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The impact of anthropogenic climate change on pediatric viral diseases

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Abstract

The adverse effects of climate change on human health are unfolding in real time. Environmental fragmentation is amplifying spillover of viruses from wildlife to humans. Increasing temperatures are expanding mosquito and tick habitats, introducing vector-borne viruses into immunologically susceptible populations. More frequent flooding is spreading water-borne viral pathogens, while prolonged droughts reduce regional capacity to prevent and respond to disease outbreaks with adequate water, sanitation, and hygiene resources. Worsening air quality and altered transmission seasons due to an increasingly volatile climate may exacerbate the impacts of respiratory viruses. Furthermore, both extreme weather events and long-term climate variation are causing the destruction of health systems and large-scale migrations, reshaping health care delivery in the face of an evolving global burden of viral disease. Because of their immunological immaturity, differences in physiology (e.g., size), dependence on caregivers, and behavioral traits, children are particularly vulnerable to climate change. This investigation into the unique pediatric viral threats

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posed by an increasingly inhospitable world elucidates potential avenues of targeted programming and uncovers future research questions to effect equitable, actionable change.

INTRODUCTION

Climate change—A primer

Climate change refers to the effects of accumulated greenhouse gases (GHGs) in the atmosphere on long-term weather patterns. GHG emissions from anthropogenic fossil fuel consumption over the past 150 years have elevated Earth's mean surface temperature by 1.1 °C in this timespan[1]—a rate of warming unprecedented in the last 50 million years (Fig. 1).[2] Higher mean global temperatures lead to drought, heat waves, and wildfires in dry regions of the world while driving extreme precipitation and flooding in wetter regions. Warming ocean temperatures and melting polar ice caps fuel more severe storms and compromise the habitability of island states such as Tuvalu and Kiribati.[3]

Climate change is also a key driver of resource scarcity, environmental degradation, precarious migration, violent conflict, and disease. Nearly 60% of all known infectious diseases have been aggravated thus far by climate change.[3,4] Here, we specifically explore the impacts of climate change on viral diseases in children, building on a body of literature that explores climate change effects on a range of pathogenic diseases, including malaria and bacterial infections.[5,6] Through a virus-specific lens, we examine the intersections of viral transmission with unequal socio-economic conditions, secondary effects of climate change on healthcare access, and the proliferation of non-viral comorbidities. Climate change may see viruses ranging from dengue fever to Hepatitis A, typically restricted to low and middle-income countries (LMICs), occur more frequently in Europe and North America, posing novel pathogenic threats. However, the heaviest burden of viral disease will disproportionately affect LMICs, who have contributed negligibly to GHG emissions, and have the fewest resources for climate change adaptation.[7,8] The general scientific consensus is that warming temperatures, changes in humidity and precipitation patterns, and more frequent extreme weather events are altering the burden, spread, and severity of myriad viral diseases.

Children and climate change

Nearly 90% of the disease burden of climate change will be felt by children <5 years of age.[9] Children are disproportionately vulnerable to infection, morbidity, and mortality from viral diseases because of their unique physiological, metabolic, and immunological immaturities, as well as their size and behavior.[10,11] Globally, the leading causes of death in children remain largely due to infections: pneumonia, diarrhea, malaria, and pre-term birth complications, often precipitated by viral maternal infections (see Appendix 1 for an illustrative list of clinical syndromes discussed within the paper).[12]

Narrower airways mean that irritation caused by air pollutants may result in more significant airway obstruction in children than in adults, increasing their vulnerability to infections.[13,14] The disease experience of acute respiratory infections is more severe in children, as their underdeveloped accessory respiratory muscles struggle to clear phlegm.[15,16] Children's increased diarrheal mortality risk is also driven by their physiological and metabolic vulnerabilities.[17] Children have increased water losses due to faster respiratory rates and higher metabolic rates and may not be able to rehydrate because they cannot verbally communicate their need to do so.[18-20] A less developed thermoregulatory system and a greater body surface area-to-mass ratio engender higher vulnerability to heat extremes in children.[21-23]

Critical gaps in children's underdeveloped immune systems make the early years of life particularly dangerous. Mothers confer maternal antibodies to fetuses transplacentally, wherein fetuses benefit from maternal immunization and previous exposure to disease. However, vulnerabilities remain for novel diseases that mothers experience over the course of pregnancy, as early IgM antibodies will not cross the placenta.[24-26] Breastmilk provides another route for young infants to receive maternal antibodies and protect against viral disease.[27,28] Nevertheless, infants enter a critical vulnerability period as maternal antibodies from birth and breastfeeding wane, and they lack the adaptive immunity to respond to environmental pathogens.[29-31] Though vaccination can bolster these immunological gaps, some vaccines are reserved for older children who can mount an appropriate immune response.[32-34] Therefore, infants and young children constitute an immunologically naïve population to infectious diseases against which adults have acquired immunity.

Children's behavior often puts them in closer contact with environmental risks. School-aged children spend much of their daily lives in congregate classroom settings, increasing their mean contact rate for respiratory illnesses in poorly ventilated indoor spaces.[35] Per unit of body weight, they consume more drinking water, eat more food, and ingest more soil than adults, all of which are potential water-borne and soil-borne transmission.[36] Young children, owing to crawling habits and their size, are physically closer to the ground, making them especially prone to zoonotic exposures as well as tick bites.[37]

Children are a heterogenous class, and the impact of viral infections may be vary at different ages. For example, mortality rates of H5N1 differ widely by age group: from 1997-2010, case fatality rate (CFR) was 80% for adolescents between 12–17 years old, compared with 27% in children under 5.[38] Climate-related exposure risk similarly fluctuates by age: children under 1 are most affected by heat waves due to their metabolic immaturity and reliance on caregivers, but children aged 5-14 spend more time outside and are therefore exposed to excess heat and disease vectors.[37]

As climate change increases food insecurity worldwide, children will bear the largest brunt of morbidity and mortality.[39] Undernutrition has contributed to 45% of all deaths in children under 5.[40] Acute malnutrition, which affected 45.4 million children in 2020, can lead to dramatic reversals in children's health over a short period of time, while chronic malnutrition, which impacted an additional 149.2 million children in 2020, is associated with poor mental and physical development.[41-43] Undernutrition leads to reduced caloric input and loss of critical micronutrients, weakening children's immune systems and thereby increasing infection severity and duration.[44-46] Concurrently, infections contribute to worsened malnutrition outcomes, as illnesses like recurrent diarrhea disrupt the absorptive capacity of the gastrointestinal tract and require high caloric intake for adequate immune response.[47,48] Maternal undernutrition, low birth weight, and suboptimal breastfeeding are all risk factors for developing childhood malnutrition.[40] This negative causal loop will only accelerate as child food insecurity and pediatric illness incidence increase as a result of climate change.

The vast majority of children and adolescents live in LMICs, where they make up almost 50% of the populations, meaning that the effects of an increasing pediatric viral burden will be felt most acutely in countries with significant resource constraints.[49] Thus, mitigation and adaptation strategies designed to reduce viral transmission must employ an equitable framework, ensuring that solutions are effective in a myriad of socio-political contexts.

VIRAL DISEASE THREATS

Zoonotic (non-arbovirus) diseases

As climate variation causes systemic shifts in animal habitats, wildlife will come into increasing contact with human populations, introducing more potential for zoonotic disease spillover (i.e., animal pathogens which make the evolutionary leap to human hosts). Environmental fragmentation will provoke an estimated 15,000 or more novel viral sharing events by 2070, many of which will involve human hosts in tropical hotspots with high population density.[50] Of similar concern, novel cross-species transmission from animal to animal can lead to the unanticipated selection of different genetic mutations that can increase the transmissibility and pathogenicity of certain viruses, as has been hypothesized in interactions between wild migratory birds and domestic fowl that increase the pandemic potential of H5N1.[51-54]

Bats are expected to drive the majority of novel zoonotic spillover into human populations due to the phylogenic relatedness of human and bat viruses.[55] Fruit bats, the apparent animal reservoir of Ebola virus disease (EVD), are anticipated to expand beyond their current range, as warming temperatures create suitable conditions in new countries in West and Central Africa, leading to a 1.63-fold higher epidemic likelihood over the next 50 years.[56-59] As a likely zoonotic reservoir of several coronavirus (CoV) outbreaks in human populations, including Middle East respiratory syndrome (MERS)[60,61] and SARS-CoV-1,[62] bats will continue to play a large role in future zoonotic outbreaks of CoV as climate change-affected migratory patterns promote genetic mixing between bat populations.[63,64] These epidemiological changes complicate the landscape of our current preventative measures, as unexpected phylogenic and host shifts introduce new channels of infection into human populations.[50,65]

Extreme weather events will drive animals into closer proximity with human populations, increasing interactions and potential spillover events. Climate-driven food shortages cause fruit bats to feed more often in domestic horse paddocks and swine farms, in which horses and pigs become mediating hosts that facilitate spillover into humans, as is the case for increasing Hendra virus spillover events in Australia[66-68] and outbreaks of Nipah virus in Malaysia.[69] Excess rainfall and subsequent crop damage can push rodents into human habitations for shelter and food, causing outbreaks of rodent-borne diseases such as hantavirus cardiopulmonary syndrome in the Southwestern US[70,71] and Lassa fever in West Africa.[72,73]

Due to the high lethality and virulence of certain avian flu strains, their endemic presence in Asia, their increasingly large host reservoir, the climate-driven changes in host migration patterns, and the significant rate of viral mutation, highly pathogenic avian influenza (HPAI) is one of the world's greatest pandemic threats.[74-77] Inadequate identification of emerging pandemic threats can be particularly hazardous when early treatment initiation increases child survival, as is the case of H5N1 avian influenza being commonly mistaken for seasonal flu in children, causing increased fatality rates for each day of delayed treatment.[38,78]

Driven in part by climate-induced contraction of natural resources, the proliferation of high-density, large-scale livestock operations can intensify the speed and spread of infections among animal hosts, while also increasing the rate of genetic mutation.[79-82] There have been numerous examples of livestock as intermediary or amplifying reservoirs for viral pathogens, from pig farms driving the 1998-1999 Malaysian Nipah virus outbreak[83] to the emergence of avian influenza H5N1 and H7N9 in China as a result of the rapidly intensifying poultry sector.[84] A One Health approach is needed to address increasing food insecurity while safely managing agricultural systems to reduce zoonotic spread.[85]

Time spent playing outdoors puts children at a high risk of interacting with wildlife and domestic livestock, as seen in select Nipah outbreaks and the majority of rabies cases, and in the increased potential for future avian flu spillover.[51,86-88] Ultimately, children's behavior, immunological immaturity, and unique physiology put them at greater risk for morbidity and mortality in an increasingly dangerous, climate-mediated future of expanded zoonotic transmission.

Vector-borne diseases

Much research on climate impacts on global infectious disease is centered on vector-borne diseases, i.e. pathologies transmitted between animals via blood-feeding arthropods. Because arthropods are dependent on ambient temperature to maintain homeostasis, the general scientific consensus is that most disease vectors will do better in a warmer world, by becoming more abundant and expanding their range (Fig. 2).[89-93] Ticks and mosquitos, the primary vectors of arthropod-borne viruses (arboviruses), are inhabiting higher latitudes and altitudes, which could expose previously unaffected populations to tick and mosquito-borne diseases.[2,94-99] Warmer temperatures tend to accelerate viral replication rates and enhance vector competence, leading to further viral spread.[89,100-102] Therefore, almost all vector-borne viral diseases will see a larger portion of the globe become suitable for transmission in upcoming decades.[3]

Dengue

Caused by the dengue virus (DENV), dengue is the most common arbovirus, with 400 million cases and 40,000 deaths reported each year.[93,103] Though most children infected with dengue will be asymptomatic or minimally symptomatic, children are more likely than adults to face severe and long-lasting symptoms and die of the virus.[104-106] The primary vector of dengue transmission, the *Aedes aegypti* mosquito, prefers tropical and subtropical urban environments, where breeding habitats and blood meals are abundant.[91,107,108] Over the past half-century, DENV has drastically expanded its range, likely due to globalization, widespread urbanization, and insufficient vector control.[107] In the wake of extreme precipitation and flooding in Pakistan in June 2022, pools of stagnant water and limited potable water created abundant breeding sites and feeding opportunities for mosquitos, driving surges in malaria and dengue.[109,110] Catastrophic flooding also causes widespread malnutrition, outbreaks of gastrointestinal disease, and impediments to accessing medical care, which compromise children's ability to withstand dengue.[110,111] Dengue incidence is skyrocketing in endemic areas such as India[112,113] and Southeast Asia;[114-119] and is projected to reach new regions such as northern China,[120,121] south-central Africa,[91,99,122,123] mountainous regions in south Asia,[121] the Americas,[104,124] and the Mediterranean and Adriatic coasts of Europe.[121,125,126]

Chikungunya

Like dengue, chikungunya (CHIKV) is transmitted by *Aedes*-species mosquitos, which have proliferated globally in recent decades.[124,127,128] In Brazil, a CHIKV variant has been the principal driver of over three million chikungunya cases since the introduction of the virus in 2013.[129,130] In March 2023, neighboring Paraguay experienced an outbreak of over 13,000 chikungunya cases in which over 400 people, mainly children, were hospitalized.[124] Climate change is expected to push chikungunya to higher latitudes in the Americas.[99,128] In the Eastern Hemisphere, chikungunya epidemic potential is predicted to increase in southern and south-central Africa[122,131] and continental Europe.[2,126,128,132,133] Due to globalization and climate change, chikungunya's rapid worldwide spread over the course of two decades is increasingly likely to repeat itself with presently under-explored arboviruses, which have not yet crossed paths with widely distributed mosquito species. If a novel arbovirus is picked up by a ubiquitous mosquito it could quickly become endemic across continents.

Zika

Zika virus (ZIKV) is a flavivirus transmitted by *Aedes*-species mosquitos that can cause severe neurological birth defects via transplacental infection.[134] While most people infected with ZIKV will experience little to no symptoms, the virus can compromise the placental lining in pregnant individuals, subsequently crossing the placenta and damaging fetal brain tissue.[135,136] Particularly during the first and second trimesters of pregnancy, maternal infection can lead to a 5–13% risk of the fetus developing severe brain damage, namely microcephaly.[137-140] Brain damage due to ZIKV infection, labeled Congenital Zika Syndrome (CZS), is difficult to detect prenatally, and 10% of infants born with CZS will die within the first few months of life.[141] Longer warm seasons in tropical and subtropical areas could create ideal conditions for ZIKV spread,[136,142,143] and temperate regions may also become susceptible to seasonal epidemics when summer temperatures reach the 30°C range.[144] Up to 1.3 billion additional people may be exposed to Zika by 2050 under circumstances of unmitigated global warming.[145]

Other mosquito-borne viruses

West Nile Virus (WNV) is the most widely distributed known arbovirus in the world, transmitted primarily by *Culex*-species mosquitos. Historically, major WNV outbreaks have been preceded by heat waves, which will become more frequent in upcoming decades.[109,146,147] Planetary warming is driving WNV endemization across much of Europe, western Asia, Australia, and North America.[2,89,95,101,126,148] Substantive epidemiological evidence exists to support the predicted expansion of Rift Valley Fever Virus (RFVF) to higher altitudes in East-Central Africa[94,106,122] and Ross River Virus (RRV) and Barmah Forest Virus (BFV) in Australia.[149-153] In Latin America, Oropouche (OROV) and Mayaro virus (MAYV) harbor epidemic potential as disease vectors expand their range to encompass immunologically naïve human populations, in which children occupy a particularly vulnerable niche.[154-157] A climate-mediated increase in emerging infectious febrile viruses, like Mayaro virus, may lead to increased antibiotic treatments for novel viruses with low access to diagnostic facilities.[158-160] Antimicrobial resistance is a growing concern of global pediatric health;losing therapeutic options to resistance could bring us back to a pre-antibiotic era when simple infections had fatal consequences.[161]

Tick-borne viruses

Climate change has affected the distribution and behavior of ticks, as well as the viral diseases they carry, through multiple pathways.[162-164] In central and eastern Europe, the *Ixodes ricinus* tick, which carries the tick-borne encephalitis virus (TBEV) has been inhabiting higher altitudes in mountainous regions,[97,165,166] and becoming more plentiful in the areas they currently inhabit.[94,167,168] In conjunction with the expansion of *I. ricinus* due to climate change, the risk of TBEV is increasing as well.[162,167,169-171] This is partially behavioral: ticks spend more time questing—that is, primed to latch onto a host—when temperatures are warmer.[169,170,172] Incidence of Crimean Congo Hemorrhagic Fever (CCHF), transmitted by *Hyalomma*-species ticks, is also associated with temperature, and is predicted to become more prevalent as global mean temperatures increase.[163,172-179] Warmer weather will most likely push humans, particularly children, outdoors more often, increasing their contact with questing ticks in grassy settings.

Vertical Transmission

Preterm birth is the leading cause of neonatal morbidity and mortality, responsible for approximately 900,000 neonatal deaths in 2019, the highest proportion of which were found in LMICs.[12] Increasingly inhospitable climate conditions will affect mothers and neonates alike, as extreme maternal heat exposure has been positively correlated with pre-term birth, low birth weight, and risk of stillbirth.[180] In resource-constrained settings, premature birth is often a death sentence for neonates within the first month of life.[181] Preterm birth has a number of other causes, but maternal infection during the course of pregnancy often plays a significant role.[25,182,183] Maternal influenza and SARS-CoV2 infections, as well as viral hemorrhagic fevers like Lassa, Ebola, Marburg, and Rift Valley fever virus have particularly deleterious effects on premature birth rates and neonatal mortality.[184-187] As these diseases often lead to the death of the mother, there is serious concern for neonatal survival given the loss of primary caregiver.[188]

Of similar concern are the congenital abnormalities that result from vertical transmission through the placental barrier, causing chronic health issues in neonates that last a lifetime, often leading to an early death. Zika, chikungunya, and dengue fever have all been associated with developmental abnormalities and congenital defects, like the much publicized microencephaly in children born to mothers infected with Zika.[134,189-191] Viral in-utero infections, including cytomegalovirus, HIV, herpes simplex virus, are also common causes of neonatal morbidity, mortality, and congenital abnormalities, most significantly affecting neonates in LMICs.[192,193] As climate change increases the spread of viral vector-borne threats and shifts the seasonality of such respiratory diseases as influenza, preventative measures like vaccination for pregnant women will have positive downstream effects on pediatric health.[194,195]

Water-borne and fecal-oral diseases

Climate change is expected to increase overall precipitation across much of the globe, but also augment the likelihood and severity of drought in dry regions such as the American Southwest, Sahel, Eastern Horn of Africa, and much of Australia.[196] The 2022 IPCC report demonstrates high confidence that warming temperatures and heavy precipitation are associated with increased incidence of water-borne diseases. Extreme rainfall can lead to flooding, which can introduce pathogens into the drinking water supply.[197-199] Drought also heightens the risk of water-borne disease, forcing people to turn to alternate unsafe water sources for hydration, share limited existing water resources, which can concentrate pathogens, and compromise hygiene and sanitation practices.[199,200]

There is significant overlap between water-borne and fecal-oral diseases, which are transmitted when fecal material passes into the mouth. Water is the principal medium for ingestion of fecal matter: nearly 25% of the global population is consuming fecally-contaminated water, and this figure is expected to rise as climate disasters continue.[201] Diarrheal diseases, the second-leading cause of death in children under five years of age, are primarily caused by viruses spread via water-borne and fecal-oral routes.[2,197,198,202-205] Associations between temperature and/or rainfall and all-cause diarrhea have been extensively documented across the globe.[199,206-209] Many diarrhea-causing viruses are nameless and do not cause major epidemics, but their cumulative impact on children cannot be understated. Increasingly, scientists are identifying and researching these emerging pathological agents, which tend to fall into the rotavirus, adenovirus, astrovirus, and norovirus families.[201,210-215] For example, *Sapovirus*—a norovirus-adjacent genus in the calicivirus family—is recently being recognized as a leading cause of diarrheal disease, accounting for up to 17% of diarrheal episodes worldwide.[214]

Poliomyelitis

Spread through food-borne, waterborne, and fecal-oral routes, poliomyelitis (polio) predominantly affects children under five years of age;one out of every 200 infections can lead to irreversible paralysis, which can beget respiratory failure and death.[216] Though preventable through vaccination, polio has experienced a resurgence in recent years, and as the WHO notes, “as long as a single child remains infected, children in all countries are at risk of contracting polio.”[217] Worryingly, droughts are known to stymie polio vaccination campaigns.[218] Though the effects of climate change on polio transmission dynamics are not fully understood, polio is considered a climate-vulnerable disease.[219]

Hand-foot-and-mouth

Hand-foot-and-mouth disease (HFMD) is a fecal-oral and contact viral illness that predominantly affects children under five years of age, who are also at highest risk of developing severe symptoms including meningitis, encephalitis, respiratory failure, and cardiac failure.[220] There is robust scientific data supporting the role of climate change, namely warming temperatures and higher relative humidity, in driving the rise in HMFD cases across Pacific Asia, where the virus has become a pressing public health threat.[221-229] The relationship between HMFD infections and temperature are often non-linear, with one to two temperature peaks for optimal transmission, as children spend more time outside in warm weather, yet retreat inside during extreme heat.[220,222,223,227] Additionally, enterovirus survival and infectiousness is enhanced in warmer weather as well as humid conditions, because enteroviruses can attach to airborne water droplets, which subsequently stick to frequently-touched surfaces including children's toys.[220,224,226] Climate change, then, is expected to make more months out of the year conducive to HMFD transmission.[220]

Respiratory diseases

Climate change has a complex influence on the transmission of viral respiratory diseases. The distribution of acute respiratory infections (ARIs) varies by region, but ARIs continue to be one of the most significant causes of hospitalization and mortality among children globally.[230-234] As the global distribution of ARIs is affected by climate change in the coming years, respiratory illness hospitalizations and related mortality will continue to be a pressing pediatric concern worldwide.[235-239]

Humidity and temperature have a significant but inconsistent effect on the regional incidence of viral respiratory infections, as each virus has a different "u-shape" curve of ideal transmission conditions, affected to varying degrees by a constellation of environmental and host factors.[240-251] For example, while warmer winters are associated with fewer infections of influenza A and B, they have been shown to precipitate severe annual influenza seasons with earlier onset in the following year, as there is a larger immunologically susceptible population to attack.[252] Conversely, warmer winters shorten the RSV season, creating a protective effect for an immunologically naïve child population.[237,253] More climate prediction complexity is introduced on a particle level, where higher temperature and humidity are associated with a shorter virus half-life.[254,255] Hotter temperatures and frequent storms could drive people indoors, creating optimal environments for increased circulation of respiratory pathogens in enclosed spaces for more days out of the year.[256-259] In settings of water scarcity, hygiene and sanitation may be curtailed, enhancing the spread of viral pathogens through droplets.[260,261]

Ambient air pollution, a result of fossil fuel combustion through wildfires and human activity, is expected to increase over the coming years.[262,263] Increases in air pollution have been directly linked to increased hospitalization rates of ARIs in children, such as pneumonia.[264-268] Increased time spent indoors, caused by excess heat or precipitation, exposes children to household air pollution from the combustion of solid fuels for cooking and heating indoors.[269-271] Large-scale global and local reductions of fossil fuel emissions are necessary to mitigate these primary and secondary threats to pediatric respiratory health.

SECONDARY CLIMATE-MEDIATED THREATS TO PEDIATRIC BURDEN OF VIRAL DISEASE

Climate-induced migration

Natural disasters, desertification, and rising sea levels are making large swaths of the world uninhabitable, prompting migration that will fundamentally alter the distribution of people across continents.[8,272-274] In 2020, close to 10 million children were displaced in the aftermath of weather-related shocks.[275] Displacement has myriad impacts on viral disease.

The most common viruses in displaced persons camps are diarrheal diseases and respiratory infections, which significantly impact children's health.[276-279] Crowded living conditions are conducive for the rapid outbreak of respiratory illness, such as measles, varicella, influenza, and other acute respiratory infections, and viruses spread through skin-to-skin contact, such as molluscum and human papillomaviruses.[280-283] Isolated outbreaks of poliovirus have been reported in refugee camps, likely due to displacement-related gaps in routine immunization activities and inadequate water, sanitation, and hygiene (WASH) infrastructure.[284,285] Other water-borne pathogens, such as Hepatitis A and E, can spread quickly in resettlement camps with over-crowding and poor sanitation, especially those built in areas vulnerable to persistent flooding during rainy seasons.[286-288] Poorly planned waste management systems increase the amount of refuse, such as water bottles, old tires, and cans, near human dwellings, which creates more breeding grounds for mosquitos and attracts rodents, leading to outbreaks of dengue, West Nile virus, and Lassa fever.[289-291]

As families migrate, it is exceedingly difficult to maintain routine immunization schedules for their children.[292,293] Migration and infectious disease transmission work bidirectionally, wherein migrants are exposed to new pathogens in host communities to which they have no acquired immunity, and diseases also travel with migratory populations, introducing new pathogens into an immunologically naïve host country.[294,295] Chikungunya was likely introduced into Singapore, a population with no natural immunity prior to 2008, as migrant workers moved from the Indian subcontinent in search of work, yet due to their poor living conditions and barriers to healthcare access, migrants themselves were most affected by the local outbreak clusters.[279,296] As migrant populations resettle in new regions, they may transport livestock with them, potentially introducing zoonotic hosts and associated vectors into novel geographic niches, as was the case of increased prevalence of tick-borne CCHF from infected livestock following the relocation of Afghan refugees to Pakistan.[297] Climate change will continue to provoke complex migratory patterns due to natural disasters, long-term environmental shifts, and lost livelihoods, and the interchange of viral pathogens into new susceptible populations will proliferate.[298,299] Migrant-sensitive health systems in host countries are critical to address these vulnerabilities.[300,301]

Compromised health systems and barriers to treatment

Extreme weather events are becoming more frequent due to climate change: many of the strongest storms in recorded history have occurred in the past few years. Tropical cyclone Freddy broke global and regional records across Madagascar, Mozambique, and Malawi.[302] The subsequent mudslides and flooding destroyed over 300 health facilities and disconnected numerous villages from health services, like life-saving antiretroviral treatments.[303-305] Severe weather can also compromise electrification, patient records, and vaccine supplies, all of which exacerbate the burden of viral disease.[306]

While patients face physical barriers to treatment and health centers suffer destruction of medical supplies and infrastructure, storms are likely to result in injuries that make access to care all the more urgent and necessary.[307] This worsens resource constraints and makes it more challenging for individuals with viral illnesses to receive appropriate diagnoses and treatment. In these situations, children are most vulnerable, particularly when their viral illnesses require advanced care: due to the specialized nature of the equipment and personnel required, pediatric emergency and intensive care units are even more susceptible to devastating supply shortages.[308]

CONCLUSION

In a warming world, the mounting threat of viral disease—which must be situated within a broader context of food insecurity, displacement, conflict, and other impacts of climate change—requires sweeping interventions. It mandates that health professionals extend their commitment to human health into the sociopolitical realm, becoming advocates for drastic cutbacks in global GHG emissions. Without these cutbacks, models forecast increases in average global temperatures by 2–5 °C (with localized extremes), which would prove devastating for much of the world's population, particularly for children.[4] Health professionals are on the front lines of this developing crisis;they must recruit their evidence-based understandings of the impacts of climate change on human health to highlight the necessity of political action.[307]

Finally, to protect the well-being of children worldwide, the vast majority of whom reside in LMICs, health professionals must grapple with the dynamics that impoverish these countries in the first place. These are the very dynamics that engineer the disproportionate vulnerability of LMICs to climate change, putting billions of children at risk of viral disease, among a host of other pathologies. For example, high-interest loans disbursed by global financial institutions to LMICs trap these countries in vicious cycles of debt, whereas unconditional economic support to the Global South would allow for the development of climate-resilient infrastructure, robust universal health care, vaccination campaigns, and research to combat infectious pathologies. By pursuing equitable solutions to systemic racism, legacies of colonialism, predatory neo-colonial extraction, and widespread human rights failings, the world can better mitigate the looming health threats posed by climate change.[309]

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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DATA AVAILABILITY

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IMPACT:

- A review of the effects of climate change on viral threats to pediatric health, including zoonotic, vector-borne, water-borne, and respiratory viruses, as well as distal threats related to climate-induced migration and health systems.
- A unique focus on viruses offers a more in-depth look at the effect of climate change on vector competence, viral particle survival, co-morbidities, and host behavior.
- An examination of children as a particularly vulnerable population provokes programming tailored to their unique set of vulnerabilities and encourages reflection on equitable climate adaptation frameworks.

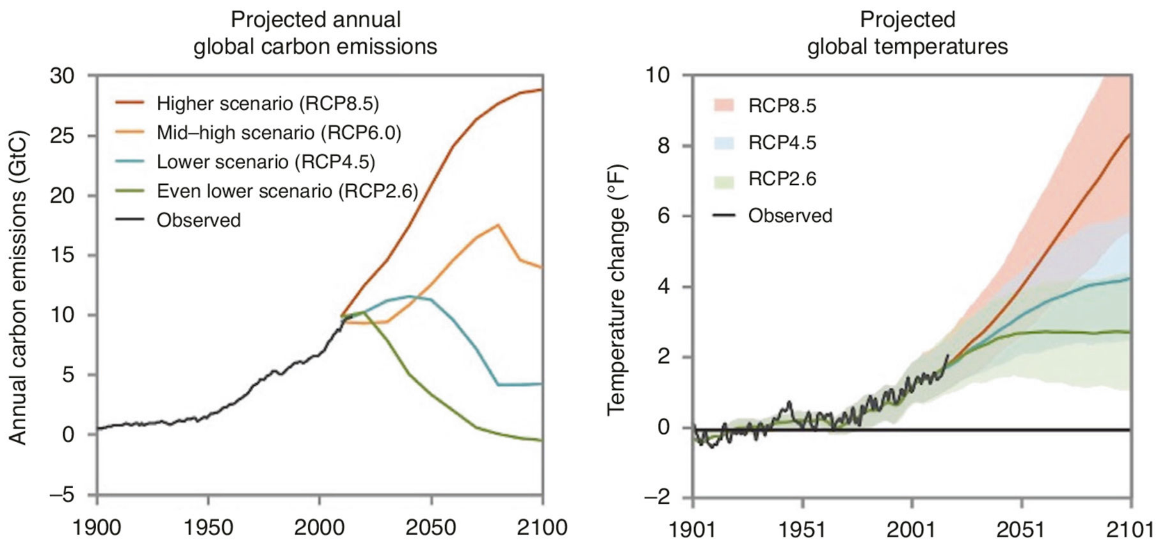

Fig. 1. Projected Emissions and Global Temperatures.

The extent of planetary warming under drastic and minimal carbon emission reduction scenarios. Source: Katharine Hayhoe, 2017.[4]

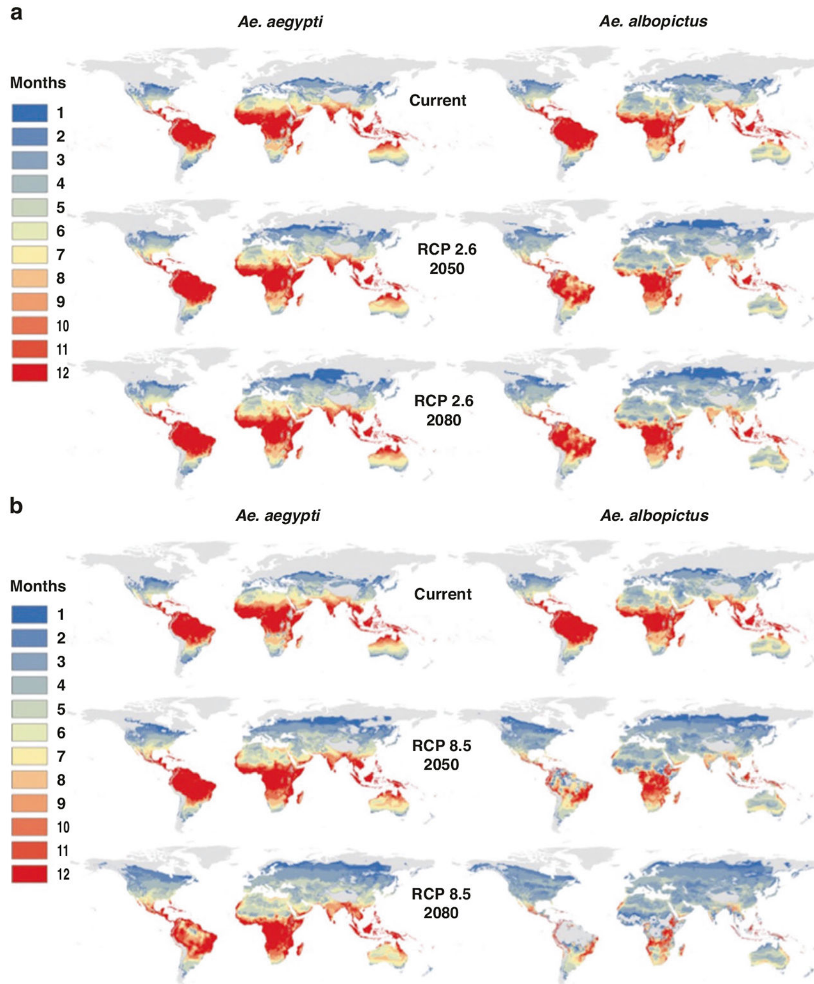

Fig. 2. Projected Range of Aedes species Mosquitos.

Projected expansion of range of *Ae. aegypti* and *Ae. albopictus* under drastic and minimal carbon emission reduction scenarios. Source: Ryan, S.J. et al. 2019.[310]