 2026). The study used a historical reconstruction of *Plasmodium falciparum* malaria prevalence in children aged 2–10 across sub-Saharan Africa from 1900 to 2015, aggregated to the admin-1 level (Snow et al. 2017). The analysis used a panel regression approach that estimated effects of temperature and extreme precipitation while controlling for administrative unit, regional seasonality, country-level trends, and large-scale variation in control efforts. The analysis found a nonlinear effect of temperature on malaria prevalence that peaked at 25°C, aligning with previous mechanistic models based on laboratory data (Mordecai et al. 2013; Villena et al. 2022), and that a 10°C increase or decrease from the optimum temperature reduced malaria prevalence by 8 percentage points (p.p.). Because of this moderate optimal temperature and magnitude of temperature effects on malaria, climate warming between 1900 and 2015 has marginally decreased (by up to 1 p.p.) malaria prevalence in historically warmer parts of West Africa, marginally increased prevalence (by up to 2 p.p.) in historically cooler parts of Southern and highland East Africa and had minimal effects in most of Central Africa. These opposing effects result in an overall continent-wide average effect that is not significantly different from zero, and many of the regional effects also have 95% confidence intervals overlapping zero. The results also suggest that climate change has extended the malaria transmission season in parts of Southern Africa but not elsewhere. Effects of precipitation anomalies were weaker and more uncertain. Estimated effects of historical malaria control programs (Global Malaria Eradication Program from 1955 to 1969 and Roll Back Malaria and the Global Technical Strategy from 2000 to 2014) resulted in substantially larger reductions of ~3–5 p.p. in average prevalence. Finally, given the moderate optimal temperature for malaria transmission, the study projected that future climate warming over the 21st century will decrease malaria in most regions of sub-Saharan Africa by 0.09–1.90 p.p. depending on the time horizon and emissions scenario, with regional increases in highland and southern regions currently below the thermal optimum.

West Nile virus: Erazo et al. investigated the impact of climate change on environmental suitability for West Nile disease in Europe by training an ecological niche model on human West Nile virus (WNV) disease cases as a function of multiple climate variables, controlling for land use change and population changes, and using a climate counterfactual to estimate the extent to which the observed spatial expansion in WNV suitability was attributable to climate change Europe (Erazo et al. 2024). The input data into the ecological niche model included human cases reported from 2007 to 2019 across Europe at the admin-3 level, along with climate, land use, and population data. Inferred relationships between climate variables and WNV suitability were observational, rather than causal (as in all other attribution studies described in this section), but were based on mechanistic hypotheses relating vector dynamics to temperature, humidity, and precipitation. The most important inferred climate variables were air temperatures in summer and winter, precipitation in summer, and relative humidity in winter and fall. Under the observed (factual) climate, the models showed expansions of WNV suitability over the past century into parts of Italy, Greece, Hungary, and Romania, especially since 1980. These spatial expansions are not present in ecological niche models using counterfactual detrended climate models, showing that the changes are unlikely to have occurred in the absence of climate change. Population growth combined with climate change expanded the number of people at risk of WNV suitability since 1901 in Europe.

Fay et al. investigated whether climate change has extended the transmission season for West Nile virus in New York State, where cool winters have historically limited the transmission season to May to early October (preprint Fay et al. 2025). They used the temperature threshold of 16.7°C to define conditions suitable for WNV transmission by *Culex pipiens* mosquitoes, based on a mechanistic transmission model parameterized from laboratory data by Shocket et al. (2020), and defined the start and end of the transmission season as the first and last days at which this minimum temperature threshold was met within two weeks of another such day. They estimated that the transmission season has increased by 20 days in the 25 years since WNV was introduced to New York, beginning 4 days earlier and ending 16 days later on average statewide. Longer transmission seasons in turn correlated with higher WNV prevalence in mosquito surveillance pools, earlier WNV detection in mosquito pools, more human WNV cases, and later human WNV cases statewide, demonstrating the epidemiological impact of extended temperature suitability. Analyses of GCMs documented robust evidence for increases in season length—starting earlier and ending later—between the historical baseline and current periods and that the observed trend in season length from 1999 to 2024 was 6.4× more likely due to anthropogenic climate warming.

Attribution studies require well-understood mechanisms, robust long-term observational data, and specific analytical methods. Statistical causal inference studies grounded in biological understanding, such as the analysis of climate-driven dengue suitability, demonstrate how attribution can be achieved and used to inform projections, thereby complementing mechanistic modeling (Childs et al. 2025). However, several key pieces of evidence are lacking for formal climate attribution to be conducted in many systems. First, climate drivers need to be understood mechanistically rather than only correlatively, for example, through controlled laboratory experiments or through “natural” experiments that vary climate variables quasi-randomly. Second, mechanistic hypotheses need to be tested in field-based studies quantifying impacts of climate variables within the full context of disease transmission. Third, climate-disease relationships need to be quantified in the field across a gradient that varies in the climate exposure over space, over time, or ideally both, while controlling for other processes that also vary over space and time. Outbreaks of climate-sensitive disease that occur coincident with anomalous weather may be suggestive of climate change impacts but are not by themselves conclusive evidence.

Opportunities for better integration of microbiology and climate science.

These limitations provide opportunities for better integration of microbiology and climate science. Microbiologists, epidemiologists, and clinical microbiologists can perform physiological and mechanistic studies for pathogens and provide microbial data via improved diagnostics and surveillance systems, while climate scientists and modelers can expand integrated data systems to track environmental and ecological data and build counterfactual models for more complete attribution studies. Coordination among scientific disciplines along with community input will allow for more refined hypothesis generation that can lead to future research projects.

Solidifying the evidence for climate change impacts on infectious diseases requires establishing mechanisms, documenting patterns, formally assessing and quantifying causal relationships, and examining climate counterfactuals. Research on different pathogens and disease systems is at different phases of this scientific process.

Key Research Priorities and Challenges

Infectious disease–climate research has matured from documenting associations to developing mechanistic and predictive tools. Nevertheless, realizing its full public health potential will require better data, multidimensional experiments, rigorous attribution, and closer alignment between science and decision-making.

More Longitudinal Studies

Climatic impacts unfold over extended temporal scales (Flahault et al. 2016; Metcalf et al. 2017). In most cases, climatic impacts on disease emergence, incidence, and spread are delayed, cumulative, and nonlinear, often manifesting only after prolonged exposure to altered environmental conditions or ecosystem reorganization. To conclusively identify the consequences of these impacts, multiple seasons or even decades of longitudinal studies are necessary (Flahault et al. 2016; Metcalf et al. 2017).

Attributing health impacts to climate change requires moving beyond correlation toward causal inference, which in turn demands long time series and longitudinal studies of both climate and disease data. Longitudinal studies allow for repeated observation of the same environments, hosts, and populations across seasons and years (Alcayna et al. 2025; Romanello et al. 2023). When paired with causal inference frameworks, long-term datasets allow researchers to examine how environmental variability progressively reshapes ecosystems, pathogen reservoirs, transmission pathways, and disease risk (Guevara et al. 2024). This approach makes it possible to detect delayed responses, thresholds, and ecosystem shifts and to evaluate whether observed changes in disease dynamics persist across climatic cycles (Alcayna et al. 2025; Romanello et al. 2023). Importantly, longitudinal studies also provide a credible framework for investigating changes in outbreak timing, expansion of transmission seasons, or the emergence of novel transmission routes under altered environmental conditions (Wright et al. 2025; Sipari et al. 2022; Colón-González et al. 2021; Carlson et al. 2022; Carlson et al. 2025).

Longitudinal studies provide a reliable foundation for estimating the causal impact of climate change on infectious disease transmission

By moving beyond short-term associations, longitudinal studies provide a reliable foundation for estimating the causal impact of climate change on infectious disease transmission. These data are essential for improving predictive models, identifying early warning signals, and informing climate-sensitive disease forecasting. From a policy and preparedness perspective, longitudinal evidence also can guide the timing and targeting of surveillance, resource allocation, and intervention strategies, particularly in regions not sufficiently equipped with resources to handle these rapid fluctuations (Jayakumar et al. 2024). As climate change continues to reshape disease landscapes, temporal monitoring will be critical for anticipating future risks, supporting proactive public health planning, and reducing uncertainty in projections of infectious disease emergence and spread.

Better Surveillance and Diagnostics

To detect the impact of climate change on infectious diseases, broader surveillance as well as diagnostic testing capabilities is warranted. Recognition of emerging or reemerging diseases related to climate change is likely to pose diagnostic challenges. Versatile platforms for the rapid development of new diagnostics are critical for modern healthcare, particularly to manage emerging infectious diseases. This will include temperature resilient diagnostic platforms with minimal sample requirements that are accessible and affordable for low-resourced settings.

Proactive public health systems rely on early identification of infectious diseases and effective contact tracing. However, in large regions of the world, resources for testing are sparse or simply absent, resulting in a limited ability to identify the true burden of infectious diseases. For example, invasive fungal infections have been increasingly rising in the past decade, but there are few approved fungal diagnostic tests broadly available. Those that do exist work only for a limited range of fungi, take time for results, can be costly, and require well-equipped laboratories and trained staff that many communities may not have (WHO 2025). Fungal diagnostic tests have not been prioritized by public health agencies because of rarity of infections compared to bacterial and viral infections and lack of research and commercial investment (Murtagh et al. 2026). Infectious disease diagnosis, particularly in low-resourced settings where diagnostic capacity is limited, will have substantial impact on managing climate-related infectious disease outbreaks. Therefore, it is important that global and national policies consider improving diagnostic access in areas where they are not readily accessible (such as for malaria and influenza) as well as prioritizing development and cost reduction for diagnostics for diseases with few or expensive tests (such as for dengue as fungal diseases) when assessing preparedness and planning activities.

Existing data often have biases in detection across space and time. Improved diagnostics and rapid point-of-care (POC) tests for infectious diseases can help improve access to diagnosis, patient management, and future public health preparedness (Chen et al. 2019; Kozel and Burnham-Marusich 2017). Linking data on disease trends from diagnostic laboratories and POC test readers can help to provide timely information for early warning of infectious disease outbreaks and optimization of disease control efforts.

Integration of Environmental & Microbial Data

In the global context, health record systems do not integrate environmental data in real time, making them poorly equipped to manage both epidemiological and environmental data to produce actionable intelligence. Integrated surveillance systems that combine health and environmental data could mitigate the health impacts of infectious diseases related to climate change. Investments in broader surveillance systems that capture environmental data from local and remote sensing technologies need to be integrated with health record information to identify at-risk patients and inform public health decision-making processes (Jacobs et al. 2014; Jamal et al. 2024). These systems would have benefits for the regional population as well as for individuals, health systems, and governance. Benefits would include targeted interventions by health professionals to mitigate disease exacerbation as well as formulation of policies to guide disease forecasting and public health actions (Semenza et al. 2017; Jamal et al. 2024). These integrated systems will be crucial for transforming passive monitoring into active, predictive intelligence for public health.

The U.S. Centers for Disease Control and Prevention (CDC) created the National Environmental Public Health Tracking Network (Tracking Network), which integrates data from state and local health departments into an outcomes tracking network. The European Centre for Disease Prevention and Control (ECDC) has developed the European Environment and Epidemiology (E3) Network that provides access to environmental datasets for assessing determinants of infectious and modeling outputs (Fig. 6) (Sudre 2013). Linking geographic information with infectious disease surveillance data requires a thorough understanding of the infectious disease drivers and their interaction with the environment. Human case data need to be collected in a consistent way, while maintaining the confidentiality of patient data. Integrated systems will enhance clinical and public health decision-making, but integrating environmental data into healthcare surveillance systems is challenging due to both structural barriers and lack of financial incentives.

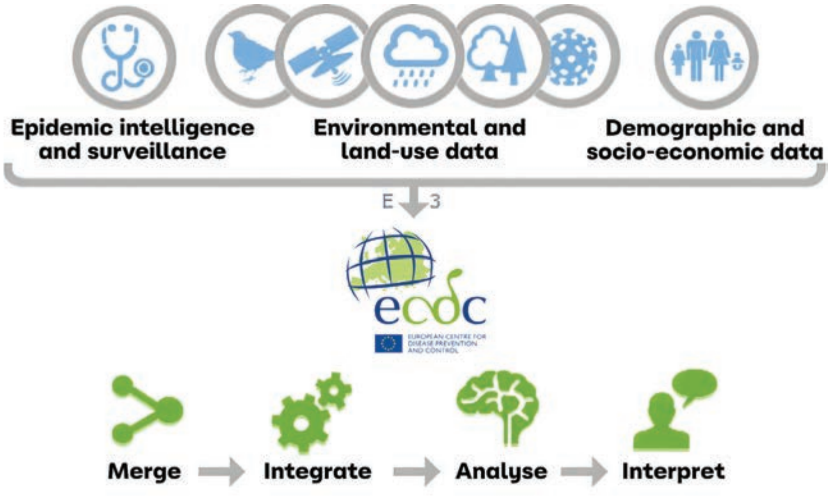


Figure 6. European Environment and Epidemiology (E3) framework to link epidemiological and environmental data to inform public health decisions. Source: European Centre for Disease Prevention and Control (ECDC).

Improved Predictive Models

Climate change is reshaping infectious disease risk through interacting physical, ecological, evolutionary, and social pathways. Two closely linked scientific goals aiming to address this challenge include (i) attribution and (ii) forecasting, which aim to anticipate future risks under novel, nonstationary conditions. Attribution is not merely retrospective; it provides the causal grounding needed to evaluate models and build confidence in forecasts.

A central challenge is that climate–infectious disease systems are intrinsically multiscale and coupled. Physical climate processes operate over broad spatial and temporal scales, while ecological and transmission dynamics often unfold locally and seasonally (Lennon et al. 2024). Evolutionary changes in pathogens and vectors can further alter system behavior (Bang et al. 2018). Human behavior spans all of these scales and provides critical linkages among them. At fine scales, behaviors such as close-contact patterns, housing quality, mobility, and vector control directly affect transmission (Lessani et al. 2024; Wilson et al. 2020). At broader scales, human activities, including urbanization, agriculture, water management, and landscape modification, reshape ecosystems, geomorphology, and microclimates, while greenhouse gas emissions alter the climate system itself (Rulli et al. 2025; Chala and Hamde 2021; Alirol et al. 2011). These interacting processes generate nonlinear dynamics and feedbacks that challenge single-scale or single-discipline models.

Mechanistic models are essential for representing causal pathways and for supporting both attribution and extrapolation beyond historical conditions (Lessler and

Cummings 2016; Caldwell et al. 2021; Thompson et al. 2022). However, increasing realism introduces substantial challenges. Model calibration becomes difficult for high-dimensional, multiscale systems that are only partially observed. Data are often sparse or mismatched across scales, and computational demands grow rapidly (Ye et al. 2025). A particularly underdeveloped issue is structural misspecification, i.e., errors arising from incorrect or incomplete model structure rather than uncertain parameters (Swallow et al. 2022). Simplified or incorrect representations of key processes, including human behavior, may bias attribution or degrade forecasts, yet the propagation of these errors remains poorly understood.

A related and promising line of research focuses on nonparametric early warning indicators based on critical slowing down, which aim to detect loss of system resilience prior to abrupt increases in disease incidence (Drake et al. 2019). Grounded in dynamical systems theory, these methods leverage changes in statistical properties such as variance and autocorrelation as systems approach critical transitions. Early warning indicators have been applied to infectious disease systems, including malaria resurgence driven by drug resistance and climate change, to identify signatures of changing transmission dynamics before large outbreaks occur (Harris et al. 2020). This approach is particularly relevant in the context of climate change, where gradual shifts in climate drivers or human behavior may push transmission systems toward thresholds without obvious early signals. However, challenges remain in distinguishing genuine early warning signals from noise in noisy, partially observed surveillance data and in extending these methods to multiscale systems with strong exogenous forcing. Integrating early warning indicators with mechanistic and hybrid modeling frameworks represents an important research priority for improving both attribution and prospective risk assessment under climate change (O'Regan and Burton 2018; Brett et al. 2018; O'Dea and Drake 2019).

Purely data-driven approaches, including many machine-learning methods, face complementary limitations. Although they can exploit expanding climate, surveillance, and remote sensing datasets, they are vulnerable to nonstationarity, which undermines assumptions that historical relationships will persist (Cazelles and Hales 2006; Cazelles et al. 2018). They also often exhibit nontransferability across regions, time periods, and sociocultural contexts, and struggle to address counterfactual attribution questions. In addition, human health data are frequently lagged, inconsistently reported, and spatially or temporally aggregated, limiting identifiability of transmission dynamics and introducing biases that data-driven models may amplify rather than resolve. These weaknesses are most acute for long-range forecasting and scenario analysis under climate change.

Addressing these challenges requires a commitment to **convergence science.** As articulated by the National Academies and the National Science Foundation, convergence science goes beyond traditional interdisciplinarity by emphasizing deep integration of theories, methods, data, and problem framing to address societally relevant vexing problems (National Research Council. 2014). A major barrier is the presence of unaligned theoretical ontologies, including differing assumptions about causality, scale, uncertainty, and human agency. For climate change and infectious diseases, steps to overcome this barrier include harmonization of climatic and case data and increased collaborations among climate scientists, clinicians, microbiologists, disease ecologists, and social scientists. Overcoming these gaps is as much

a structural challenge—implicating training, incentives, and funding—as a technical one. Long-term commitment to convergence science for climate change and infectious diseases can allow disparate groups to understand major challenges in the respective fields and what opportunities and limitations exist to meet those challenges, which is important to inform science communication strategies that have critical implications for promoting human health and public trust.

Artificial intelligence has significant potential within this convergence framework, particularly through hybrid mechanistic–data-driven approaches. Methods such as physics-informed neural networks, neural differential equation models, semiparametric models, and machine-learning emulators of mechanistic models can combine scalability with causal structure, enabling assimilation of heterogeneous data while retaining interpretability (Qian et al. 2025; O'Dea and Drake 2022). Key challenges remain, including validation under extrapolation, interpretation of learned representations (especially of human behavior), and robust uncertainty quantification.

Major Recommendations to Improve Climate Associated Infectious Disease Predictions

Climate change is driving new pathogen dynamics and exposing more people to diseases. Disease attribution studies quantify the impacts of climate change and infectious disease on human health and aid in predicting future disease burdens. Additional rigorous attribution studies along with broader surveillance, better diagnostics, longer-term studies, and harmonized data streams all can improve predictive infectious disease models, which inform mitigation, adaptation, and public health preparedness strategies. Realizing the promise of improved predictive models will require sustained investment in research infrastructure and funding mechanisms that support long-term, team-based, and integrative work.

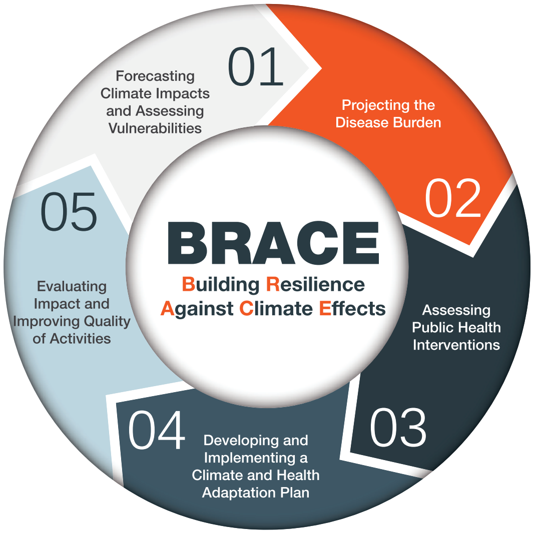
Building Resilient and Rapid Response Systems to a Changing Infectious Disease Landscape

Health systems will need to respond to altered infectious diseases dynamics as the environment and humanity react to climate change. This will be a challenge as global public health systems are under stress from declining government funding, outdated infrastructure, and inadequate workforce retention and recruitment (Kadakia et al. 2021). Workforce training, improved public health infrastructure, sustained funding, strengthened community engagement, and proactive measures informed by attribution studies and forecasting models can help to promote human health and well-being.

Lessons Learned from the Pandemic for Public Health Systems

The COVID-19 pandemic created an enormous shock to health systems worldwide, which aggravated existing health inequalities, strained resources, and frayed already-fragile mechanisms of international cooperation (Traore et al. 2023). Although the collective response helped in bringing about an end to the pandemic, shortcomings were identified that will require urgent attention to strengthen future responses to global health challenges. This included inadequate coordination between national health agencies, overwhelmed acute care facilities, disrupted supply chains, miscommunication and dissemination of disinformation, structural disparities among countries and populations, a fragmented clinical trial apparatus, and public resistance to mandates aiming to control the rate of the spread of infection (Sachs et al. 2022). The increasing politicization of public health recommendations has divided public opinion and led to an overall deterioration of trust in institutions worldwide (Abi-Rizk 2025; Sheldenkar et al. 2025; Perlis et al. 2024). Societal divisions have persisted, and the situation has only worsened in the U.S. starting in 2025 due to reductions in the U.S. federal workforce, politicization of health agencies and vaccine policies, declines in research funding, and attacks on academic institutions (Halabi et al. 2025).

Figure 7. Building Resilience Against Climate Effects framework to prepare for the health effects of climate change. Source: Centers for Disease Control and Prevention. Preparing for the Regional Health Impacts of Climate Change in the United States. 2024.



A public health system must be able to mount rapid and effective responses to health emergencies, including those that are climate related. Preventive measures should include risk assessment and development and continuing support of policies to improve community readiness. The effectiveness of these activities will depend upon communication, community partnerships, and a robust and resilient health care infrastructure. The Building Resilience Against Climate Effects framework provides a useful blueprint for specific actions (Fig. 7) (Marinucci et al. 2014; Centers for Disease Control 2024).

First responders must be prepared for health consequences of more common extreme weather events, which will disproportionately affect populations made vulnerable by poverty, age, occupation, or other factors. Coordinated and rapidly deployable responses to extreme weather events should include personnel with relevant expertise and necessary laboratory support to address infectious threats. Microbiologists and epidemiologists working in the emerging field of **disaster microbiology** can help to identify the distinctive agents that are likely to complicate such events (Smith and Casadevall 2022).

Key Research Priorities and Challenges

Public health systems have learned lessons from the COVID-19 pandemic, but there is still much to do to make these systems more resilient to the impacts of climate change. Improving health systems, expanding workforce training, and expanding disease treatment and prevention strategies that meet the needs of local communities are all necessary.

Trusted Healthcare Networks

Scientists, climate professionals, and health workers will play an essential role in the creation of climate-resilient health systems (Dagneau et al. 2025; WHO 2015). Improving local technical and professional capacity should be a priority. Researchers and practitioners are needed with expertise in a broad range of fields including epidemiological modeling, host-microbial interactions, vector biology, artificial intelligence, and implementation science to come together and collaborate. Workforce capacity in vector and disease surveillance, data management, integrated surveillance, and leadership should be expanded, and workforce training should be provided across different fields in core climate-related competencies (Houghton et al. 2025). Healthcare systems should foster a collaborative ecosystem for transdisciplinary learning, information sharing, and cooperation.

Medical professionals will require new knowledge to recognize and manage an evolving spectrum of emerging and remerging pathogens (Table 2), which will require the development of educational materials to address current gaps and clinical guidelines for the diagnosis and treatment of climate-impacted infectious diseases. Microbiologists and climate scientists can contribute to these educational resources and guidelines as well as learn from their medical colleagues about their most pressing needs, which can help to inform future research priorities.

Public health systems will only be able to respond effectively to climate-related infectious disease threats if they have robust public support and adequate public funding. This will require the restoration of social capital and trust in public institutions, vaccines, and public health, as well as effective messaging and countering of disinformation (Rowland et al. 2022; Richmond et al. 2024; National Academies of Sciences, Engineering, and Medicine 2025b). Scientific organizations and their outreach arms, along with subject-matter experts, can be sources of authoritative, timely, nonpartisan information, particularly during outbreaks or epidemics. Community education and community health workers can play a critical role in outreach efforts and identifying changes in local disease incidence.

Table 2. Examples of Climate-Sensitive Emerging and Reemerging Diseases

Vector-borne Diseases	**Waterborne and Soilborne Diseases**	**Fungal Diseases**
• Dengue Fever • Malaria • Plague • West Nile Virus	• Cholera and noncholera vibriosis • Melioidosis • Salmonellosis • Schistosomiasis	• Candidemia • Cryptococcosis • Valley Fever
How Public Health Systems Are Responding		
The U.S. CDC developed a vector-borne disease (VBD) strategy to address the increase in cases of VBD in the past two decades, such as cases of dengue and West Nile virus (CDC 2024).	The ECDC developed the Vibrio Map Viewer to predict environmental conditions that favor Vibrio proliferation, which accurately anticipated a noncholera vibrios outbreak in Sweden in 2014. Today, similar systems have been deployed in Haiti, Nepal, Yemen, Ukraine, Malawi, and Zimbabwe to warn for cholera outbreaks. (Semenza et al. 2017; Brumfield et al. 2025)	Central California public health agencies developed Valley fever awareness and testing campaigns for at-risk communities to coincide when infection risk is highest (such as after dust storms) (Matlock et al. 2019).

Strengthened Public Health Infrastructure and Data Systems

Research and the implementation of novel interventions will require a substantial investment in new infrastructure. Many public health buildings and hospitals are in need of facility updates and modernization to meet current needs (American Hospital Association). Health systems also need to be strengthened to be more resilient to future changes and emergencies, such as extreme weather events and pandemics (National Academies of Sciences, Engineering, and Medicine 2025a). The COVID experience underscored the need for more resilient diagnostic capacity and health-related supply chains, preferably without cold chain requirements (Hannay et al. 2022; Sherman et al. 2023). Distributed networks may provide greater resiliency over centralized networks, along with the creation of stockpiles of supplies, drugs, and vaccines. Regional centers of excellence can be created for diagnostics, surveillance, genomics, test kits, and vaccine development, manufacturing, and distribution. Investment in research supporting public health, such as at national research laboratories, is needed. Attention must be paid to the equitable distribution of resources, which will require a greater relative investment in LMICs.

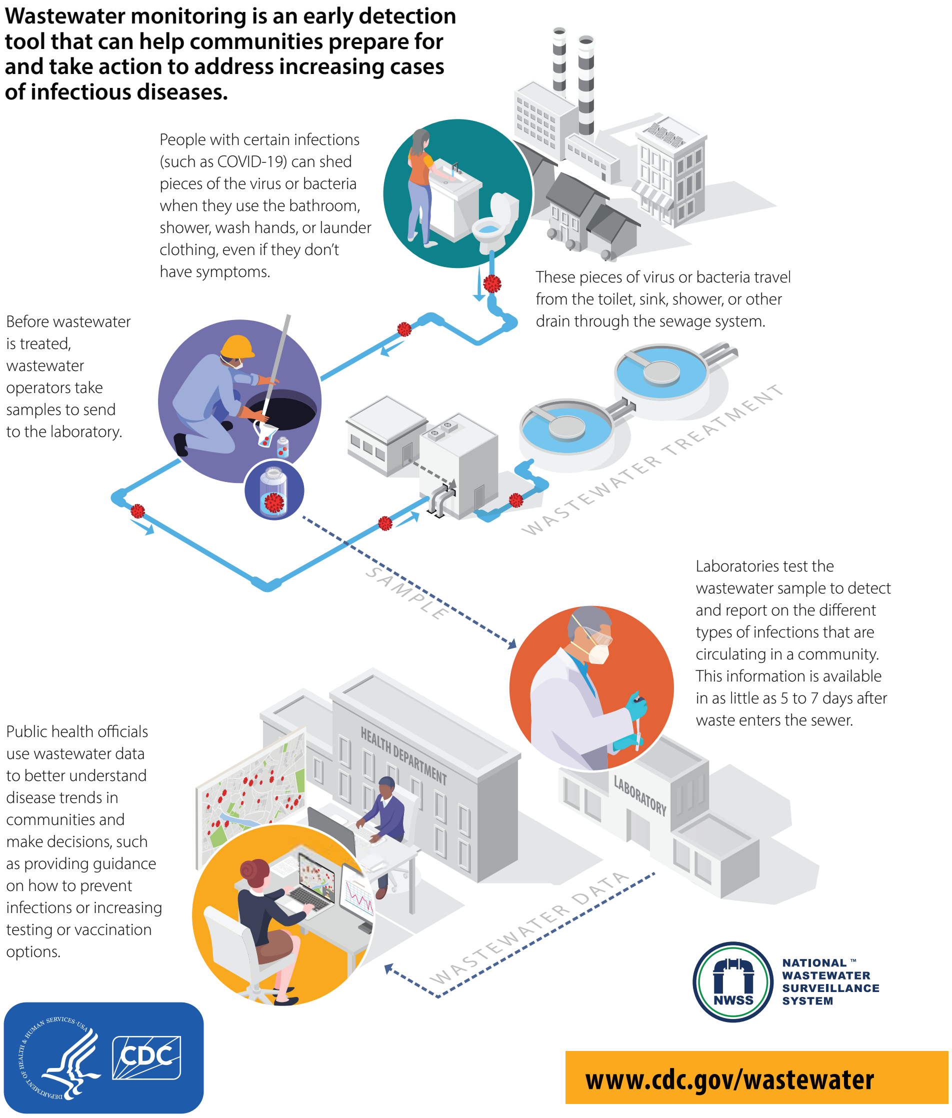
Health systems also need to be strengthened to be more resilient to future changes and emergencies

Access to clean drinking water is a foundational component of public health. One in four globally, about 2 billion people, do not have access to safe drinking water (WHO and UNICEF 2025). More than 3.5 million deaths are attributed to waterborne pathogens annually (Wellcome 2022). Strengthened water, sanitation, and hygiene practices are critical to improving human health, especially as climate change threatens water resources (American Society for Microbiology 2025). Investments in sanitation and water infrastructure are needed. Inexpensive and low-tech options, such as water filters, can be employed in low-resource settings where people are twice as likely to lack access to basic drinking water and sanitation (WHO and UNICEF 2025).

Successful response to climate-sensitive infectious diseases requires integrated data systems that link health surveillance with environmental and climate information in real time (Dasgupta et al. 2025). Massive computer resources are likely to be required to maximally leverage artificial intelligence and data science, including facilities for data storage and sharing. Currently, clinical and environmental data streams remain largely siloed: epidemiological surveillance, meteorological monitoring, and genomic sequencing operate in parallel rather than in concert. This limits the ability to detect climate-driven disease emergence and attribute outbreaks to specific environmental drivers (Dasgupta et al. 2025). Instead, surveillance must drive action.

Effective surveillance systems require explicit attention to attributes including timeliness, data quality, and interoperability (Groseclose and Buckeridge 2017). In the context of climate change and infectious disease data systems, this would require that health and climate data systems use common standards and formats that allow seamless integration across sectors and borders.

Pathogen genomic surveillance has emerged as a critical component of this public health infrastructure, especially wastewater surveillance (Fig. 8) (Sunchatawirul et al. 2026; Leung et al. 2024; Togo et al. 2024). These surveillance systems allow for real-time tracking of infections to inform decisions about public health interventions and support communication with local communities (National Academies of Sciences, Engineering, and Medicine 2023). In addition, genomic data provide high-resolution insight into pathogen evolution, transmission dynamics, and geographic spread, enabling earlier outbreak detection and more precise source attribution (Markov et al. 2023). When integrated with epidemiological and environmental data, genomics allows researchers to link evolutionary change to ecological pressures such as temperature shifts, altered rainfall, and changing vector distributions. The COVID-19 pandemic demonstrated the transformative potential of platforms like the Global Initiative on Sharing All Influenza Data for real-time genome sharing, while also



Wastewater monitoring is an early detection tool that can help communities prepare for and take action to address increasing cases of infectious diseases.

People with certain infections (such as COVID-19) can shed pieces of the virus or bacteria when they use the bathroom, shower, wash hands, or launder clothing, even if they don't have symptoms.

These pieces of virus or bacteria travel from the toilet, sink, shower, or other drain through the sewage system.

Before wastewater is treated, wastewater operators take samples to send to the laboratory.

Laboratories test the wastewater sample to detect and report on the different types of infections that are circulating in a community. This information is available in as little as 5 to 7 days after waste enters the sewer.

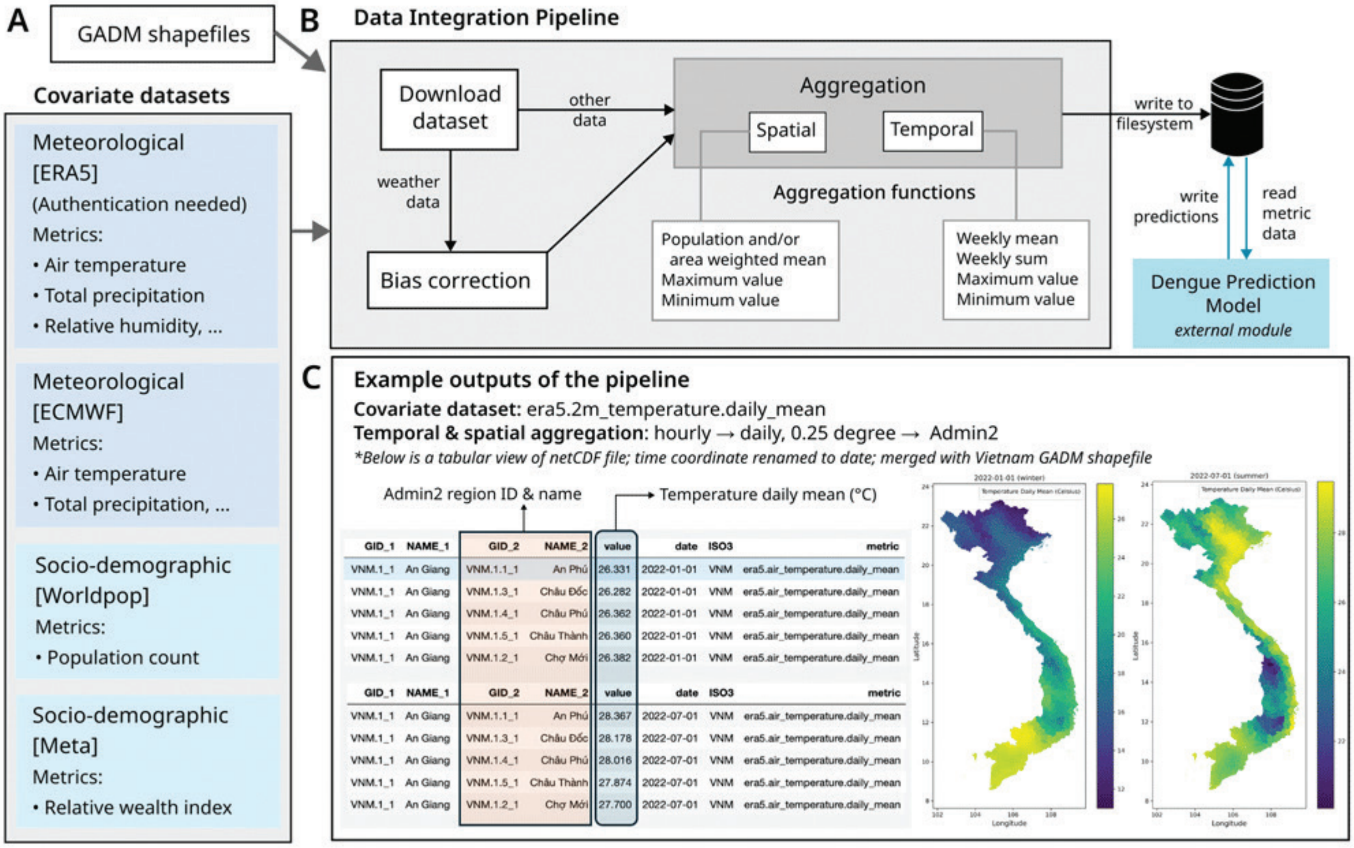
Public health officials use wastewater data to better understand disease trends in communities and make decisions, such as providing guidance on how to prevent infections or increasing testing or vaccination options.

Figure 8. Example of wastewater surveillance system informing public health decisions. Source: CDC.

exposing persistent inequities in sequencing capacity (Markov et al. 2023; Fischer et al. 2025; Brito et al. 2021).

Low- and middle-income countries, often hardest hit by climate-sensitive diseases, face the greatest gaps in data infrastructure. Many lack reliable electricity, internet connectivity, laboratory capacity, and trained personnel to sustain integrated surveillance systems. Historically, this has meant shipping biospecimens and data to institutions in high-income countries for processing and analysis, with intellectual property and publications accruing to external partners rather than local institutions. Equitable partnerships require a different model: building local capacity so that countries can analyze their own data to inform their own public health decisions. This means investing in laboratories, computing infrastructure, and workforce training, as well as respecting data sovereignty. Some countries have legal restrictions on health data export; rather than treating these as obstacles, researchers have developed locally deployable solutions. In Vietnam, where epidemiological data cannot legally leave the country, researchers developed Dengue Advanced Readiness Tools (Fig. 9), an open-source pipeline that integrates climate, socioeconomic, and health data for dengue forecasting entirely within local infrastructure (Dasgupta et al. 2025). At continental scale, the Africa Pathogen Genomics Initiative represents a paradigm shift. Before 2020, only seven African Union member states had next-generation sequencing capacity in public health laboratories, and most sequencing was done in Europe or the U.S. By 2022, thirty-one countries had this capacity, and African-generated SARS-CoV-2 sequences increased from 5,000 to over 120,000 (Africa CDC; Mboowa et al. 2024). Africa CDC is now building a pan-African data sharing platform so that genomic data can be archived

Figure 9. Dengue Advanced Readiness Tools (DART) in Vietnam is an example of an integrated data pipeline for dengue tracking and forecasting. Reference: Dasgupta et al. 2025.



Covariate dataset: era5.2m_temperature.daily_mean

Temporal & spatial aggregation: hourly → daily, 0.25 degree → Admin2

**Below is a tabular view of netCDF file; time coordinate renamed to date; merged with Vietnam GADM shapefile*

GID_1	NAME_1	GID_2	NAME_2	value	date	ISO3	metric
VNM.1_1	An Giang	VNM.1.1_1	An Phú	26.331	2022-01-01	VNM	era5.air_temperature.daily_mean
VNM.1_1	An Giang	VNM.1.3_1	Châu Đốc	26.282	2022-01-01	VNM	era5.air_temperature.daily_mean
VNM.1_1	An Giang	VNM.1.4_1	Châu Phú	26.362	2022-01-01	VNM	era5.air_temperature.daily_mean
VNM.1_1	An Giang	VNM.1.5_1	Châu Thành	26.360	2022-01-01	VNM	era5.air_temperature.daily_mean
VNM.1_1	An Giang	VNM.1.2_1	Chợ Mới	26.382	2022-01-01	VNM	era5.air_temperature.daily_mean

GID_1	NAME_1	GID_2	NAME_2	value	date	ISO3	metric
VNM.1_1	An Giang	VNM.1.1_1	An Phú	28.367	2022-07-01	VNM	era5.air_temperature.daily_mean
VNM.1_1	An Giang	VNM.1.3_1	Châu Đốc	28.178	2022-07-01	VNM	era5.air_temperature.daily_mean
VNM.1_1	An Giang	VNM.1.4_1	Châu Phú	28.016	2022-07-01	VNM	era5.air_temperature.daily_mean
VNM.1_1	An Giang	VNM.1.5_1	Châu Thành	27.874	2022-07-01	VNM	era5.air_temperature.daily_mean
VNM.1_1	An Giang	VNM.1.2_1	Chợ Mới	27.700	2022-07-01	VNM	era5.air_temperature.daily_mean

and analyzed within the continent. Additionally, more data should be obtained from areas such as Africa, the Middle East, and Latin America, which have already experienced substantial climatic shifts.

Several obstacles impede further progress. Fragmented governance and siloed institutions result in ad hoc data exchange rather than sustained integration; coordination across health, environmental, and emergency sectors remains limited. Privacy concerns create legitimate barriers to cross-border data sharing, requiring strong data protection frameworks and potentially privacy-preserving technologies. Countries that share surveillance data also risk punishment for transparency. When South Africa rapidly identified and reported the Omicron variant of SARS-CoV-2 in late 2021, the international response was immediate travel bans and trade disruption, effectively penalizing the genomic surveillance capacity the global community had encouraged (Tegally et al. 2022). This created a powerful disincentive: countries may delay reporting or limit data sharing to avoid economic consequences. Truly integrated global surveillance requires mechanisms that reward rather than punish early detection.

Treatments and Vaccine Development

Increased disease risk will require expanded research and development of novel broad-spectrum treatments and vaccines combined with versatile platforms for rapid development and deployment. These will be especially important for fungal and vector-borne infections where vaccination is absent from the public health toolkit. Vaccines against dengue provide a positive example, with phase III trials showing high efficacy against dengue infection over four years from vaccination (Tricou et al. 2024). In addition, late-stage clinical trials of malaria vaccines are promising (Feehan et al. 2025; European Vaccine Initiative). Continued development and clinical trials for more vaccines against a range of infectious are needed.

Vaccines in general have saved more than 150 million lives over the past 50 years

The COVID-19 pandemic response highlighted the mRNA platform for rapid development and deployment of vaccines. The "plug and play" nature of mRNA vaccines allowed for faster development and production than tradition vaccine platforms. Overall, COVID-19 vaccines are estimated to have saved ~20 million lives, and vaccines in general have saved more than 150 million lives over the past 50 years and prevent about 4 million deaths annually (Shattock et al. 2024). However, the mRNA platform presents challenges. The rapid rollout of the COVID-19 vaccines fostered a high level of vaccine hesitancy and skepticism in some sectors. In addition, modified mRNA vaccines require an extremely cold chain for effective distribution. Not only is the cold chain energy intensive, extreme weather events and temperature increases associated with climate change make it critical to develop more temperature-tolerant vaccines and treatments that can be deployed globally, especially in resource-limited settings. Other vaccine modalities that are more temperature tolerant remain an important component in the arsenal to tackle climate-related emerging infectious diseases.

Development of temperature-tolerant diagnostics, vaccines, antimicrobials, and therapeutics may be more complex for bacterial, fungal, and parasitic infectious agents. There are currently no approved vaccines for fungal infections of humans or other animals, and in the history of vaccine development for parasites, it has been challenging to demonstrate efficacy. It will be important to continue to advance

development of complementary treatment modalities, including antifungal and antiparasitic drugs. Mycologists and parasitologists can share their deep knowledge of the physiology, virulence, and ecology of fungi and parasites to inform new treatments. The ongoing trials of fosmanogepix to protect against fungal infections, including *Candida* species, *Aspergillus* species, and rare molds, could serve as a blueprint for climate-driven fungal disease emergence preparedness (Hodges et al. 2025). Expansion of government-pharmaceutical partnerships could enable other therapeutic developments, such as for novel antibiotics, to enhance global health preparedness for climate-driven infectious threats.

Major Recommendations to Improve Public Health Resilience to Climate Associated Infectious Diseases

Public health systems need to be able to prepare for and rapidly respond to climate associated changes in disease burdens. This will require further research, development, and deployment strategies of therapeutics and vaccines, investments in public health infrastructure and workforce training, and strengthened organizational and governance structures to sustain these efforts. These activities must be continually informed by the growing scientific understanding of disease ecology and etiology as it relates to climate factors as well as the needs of the community to instill public trust.

Infectious Disease and Global Climate Change – Thinking Globally, Acting Locally

Climate Change's Global Impacts on Health

Climate change is a global phenomenon. Actions that take place in one country or region can have worldwide impacts on climate. For example, production of greenhouse gases by developed countries have had disproportionate impacts on the health and prosperity of low- and middle-income countries (Dhakal et al. 2022). While the impacts of climate change differ by infectious agent and geography, no place on the planet will be unaffected. As climate change is not constrained along national or regional borders, global cooperation is necessary to address its negative impacts on human health and well-being. As general prosperity has improved globally, this presents momentum to continue to make health improvements that can abate potential future harm resulting from climate change. .

Case Study: Global Environmental Change Impacts On Influenza

Influenza is a respiratory disease that exhibits a pronounced seasonality due to its sensitivity to ambient conditions outside of an infectious host: the virus survives better in the cold, dry air associated with temperate winter and, to a lesser extent, the very hot, humid conditions of the tropics (Tamerius et al. 2010; Shaman and Kohn 2009; Yuan et al. 2021). Climate change will increase both temperatures and humidity levels, but these effects will not be uniform across the globe (Sun et al. 2019; IPCC 2021). While temperature and humidity will increase broadly, these changes are expected to differ from place to place, and the impact on influenza burden in humans will manifest differently in different places. In addition, migratory birds are the natural reservoir of Type A influenza, and climate change is expected to alter the timing, flyways, food resources, and interspecies interactions of these avian hosts during migration (Tomotani et al. 2018). As a consequence, the likelihood of influenza reassortment events and spillover of novel influenza strains to humans may change, and there may be geographic shifts to where such risk is greatest (Prosser et al. 2023; Tian et al. 2015).

Key Research Priorities and Challenges

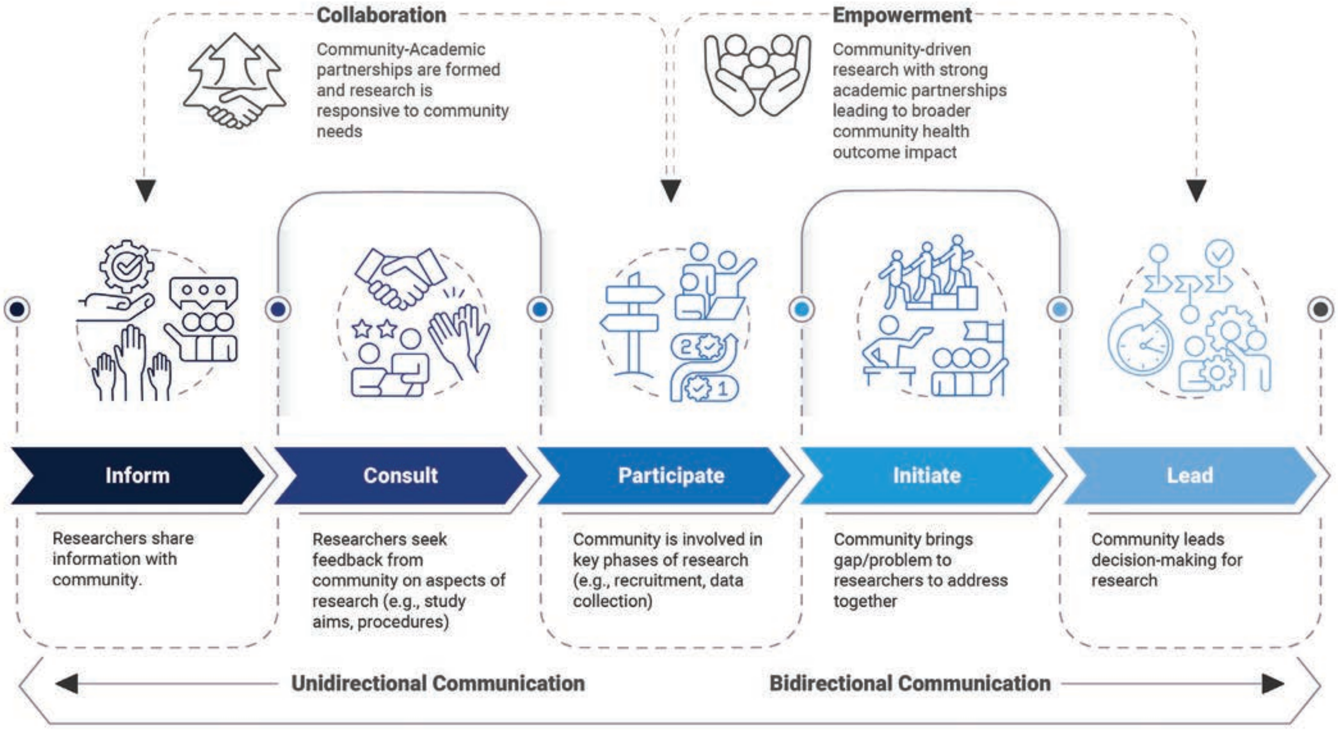
Tackling such an encompassing issue as global climate change is a daunting challenge. However, no one must do it alone—everyone can help. Community initiatives allow local voices to be part of larger conversations that in turn lead to global actions.

Community-led Research Agendas

There are significant historical precedents of community-led initiatives in response to public health emergencies associated with emerging diseases. One of the most prominent examples is the mobilization of civil society around the rights of people living with HIV since the 1980s, whose actions had a substantive impact on the definition of priorities in pharmaceutical research, as well as on the expansion of access to diagnostic and treatment (Ayala et al. 2021). More recently, the COVID-19 pandemic propelled diverse forms of community organization to play a central role in responding to the public health emergency (Alonso et al. 2023; McGowan et al. 2022).

These experiences demonstrate the potential of community-led approaches to influence research agendas, particularly those aimed at responding to public health emergencies and emerging diseases. However, the contemporary context, marked by the intensification of climate change and environmental transformations such as accelerating deforestation, increasing wildfire, and ecosystem degradation across different regions of the globe, poses new challenges and is reshaping research priorities related to emerging infectious diseases. In this context, advancing strategies focused on the anticipation of public health emergencies becomes essential, including the development of active and participatory surveillance systems that incorporate local community engagement and employ innovative mechanisms of knowledge co-production in collaboration with academia (Fig. 10). Regional centers of excellence can be established that link academic institutions with their local communities, engaging in science and public health communication while also being receptive and responsive to the needs of their community (Patz et al. 2004).

Figure 10. Community-engaged research steps and strategies. Source: Penn State Clinical and Translational Science Institute.



With regard to research funding, traditional scientific funding models tend to prioritize well-established lines of inquiry associated with lower methodological risk and greater predictability of outcomes (Gross and Bergstrom 2024). In contrast, research focused on emerging infectious diseases and the surveillance of health threats often involves higher methodological uncertainty and produces outcomes whose relevance may not be immediately observable. In many cases, the success of such research lies precisely in the prevention of adverse events such that its impacts are reflected not in observable crises, but in the absence of emergencies, a result that is paradoxically undervalued within traditional scientific evaluation frameworks.

The funding barriers become even more pronounced in the current context, in which the speed, scale, and interconnectedness of environmental and epidemiological processes demand rapid, integrated, and territorially grounded scientific responses. However, the lack of flexible, long-term funding mechanisms oriented towards community participation limits effective coordination between society, researchers, and decision-makers, including with regard to the threats of climate change (Fine et al. 2025). Compounding this scenario is the contraction of investments in global health research projects, particularly since 2023; this retrenchment has affected initiatives that transcend national boundaries and has undermined both regional efforts and international cooperation aimed at addressing shared global challenges (Schmallenbach et al. 2025).

The scarcity of financial resources also negatively affects science communication and community engagement processes, which are central to the effectiveness of community-led research agendas. The translation of scientific knowledge into accessible formats is critical for sustaining participatory processes, particularly for the in situ collection of environmental, climatic, and socioeconomic data (Albagli and Iwama 2022). Obtaining local data, in addition to engaging communities, is also essential in proposing analyses and policies dedicated to the prevention and control of emerging diseases (Fig. 10).

Strengthening community-led research agendas in the areas of emerging infectious diseases in the context of climate change will require overcoming funding barriers. This will involve developing more inclusive, participatory, and risk-sensitive funding models, as well as continuous investment in scientific communication and community engagement strategies, which are essential for building equitable, effective, and socially legitimate responses to contemporary health challenges.

Climate change and infectious disease are global issues

Global Coordination of Research

Climate change and infectious disease are global issues (Hess et al. 2020). No one country, region, or continent can address them alone. However, building global collaboration is difficult. Countries have differing priorities, resources, and societal issues, presenting a challenge to build unified and coordinated strategies to address climate change and health.

Scientists have successfully developed international research groups, providing a foundation for continued global coordination, but barriers still exist. Journal paywalls can present barriers to research dissemination, with resource-limited research settings most negatively impacted. Pushes for Open Science and Open Access data and journals are aimed to overcome this barrier, but high publication fees can further disadvantage scientists at undersupported institutions or developing countries disproportionally (Matheka et al. 2014). In addition, most scientific research is published in English (Ramírez-Castañeda 2020). This limits who can access the research findings as well as those who can contribute to the scientific dialog, as research published in non-English languages is not as well cited (Di Bitetti and Ferreras 2016). Journals and professional societies can help by welcoming submissions in multiple languages and leveraging AI and subject-matter experts to translate research in languages other than English. Scientists in all fields can work to establish research partnerships with global colleagues to find ways to share data and resources when possible.

Real-time data flows that link meteorological monitoring with disease case reporting will enable rapid detection of climate-disease signals and support timely public health responses. Making data freely available to researchers and public health agencies worldwide, in accordance with open access principles, will accelerate scientific discovery and improve local decision-making. Unfortunately, funding support for integrated data systems is inconsistent and inequitable, and LMIC public health agencies often depend on short-term donor funding that undermines long-term infrastructure development. These challenges have recently intensified (Franz and Bozorgmehr 2025). Significant reductions in support for global health security programs, withdrawal from multilateral coordination mechanisms, and closure of programs that built surveillance and laboratory capacity in vulnerable regions pose immediate threats to infrastructure built over decades, precisely when climate-driven disease pressures are intensifying. Addressing these gaps requires sustained international cooperation and investment: bolstering foundational infrastructure in LMICs, developing governance frameworks for cross-sector data sharing, mandating open standards, and ensuring predictable long-term funding.

Infectious agents do not recognize borders, underscoring the importance of health systems, international cooperation, and strong transnational organizations and agreements in addressing global public health threats (Lee et al. 2019; Lugten et al. 2022). New models of partnerships are needed, including those at the subnational level, such as city networks. Cooperative efforts across disciplines may be encouraged by the creation of international research consortia, academic–public health collaborations, and multidisciplinary training programs. Climate-resilient health systems depend on data integration supported by inclusive partnerships, modern technology, and public commitment to global health security. In addition, climate, microbial, and related environmental sciences should be incorporated into standard global public health training and practice.

Conclusions & Future Directions

Climate change is altering the landscape of infectious diseases. Attribution studies aim to quantify the extent to which recent climate change altered the burden of climate-sensitive health outcomes. These studies are useful to inform public health strategies, encourage adaptation and mitigation actions, and build confidence and trust in scientific findings. However, disease attribution studies that focus specifically on infectious disease burdens are scant, limiting our ability to predict and prepare for future outbreaks. Meanwhile, public health systems must address the current rise of cases of new and reemerging diseases. This leads to a central question of how to manage risk and uncertainty for infectious diseases and climate change.

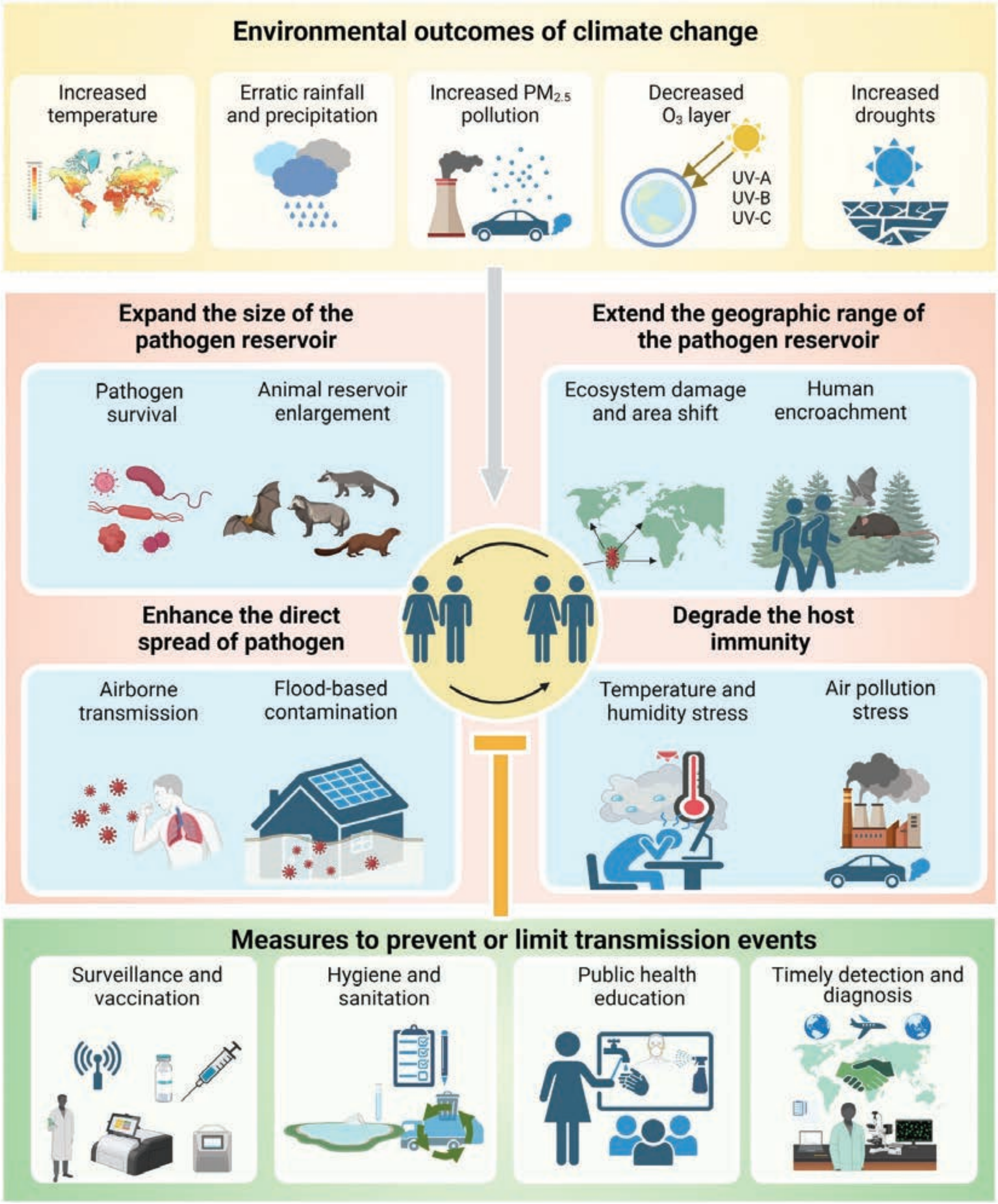


Figure 11. Linkages between climate change and infectious diseases along with potential prevention measures. Source: Liao et al. 2024.

Though usually considered problems as pathogens, microbes were noted by the colloquium participants for their great potential to be a key part of the solution going forward. As disease risks are likely to develop faster than research timelines, the colloquium participants highlighted how microbial data can help bridge the need for more research with rapid public health responses. Future attribution studies can build on the wealth of knowledge on pathogens, vectors, and host-microbe interactions. Microbiologists and climate scientists need to partner to quantify, not only correlate, climate change with disease incidence. In the context of climate and infectious disease modeling, this entails integrating climate science, ecology, epidemiology, evolutionary biology, behavioral science, statistics, computer science, and microbiology within shared frameworks for truly convergent science. Public health systems must build on these models to inform workforce training and preparedness while continuing to provide surveillance and case data that feed into and strengthens future model predictions (Fig. 11).

The colloquium participants outlined major opportunities for strengthening climate change and infectious disease research and prevention systems.

- **Linking Climate Change to Altered Infectious Disease Patterns.** Given the complexity of social, ecological, and health systems, it remains challenging to disentangle the precise effects of climate change on disease dynamics. More attribution studies are needed to clarify how specific climate drivers affect different diseases across regions and populations. Meeting this need, while keeping pace with the accelerating rate of climate change, will require microbiologists to expand surveillance systems, perform mechanistic studies on emergence and reemergence of pathogens, improve diagnostics, establish long-term ecological and epidemiological studies, and provide harmonized data streams for more refined predictive models that can capture interactions between climate, microbes, and human demography and behavior.

- **Responding to Increased Disease Burden.** Climate change can expand the geographic range, seasonality, and burden of pathogens and increase the probability and magnitude of infectious disease outbreaks. Clinical microbiologists and public health workers must support health systems that are prepared to respond rapidly and equitably to these developing threats. Strengthened infrastructure, modernized data systems, and sustained investment in treatments, vaccines, and public engagement will be essential for building trust and resilience in the face of the risks and uncertainties posed by climate change.

- **Working Together – Locally and Globally.** Global coordination and transdisciplinary collaboration will be critical for studying, predicting, and managing climate-sensitive infectious diseases. Community-led research programs, supported by basic science and transnational partnerships, can ensure that global efforts are grounded in local realities. Integrating the rigor of attribution science with the urgency of public health action can protect human health in a changing climate.

Attribution research and preparedness should proceed together; while scientists refine causal estimates, health systems must act proactively through surveillance, training, vaccines, and infrastructure to manage a rapidly changing disease landscape. Together, they can help humanity meet the infectious disease challenges of a changing climate.

Major Recommendations

Climate change is impacting infectious diseases, but there are few direct linkages and limited understanding of the roles that climate variability and change play in temporal and spatial patterns of disease. Health systems must work in a sustained manner to improve understanding of the linkages between climate and infectious diseases to prevent, mitigate, and respond to the long-term health threats posed by emerging infections. Colloquium participants identified multiple areas where further research and development can improve the ability of public health to respond to climate impacts.

Improve Infectious Disease Models and Policies

- Conduct longer-term research studies in more diverse geographic areas for a fuller understanding of the global and local impacts of climate change on different infectious diseases.
- Perform additional infectious disease health attribution studies to build a foundation of knowledge that quantifies and directly links anthropogenic climate change to disease burden.
- Harmonize data streams that integrate environmental, pathogen surveillance, and health data to inform predictive disease models.

Strengthen Public Health Responses

- Invest in public health and data infrastructure that standardizes, tracks, and integrates health, surveillance, and climate data to inform clinical decision-support systems and preparedness policies.
- Develop improved diagnostics, therapeutics, and vaccines for climate-sensitive diseases that are accessible and deployable globally, especially in low-resource settings.
- Update public health workforce development and clinical guidelines with new knowledge about diagnosis and treatment of climate-impacted infectious diseases.

Coordinate Locally and Globally

- Strengthen global health systems and local workforce capacity.
- Build transdisciplinary and global research collaborations and training programs that are rooted in community-led research agendas.
- Establish regional centers of excellence to build stronger integration among researchers, public health systems, and the communities they serve.

Glossary

Climate: average or typical weather over a long period of time (usually at least 30 years) for a specific area (NOAA).

Climate change: a long-term change in Earth's, or a specific region's, climate, which is attributed directly or indirectly to human activity, that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods (UNFCCC).

Climate variability: natural, shorter-term deviations from average climate conditions.

Convergence science: idea that physical and biological sciences can each benefit from being more fully integrated together.

Detection and attribution: area of climate science focused on distinguishing sources of variability in the climate system, including anthropogenic external forcings, natural external forcings, and natural internal variability.

Disaster microbiology: field of study focused on the microbial impacts from severe storms and natural disasters.

Disease attribution: field of study to quantify the contribution of anthropogenic climate change on disease burdens.

Health attribution: field of study to quantify the contribution of anthropogenic climate change to a particular health outcome.

Weather: atmospheric conditions that occur locally over short periods of time.

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