Solving the “small outbreak problem” in climate epidemiology

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Abstract

Climate change can cause outbreaks of infectious diseases in unfamiliar locations — but how do we know which unusual outbreaks are the result of climate change? Scientists often hesitate to guess, leaving the task to journalists or the public. All of these audiences would benefit from a clear and consistent framework for thinking about causality, especially in situations where outbreaks are too small for modeling to provide useful insights. This review provides a guide to different ways that climate change may be involved in an outbreak, with an eye towards the often-overlooked effects of climate change on “source” populations with endemic disease. By considering the full set of possible influences – including everything from pathogen ecology to civil conflict – I suggest that scientists and science communicators can make reasonably robust statements about the evidence for climate change involvement in specific unusual outbreaks.

Summary Box

- Experts should consider climate change as an explanation for small, unusual outbreaks – but should avoid being reductive about causation.
- Considering the full pathogen life cycle – including both ecology and epidemiology – can lead to a fuller view of where climate change is acting on a system.
- Everything comes from somewhere. Climate change impacts on disease-endemic areas can cascade into downstream risks for disease-free populations.

Introduction

In infectious disease epidemiology, climate change impacts are often summarized as “familiar problems in unfamiliar places.” Over the coming decades, many infectious diseases will follow rising temperatures and become established at higher latitudes and elevations; in some cases, such as the incursion of dengue fever into southern Europe, this trend is already visible. In their earlier stages, though, these trends will likely start small, with isolated cases or small clusters of self-limiting (i.e., $R_0 < 1$) transmission following introduction into disease-free populations. Can we reliably identify these “first wave” outbreaks when they happen? Not every “familiar problem in an unfamiliar place” is the direct consequence of climate change, but conversely, it can seem naive not to treat climate change as a potential cause of a climate-sensitive disease outbreak, especially if scientists have already warned that similar events are likely to happen more often.

These are familiar communication challenges for climate scientists. In the early days of the climate crisis, experts usually told journalists that the role of climate change in a specific event (e.g., Hurricane Katrina) was impossible to know, but similar events would become more common or more intense in the near future. These answers were unsatisfying for everyone involved, driving the invention of extreme event attribution [1,2], a set of tools that scientists use to explain the contribution of climate change to specific weather events. Similarly, tools from attribution science are increasingly applied to climate change impacts, including infectious disease dynamics [3]. However, these frameworks make sense of unusual epidemics or shifting endemicity in the context of long-term trends, and so will be of little help for singleton outbreaks.

In the absence of formal attribution, scientific literature on infectious disease outbreaks often hesitates to suggest any connection to climate change. These omissions may, in turn, lead to slower scientific acceptance that observed trends are early climate change impacts. Science journalists are often more willing to make speculative connections, but rely on off-the-cuff input from experts (including both climate scientists and clinicians), which is often contradictory or imprecise. The immediate impact on outbreak containment may be relatively small, but it undoubtedly colors the public’s perception of the lived experience of climate change. As new outbreaks continue to accumulate, this problem becomes more important to solve.

Here, I suggest a simple framework for how both experts and non-experts can navigate the “small outbreak problem.” When climate change is being considered as a contributing factor in small, unusual outbreaks, scientific assessment should fall back on three relatively simple tests: (1) Was transmission in the affected area possible (or a matter of historical fact) before climate change? (2) Has climate change increased the rate of imported cases? And: (3) Has climate change increased the risk that imported cases will lead to secondary cases?

One connected system, several entry points

To the great benefit of public health, pathogens cannot materialize spontaneously, even if the environment has become more favorable to transmission; everything comes from somewhere. Some diseases persist in the environment, or at low levels of endemicity, until circumstances become favorable for human outbreaks. However, in most of the cases that capture public interest – and that defy formal attribution through quantitative modeling, which I focus on here – the disease of interest is new or unusual in the affected region. By definition, these outbreaks are always imported from somewhere else; climate change can therefore be acting in three places: the human population or ecosystem of interest, the source population or reservoir, and the processes of human or animal movement that connect the two (Figure 1).

In a source population, where a pathogen is established, long-term trends in temperature and rainfall [3,4] (or specific extreme weather events [5]) may be increasing the baseline prevalence of the disease, or may be responsible for unusually-large epidemics; both of these can lead to a higher number of imported cases in any connected population. Sometimes, climate change also increases the number of sick travelers by putting people in motion, through both short-term displacement (e.g., due to storms or civil conflict) or long-term changes (i.e., migration). Without data on the epidemiology of the source population, the two may be difficult to distinguish.

Climate change can also increase the odds that imported cases lead to secondary outbreaks in new populations. In very specific cases, the effect of climate change may be like "flipping a switch": for example, climate change may be responsible for the geographic range expansions of newly-present arthropod vectors or reservoir hosts [6,7]. Similarly, rising local temperatures may exceed a biological threshold below which pathogens or vectors cannot efficiently complete their life cycle, allowing sustained transmission (i.e., $R_0 \approx 1$ or $R_0 > 1$) to happen for the first time [8]. In these sorts of circumstances, climate change has made outbreaks *possible* for the first time. In most cases, though, outbreaks are at most more *likely* because of climate change: for example, local climate can directly modify the risk of onward transmission [9], can increase the abundance of mosquito and tick vectors, can extend the possible duration of the transmission season, or can amplify socioeconomic risk factors.

Each of these mechanisms may be acting, independently or in concert, on a specific disease system. Considering each in turn, and attempting to distinguish the evidence for each based on system-specific knowledge, will lead to better overall inferences about climate change. To illustrate this exercise, I provide four examples below. Each outbreak fits the same broad pattern – climate change is expected to increase vector-borne disease in the United States – and has been covered in the popular press as an example of that trend. However, the similarities among these outbreaks are superficial, and a careful examination leads to very different insights about whether and how climate change was responsible for each.

Example 1: Powassan fever in North Dakota, 2011–present

Powassan virus is a rare tick-borne virus endemic to the northeast United States and Canada. Reported cases of the disease have increased sharply in the last decade, and have been reported progressively further south along the Atlantic coast and deeper into the Midwest [10]. Human cases have been reported as far west as North Dakota, with a case report from 2011 [11] and two confirmed cases reported by the CDC in 2017 and 2019.

Genetic evidence suggests that the virus has expanded its range over several decades [12], and most experts agree that the expansion of human cases coincides with the ongoing range expansion of a human-biting vector, the blacklegged tick (*Ixodes scapularis*) [13,14]. That range expansion is generally assumed to be the result of changes in land use, mammal community composition, and – at least partially – rising temperatures in the northern parts of the species' range [15–17]. Most of North Dakota sits at or beyond the edge of favorable climates for this species [18], but as temperatures rise, that may already be changing. Given that human cases of Powassan virus in North Dakota would have been very unlikely or rare before the invasion of the human-biting vector (regardless of maintenance in wildlife), and given that most experts accept at least some role of climate change in the expansion of that vector, climate change should be considered at least a contributor to these outbreaks; further research might even confirm that the vector would not have been able to invade these areas without its influence.

Example 2: Dengue fever in California, 2023

The first known locally-transmitted case of dengue fever in California was reported in Pasadena on October 20, 2023; a second case in Long Beach was reported shortly after, on November 1. Southern California has a baseline climate that would allow mosquitoes to transmit dengue fever during at least part of the year [19], but not necessarily in early winter. *Aedes* mosquitoes also only began their invasion of California in 2011 [20]; climate change may not have been a prerequisite for their establishment, but it has almost certainly accelerated their spread across the West Coast [7], increased the abundance of populations in Los Angeles [21], and thereby substantially increased the local risk of dengue virus establishment [22]. In total, climate change very likely increased the risk of a local transmission event like the 2023 outbreak; it is also possible that local transmission so late in the year would not have been possible in its absence.

Los Angeles is also a major hub for international travel in the United States, and climate change has been implicated in unprecedented dengue fever epidemics nearly worldwide. It seems very likely that this has increased the number of travel-related cases in any non-endemic country, including the United States [23,24]. However, between 2016 and 2023, California Department of Public Health has regularly reported a few dozen imported cases in Los Angeles County, with no clear upward trend [25]; more formal analysis is likely needed to resolve this hypothesis.

Example 3: Zika virus in Florida and Texas, 2016-17

During the Zika virus epidemic in the Americas, a total of 231 locally-transmitted cases of Zika virus infection were confirmed in Florida (220 cases) and Texas (11 cases) [26,27]. These outbreaks were mostly self-limiting, and sustained by large numbers of imported cases, especially from the Caribbean [28]. A handful of cases are still imported each year, but local transmission of Zika virus has not been recorded in the continental United States since 2017.

The most relevant mosquito vector, *Aedes aegypti*, has been endemic in the southeastern United States since its introduction via the trans-Atlantic slave trade; in this part of its range, temperatures are suitable for dengue virus transmission during most or all of the year [19], and sporadic outbreaks of dengue fever are often reported in both Florida and Texas. However, Zika virus has a minimum thermal limit to transmission that is 5 °C higher than dengue virus [29], and temperature appears to have predicted secondary transmission risk, at least in Texas [9]. It is therefore possible that the local risk of transmission in both states was increased by climate change. However, there is a much stronger case that rising temperatures contributed to the intensity of Zika virus outbreaks throughout the Americas [30]. As such, it is more likely than not that climate change was at least a small contributor to outbreaks in the United States, but largely as a symptom of its more dramatic impacts on populations with sustained epidemics.

Example 4: Malaria in the United States, 2023

In summer 2023, seven locally-transmitted cases of malaria were reported in Sarasota County, Florida. A similar outbreak occurred twenty years prior, with eight cases in Palm Beach County; in both cases, an endemic mosquito (*Anopheles quadrimaculatus*) has been presumed to be the main vector [31]. Temperatures across the state are already suitable for malaria transmission year-round [32], and sustained malaria transmission in the past; malaria was not eradicated from the southeast United States until partway through the 20th Century [33]. As such, climate change is unnecessary as an explanatory factor for this outbreak.

What made this outbreak notable was its context: over the same year, Texas, Arkansas, and Maryland all also reported locally-transmitted cases of malaria, an essentially unprecedented coincidence. This collection of small imported outbreaks superficially resembles recent experiences with dengue fever in the United States and Europe. However, unlike dengue fever, malaria is declining in most of the world, due to eradication efforts with an effect several times stronger than any known effects of climate change [3,34]; any net increases are probably localized to small hotspots (e.g., parts of the Andes or east Africa). State-level data on imported malaria cases also do not support the idea that traveler force of infection has recently suddenly increased [35]. A more compelling explanation could be local vector dynamics: if *Anopheles* mosquito populations have recently increased across the southeast United States, areas that have always been able to support malaria transmission could still see a synchronized increase in outbreaks resulting from imported cases. Future research should explore this possibility more.

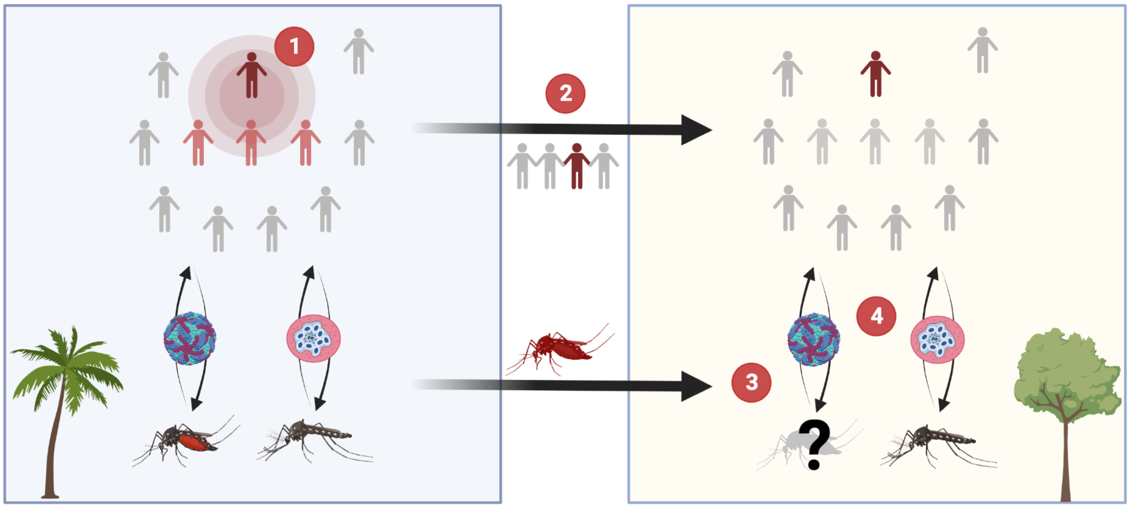
Conclusions

Over the coming decades, the number of small, unusual outbreaks linked to climate change will continue to grow. Experts and communicators should continue to consider the possible role of climate change – and should be ambitious about how they use available evidence, however limited – but should be more systematic and critical than simply fitting outbreaks to a broad profile of “what climate change impacts will look like.” That scrutiny can even lead to new insights about epidemiology and ecology, and inspire directions for future scientific work.

Over time, this exercise may also help shift focus onto new parts of the world. As highlighted by three of the four examples discussed in this piece, “familiar threats in unfamiliar places” is often just a shorthand or euphemism for “neglected tropical diseases in temperate, high-income countries"—a set of very real risks, driven just as much by latitudinal gradients in temperature as latitudinal gradients in the economic legacy of colonialism, that are nevertheless unduly prioritized due to an orientalist view of health, development, and race [36]. Separating these two ideas starts with realizing that the worst impacts of climate change are usually being experienced by the populations where diseases are already endemic. Using the framework discussed here, small outbreaks in the United States and Europe can become a vehicle for storytelling about public health in populations that are much more vulnerable to climate change impacts. But this framework can and should also be applied to other kinds of outbreaks around the world, and doing so might lead to new examples of what a climate-linked outbreak looks like; for example, climate change helped cause the Syrian drought in 2007-10 [37], in turn leading to a civil conflict and migration crisis that introduced new strains of leishmaniasis to Turkey and Lebanon [38]. Cutaneous leishmaniasis in Turkey should be no less compelling than malaria in Maryland: both embody an increasingly unfamiliar landscape of global outbreak risks. Dozens of these examples probably exist; it's time to start finding and telling those stories.

Figure Captions

Figure 1. Small, unusual outbreaks of infectious disease in unexpected populations are an expected hallmark of climate change—but not every outbreak that fits the profile is part of the pattern. Experts should interrogate how climate change acts separately (but cumulatively) on (1) disease incidence in the source population; (2) traveler volume; (3) the introduction, invasion, or other geographic range expansion of animal hosts and vectors, and (4) transmission potential in the population of interest. (Figure prepared using BioRender.)



Acknowledgements

Thanks to Zoya Teirstein and Rebecca Katz for feedback on early drafts, and to Katelyn Jetelina, Sadie Ryan, Rory Gibb, and Daniel Becker for thoughtful conversations about causation, communication, and climate change.

Funding Statement

No funding supported this manuscript.

Competing Interest Statement

I declare no competing interests.

Ethics Approval Statement

No Ethics Approval needed.

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