

Climate change and infectious diseases in pediatric global health

Cambio climático y enfermedades infecciosas en la salud pediátrica global

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Abstract

In recent years, the consequences of climate change on global health have drawn increasing attention. Climate change is known to trigger extreme weather events, alter rainfall patterns, raise ocean/sea levels, and disrupt ecosystems, resulting in devastating effects on human life and the environment. Children, especially those living in low-income countries, are particularly susceptible to climate change-related health risks. This article explores the implications of climate change on pediatric global health, particularly through its impact on infectious diseases. Infectious diseases, notably those transmitted by vectors like mosquitoes, are acutely sensitive to climate fluctuations. Warmer temperatures expand the geographic range of disease-carrying vectors, fostering the transmission and outbreak of diseases such as arboviral diseases (dengue, chikungunya, etc.), malaria, and other vector-borne infections. Climate-induced changes in water availability and food security heighten the risk of diarrheal diseases, disproportionately affecting vulnerable populations like young children. HIV and other viral diseases are also influenced by climate change. As well as in tuberculosis, these diseases are strongly determined by socioeconomical factors; and poverty, poor housing, forced population movement, or health system disruptions driven by climate change exacerbate disease burden and hinder their effective epidemiological control. Moreover, new infectious diseases may emerge from adaptation of microorganisms to higher temperatures. For example, fungal infections pose a significant concern, particularly for immunocompromised children. Addressing the multifaceted challenges of climate change on infectious diseases and child health demands urgent action. Establishing robust disease surveillance systems, implementing public health interventions, and fostering international collaboration are crucial in mitigating the incoming threats.

Keywords: Climate Change, Pediatrics, Infectious diseases, Global Health, Environment and Public Health.

Resumen

En los últimos años, las consecuencias del cambio climático en la salud global han captado una atención creciente. Es conocido que el cambio climático desencadena eventos climáticos extremos, altera los patrones de precipitación, eleva el nivel del mar y altera los ecosistemas, lo que genera efectos devastadores en la vida humana y el medio ambiente. Los niños, sobre todo aquellos que viven en países de baja renta, son particularmente susceptibles a los riesgos para la salud derivados del cambio climático. Este artículo analiza el impacto del cambio climático sobre la salud global pediátrica, concretamente en el campo de las enfermedades infecciosas. Las enfermedades infecciosas, especialmente aquellas transmitidas por vectores, como los mosquitos, son muy sensibles a las fluctuaciones climáticas. Las temperaturas más cálidas amplían el rango geográfico de los vectores portadores de enfermedades, lo que favorece la transmisión y el brote de enfermedades como las arbovirosis (dengue, Chikunguña, etc.), la malaria y otras infecciones transmitidas por vectores. El cambio climático ha provocado problemas en la disponibilidad de agua y la seguridad alimentaria, lo que aumenta el riesgo de enfermedades diarreicas, afectando desproporcionadamente a poblaciones vulnerables como los niños pequeños. El VIH y otras enfermedades virales también están influenciadas por el cambio climático. Al igual que la tuberculosis, estas enfermedades también están condicionadas por factores socioeconómicos,

pobreza, vivienda deficiente, migraciones forzadas o interrupciones en el servicio de salud que pueden exacerbarse por el cambio climático, lo que dificulta su control epidemiológico eficaz. Además, pueden surgir nuevas enfermedades infecciosas debido a la adaptación de microorganismos a temperaturas más altas; por ejemplo, las infecciones fúngicas son una preocupación importante, especialmente para los niños inmunodeprimidos. El cambio climático plantea desafíos complejos para la salud infantil y las enfermedades infecciosas, los cuales requieren una atención urgente. Establecer sistemas robustos de vigilancia de las enfermedades, la implementación de intervenciones de salud pública y el fomento de la colaboración internacional son cruciales para mitigar las amenazas venideras.

Palabras clave: Cambio climático, Pediatría, Enfermedades infecciosas, Salud global, Medio ambiente y salud pública.

Introduction

In the last years, there has been an increasing interest related to the consequences of climate change in global health. Climate change is defined as a statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period - typically decades or longer - that may be attributed to natural internal processes, external forcing, or persistent anthropogenic changes in the composition of the atmosphere or in land use (IPCC, 2001). Largely due to anthropogenic gas emissions, the average surface temperature of the earth has increased by approximately 1.1°C since preindustrial times, which may become 2.5-2.9° at the end of the century despite current international policies. Climate change has demonstrated many effects on human life and environment, including: extreme weather events such as wildfires, droughts, heatwaves; more frequent and intense natural disasters like cyclones, storms, typhoons and hurricanes; changes in rainfall patterns leading to flooding and droughts; rising the ocean/sea levels and disturbing ecosystems eventually causing loss of several species (United Nations Climate Action, 2023).

Predictions show that at the end of the decade, the threat for human health and socioeconomic development will be far greater (Hassan *et al.*, 2023). Particularly, the International Monetary Fund reports that the negative impacts of climate change are concentrated in regions with hot climate and low-income residents (Lombardi *et al.*, 2022), so the poorest countries will suffer the worst disease burden.

According to the World Health Organization, between 2030 and 2050, climate change is expected to cause approximately 250,000 additional deaths per year, mainly attributed to malnutrition, malaria, diarrhea, and heat stress, which disproportionately affect children from low- and middle- income countries (LMICs); the global direct costs to health are estimated to be between USD 2-4 billion/year by 2030 (Dimitrova *et al.*, 2022; World Health Organization, 2021). Nowadays, around 74 excess deaths per 100,000 inhabitants are caused by temperature changes (Zhao *et al.*, 2021). Specifically, more than 88% of the existing burden of disease attributable to climate change occurs in children younger than 5 years, caused by a variety of insults, that range from infectious diseases to mental health (Zhang *et al.*, 2007). Children, infants, and fetuses

are especially vulnerable groups to exposure to warmer temperatures, particularly those socially and economically disadvantaged. These groups are particularly susceptible to the consequences of displacement, physical harm, and psychological trauma as a result of being forced to leave their homes. The immaturity of children's immune system and being dependent for basic care put them, comparatively, at higher risk of diseases. Additionally, chronic diseases such as asthma or mental conditions may affect them during their long life ahead, including their adulthood (Perera *et al.*, 2022). Climate change can impact children health due to both climatic and non-climatic factors. The main threats are heat stress, extreme weather events, worse air quality and higher pollution, reduced food supply and safety, decreased water quality and quantity, altered vector distribution, ecology and biodiversity disturbance, forced migration, and social factors (Aylett-Bullock *et al.*, 2022; Perera *et al.*, 2022). Thus, understanding climate change and its effects in children health becomes a global health priority essential to develop implementation plans and policies to anticipate and mitigate the risks.

Infectious diseases and climate change

Infectious diseases are the paradigmatic example of the multiple factors that can be affected by global warming, and how complex and multifaceted the epidemiological changes can become. Climate change is leading to significant shifts in global weather patterns, causing alterations in temperature, rainfall, and humidity levels. These changes can directly impact the transmission dynamics and geographic distribution of infectious diseases (Perera *et al.*, 2022).

From the vector point of view, rising temperatures can expand the abundance and geographic range of disease-carrying vectors like mosquitoes and ticks, enabling them to survive and thrive in areas where they were previously unable to. From the pathogen perspective, higher temperatures can accelerate the development and replication rates of microorganisms within vectors or hosts, reducing the time required for transmission, leading to more frequent and rapid disease outbreaks (Rocklöv *et al.*, 2020). Additionally, changes in precipitation patterns and increased flooding can contaminate water sources and create conditions towards the proliferation of waterborne diseases like cholera, dysentery, and leptospirosis. Extreme

weather events such as hurricanes and floods can also disrupt sanitation facilities or previously delicate health care systems and displace populations. Moreover, climate change can affect the ecological balance and biodiversity, potentially leading to the emergence of novel pathogens and zoonotic diseases (Casadevall, 2020; Dimitrova *et al.*, 2022).

Mosquito-borne diseases

Mosquito-borne diseases are eminently sensible to climate. A greater geographical spread of malaria, dengue, chikungunya, and zika viruses, among others, is expected with warmer temperatures. Vector abundance, survival, and feeding activity will increase with increasing temperature, as will the rate of development of the pathogen within the vector (Rocklöv *et al.*, 2020). Malaria, for example, has suffered a shift in the altitudinal distribution toward higher altitudes in Ethiopia and Colombia in warmer years (Siraj *et al.*, 2014). As a result, previously naïve populations of children are being exposed to malaria leading to an increase in disease burden and associated mortality. Epidemiological studies in Kenyan children have also confirmed the relationship between malaria transmission peaks and temperature in regions where transmission had been predicted by ecological models (Shah *et al.*, 2019). After severe floods in Uganda, a 30% higher individual risk of malaria was evidenced (Boyce *et al.*, 2016). Better comprehension of these effects is essential to design action plans specific for each region. Modelling approaches can help to identify locations likely to have unusually high or low risk of specific diseases and their relative sensitivity to climate changes (Wang *et al.*, 2015). For example, malaria incidence may vary according to geographic and seasonality patterns as evidence in Malawian children (Chirombo *et al.*, 2020). Under worst-case scenarios, it is predicted that in 2080, between 51-75 million people will be at risk of endemic exposure in Africa. Endemic areas will be created in areas previously unsuitable for malaria transmission in East and Southern Africa, exposing vulnerable populations such as women and children (Ryan *et al.*, 2020).

Dengue is the mosquito-borne viral infection with the highest spread throughout tropical regions over the past 60 years. Currently, half the world's population is at risk. Dengue is expected to have a geographical expansion due to ongoing global phenomena including climate change, urbanization, or domestic water storage (Naish *et al.*, 2014). According to an Intergovernmental Panel on Climate Change 2022 report, dengue risk will increase with longer transmission seasons and a wider geographic distribution in Asia, Europe, Central and South America, and Sub-Saharan Africa (Intergovernmental Panel on Climate, 2023). Predictions show that 2.25 billion more people will be at risk of dengue associated disease in 2080 compared to 2015 (Messina *et al.*, 2019). This includes a greater *Aedes* environmental susceptibility in many areas within the tropical and subtropical zones in South America, Southeast Asia, and Central Africa. For example, Singapore reported a 14% increased dengue incidence attributable to higher

temperatures over the last 40 years (Struchiner *et al.*, 2015). Climate has also shown to increase dengue cases in regions which were previously considered as non-susceptible for outbreaks, as mountainous regions in Nepal and even Kathmandu City (1,300 meters altitude) in recent years (Adhikari *et al.*, 2020). However, the relationships between numerous environmental factors and dengue transmission are complex and sometimes non-linear, and weather phenomena can differentially affect dengue transmission at the local level, producing heterogenous effects (Bhatia *et al.*, 2022). In Latin America, dengue outbreaks are particularly sensitive to El Niño Southern Oscillation (ENSO). The overall effect of severe ENSO events increased dengue incidence in Colombia (Muñoz *et al.*, 2021) and Peru (Dostal *et al.*, 2022). Nevertheless, some regions showed less incidence due to temperature-humidity coupling variations. For instance, Selva Baja region in Peru developed drier conditions after ENSO events that facilitated mosquito displacement to more suitable districts (Dostal *et al.*, 2022). In the Peruvian Amazon, there was a disproportionate higher incidence rate of dengue in children under 5 years old because of 1°C increase in weekly mean temperature (Charette *et al.*, 2020). Based on these data, early warning systems should be optimized according to local weather predictions for implementing public health measures for preventing or mitigating dengue outbreaks.

HIV and other viral diseases

Though the details of the relationship between HIV and climate change are still to be clarified in research and practice, the tougher socioeconomic conditions driven by climate change suggest a higher burden of disease and worse viral control in people living with HIV. For example, in a cross-sectional survey including adolescents over 15 years old during 12 years in 21 countries in Sub-Saharan Africa, heavy rainfall was associated with higher odds of acquiring HIV, sexually transmitted infections, and more sexual partners, mostly affecting women and individuals living in rural and poor areas (Nagata *et al.*, 2022). Other studies also reported that severe droughts were related to lower HIV testing (with the strongest association in adolescents) and higher probability of unprotected sex at their last sexual encounter (Epstein *et al.*, 2023).

Experts have suggested a synergistic relationship with climate change based on a conceptual framework that identifies four main pathways in which climate change may affect HIV epidemic: poorer living conditions, increased food and insecurity, increased prevalence of other infectious diseases, increased human migration, and disruption of public health infrastructure (Lieber *et al.*, 2021). These factors hinder access to diagnosis and treatment of HIV, increase risky behaviors, favor higher transmission, and complicate appropriate assessment of related diseases (Guinto *et al.*, 2022). In Lesotho, severe droughts and related migration were associated with 2-fold higher odds of HIV infection in young people, higher HIV prevalence and early sexual debut, particularly among adolescent females (Low *et al.*, 2019).

Other viral diseases evidenced a clear relationship with climate disturbances. Hand, foot, and mouth disease is an emerging transmittable disease generally caused by a coxsackievirus and mainly affecting young children. After adjustment for seasonality and long-term trend, higher daily mean temperatures, relative humidity, and solar radiation, and moderate rainfall were strongly associated with higher incidence and hospitalization rate in Hong Kong (Wang *et al.*, 2016). This spatiotemporal relationship, especially with a 2-week lag of Hand, foot, and mouth disease related to climatic factors has also been reported in the Ili River Valley Region of China (Yi *et al.*, 2021), Malaysia (Abdul Wahid *et al.*, 2021), or the Mekong Delta Region in Vietnam (Nguyen *et al.*, 2017).

Tuberculosis (TB)

Climate change effects promote factors that exacerbate existing pressures on broader determinants that influence TB epidemics, creating a conducive environment for transmission and more difficult epidemiological control. This is likely to hinder progress and threaten the feasibility of the End TB by 2050 strategy (Maharjan *et al.*, 2021).

Though mycobacteria virulence seems not to be significantly affected by environmental changes (Nerlich *et al.*, 2009), higher temperatures and less humidity conditions can enhance respiratory droplet transmission (Liu *et al.*, 2017), and data reveal a positive association of TB incidence with temperature, precipitation, and wind speed (Huang *et al.*, 2020; Rao *et al.*, 2016). However, TB is a disease strongly influenced by social factors. Poverty, place of residence (urban and rural), poor housing, overcrowding, or working conditions determine TB (Pedrazzoli *et al.*, 2017). Forced displacements, crowded living conditions, and health system inaccessibility intensify transmission and create barriers for appropriate diagnosis and treatment (Maharjan *et al.*, 2021). Moreover, host factors susceptible to the conditions created by climate change such as socio-epidemiological status, immune-compromised conditions, malnutrition, and concurrent diseases are directly linked with TB (Maharjan *et al.*, 2021). For instance, limited access to resources and gender inequalities induced by climate change make women especially vulnerable to TB infection (Eastin, 2018); and climate change has been associated with malnutrition and lower vitamin D levels, which are risk factors for developing active TB (Dini *et al.*, 2012). Few studies specifically address child age regarding this topic. However, in North-Western Ethiopia, pediatric TB incidence was associated with higher temperatures, heavy rainfalls, and internal migrations throughout the years (Alene *et al.*, 2017). And severe droughts were associated with higher mortality rates due to pediatric TB, mainly associated to HIV and malnutrition, in Tete province in Mozambique (Renzaho, 2007).

Some authors argue that the five key factors that link TB and climate change are: HIV infection, diabetes mellitus, undernutrition, overcrowding, and poverty; encouraging international community and multiple actors to adapt policies to reduce the impact of them on TB transmission (Kharwadkar *et al.*, 2022).

Diarrheal diseases and malnutrition

Water and food insecurity induced by climate change are directly involved with a higher rate of diarrheal diseases affecting particularly susceptible populations such as children under 5 years old. Though mortality by diarrhea decreased since 1990's, models predict that with a rise of 1-3° degrees, mortality rates may increase in the context of droughts, malnutrition, and contaminated water sources, exposing children to otherwise preventable bacterial, viral, and parasitic diseases (Hassan *et al.*, 2023; Singh *et al.*, 2021). Indeed, epidemiological studies have shown that the prevalence of *Escherichia coli*, *Cryptosporidium*, rotaviruses, *Giardia*, and *Toxoplasma gondii* increase with higher temperatures across many different climatic zones (Carlton *et al.*, 2016).

In a recent study in Peru, an increase of 1°C in the temperature was associated with a 3.8% higher rate of childhood clinic visits for diarrhea, particularly during intensified ENSO events and during the dry season (Delahoy *et al.*, 2021). Other reports from China, New Zealand, or Cambodia showed an increased rate of hospitalization of waterborne diseases after heavy rainfalls (Davies *et al.*, 2014; Lai *et al.*, 2020; Zhang *et al.*, 2019). In rural Bangladesh, the association between the risk of cholera and heatwaves was examined using conditional logistic regression models, controlling for rainfall and tree cover. The risk of cholera was a 50% higher in 2 days after heatwaves during rainy days, particularly in regions with less dense tree cover (Wu *et al.*, 2018). On the other hand, interventions to improve drinking water, sanitation, and handwashing with soap (WASH measures) on the risk of diarrheal disease in children in LMICs showed to dramatically reduce more than 50% the risk of diarrhea in children (Wolf *et al.*, 2022).

The World Health Organization projects that malnutrition will be the greatest contributor to morbidity and mortality as a result of climate change (World Health Organization, 2014). Without further global actions, by 2050, the risk of malnutrition could rise a 20%, and the diet-related social cost by US\$1.7 trillion per year (World Food Programme, 2021). The highest impact will occur in LMICs, where food availability will be more substantially reduced and more deaths will be attributable to underweight (Springmann *et al.*, 2016). Vulnerable populations such as children under 2 years-old (Lieber *et al.*, 2022) or pregnant women (Bryson *et al.*, 2021) will suffer the worst effects due to their specific nutritional requirements. The main reasons are reduced crop yields and dietary diversity, and disrupted water and sanitation. Climate change-related malnutrition may increase mortality and morbidity in children by malnutrition itself, but also by reducing immunity, increasing the risk of infections, and hindering growth and cognitive development (Agostoni *et al.*, 2023).

Climate change may destabilize the ecosystem by leading to lower crop yields, live-stock production, or fish catch (Agostoni *et al.*, 2023). Droughts, floods, and extreme events cause destruction of rice, wheat, soybean, or maize cereal fields. These events have been directly related to nutritional and developmental status in children in South-East Asia, Sub-Saharan Africa, or Eastern Mediterranean

Region (Al-Jawaldeh *et al.*, 2022). For example, delays in the monsoon season increased the rate of underweight and reduced height in Indonesian children (Thiede *et al.*, 2020), or increased rainfalls and temperatures were associated to moderate stunting and severe wasting in several regions of Ethiopia (Hagos *et al.*, 2014) and Nigeria (Morgan *et al.*, 2020; van der Merwe *et al.*, 2022). A recent meta-analysis from 22 articles in literature showed that drought conditions increased the odds of wasting and underweight by nearly 50% (Lieber *et al.*, 2022).

Additionally, climate change may worsen the nutrient value of foods. Elevated atmospheric CO₂ concentration may deteriorate the quality of certain grain and legumes, reducing protein concentration and increasing the risk of specific micronutrient deficiencies such as iron and zinc (Myers *et al.*, 2014). Moreover, prices of food will increase reducing affordability and accessibility to a safe and nutritious diet (Fanzo *et al.*, 2021). Higher relative prices of nutrient-dense food (such as fresh fruits and vegetables, most animal-sourced foods, eggs and dairy products) have been strongly associated with higher stunting rates (Headey *et al.*, 2019).

The World Food Program alerted about the emergency of facing this problem and proposed several pathways to mitigate the consequences. Some of them include adapting food systems to locally appropriate crops, providing farmers knowledge and tools for improving the yields of agriculture, developing sustainable energy solutions, increasing governmental promotion of climate resilient products, and minimizing food waste (Fanzo *et al.*, 2021; World Food Programme, 2021). Biofortification (developing micronutrient-dense cultivars through crossbreeding or genetic engineering) has been proposed as a low-cost, low carbon footprint strategy to enhance the quality and nutritional value of food. Currently, some programs are implementing different type of cereals, seed, and tubers with higher concentrations of iron, zinc, beta-carotene, or vitamin A (Dwivedi *et al.*, 2023).

The threat of anti-microbial resistance and fungal diseases

Moreover, new infectious diseases may emerge from adaptation of microorganisms to higher temperatures, overcoming human thermal barrier and thus becoming pathogenic (Casadevall, 2020). The relationship between climate change and antimicrobial resistance is a complex interaction involving humans, animals, and environmental activities (Magnano San Lio *et al.*, 2023). Some anti-microbial resistant bacteria, such as carbapenem-resistant *Pseudomonas aeruginosa* and *Klebsiella pneumoniae*, multi-resistant *Escherichia coli*, or methicillin-resistant *Staphylococcus aureus*, show optimal growth conditions at warmer conditions (32-36°) and their incidence increased during warm seasons and year-wise temperature rise (Kaba *et al.*, 2020). Additionally, multi-antibiotic resistant bacteria growth in agricultural activities is enhanced by rising temperatures (Reverter *et al.*, 2020), the reduced diversity associated with climate change affect the

dissemination of multi-resistant clones, and horizontal resistance gene transfer between bacteria is facilitated with higher temperatures (Philipsborn *et al.*, 2016). Overall, it is expected a higher prevalence of multi-resistant bacteria due to climate change with particular risk on major health problems as healthcare associated infections. Though specific information regarding pediatric population is scarce, it is well known that multi-resistance in adults eventually is transmitted to vulnerable children such as immunosuppressed or newborns (Patangia *et al.*, 2022).

However, there is special concern on fungal species, as seen with the global emergence of multi-resistant *Candida auris* (Lockhart *et al.*, 2017) or coccidiomycosis (MMWR, 2013), that have been linked to global warming (Casadevall *et al.*, 2019). Invasive fungal infections represent a serious threat to immunocompromised children, such as malnourished or children living with HIV. Currently, most LMICs are blind folded to fungal infections because diagnosis is challenging and expensive (Bongomin *et al.*, 2017). Additionally, the repertoire of antifungal agents is often restricted in low-income settings due to cost and insufficiently coordinated distribution (Loyse *et al.*, 2013). Developing of better Point-of-Care lateral flow devices, improving automated culture identification methods, and accessible molecular and PCR-based assays are the natural path to improve diagnosis, case management, and acquire better data for estimation of the real burden of disease. In the pipeline, some CRISPR-based techniques are promising for their specific diagnosis and associated resistance-pattern assessment, and may provide portable devices in the near future (Arastehfar *et al.*, 2019).

In summary, climate change is a global threat that can cause emergence of new pathogens or redistribution and spread of existing ones. Children are an especially vulnerable population to suffer its consequences by climatic and non-climatic factors. Infectious diseases are the paradigmatic example of how vector distribution, pathogens, host response, and socioeconomical factors interact with environmental conditions expanding the risk of exposure to diseases such as malaria, dengue, or diarrhea to disease-naïve children. The spread of these diseases to previously unexposed populations can increase their burden of morbidity and mortality. Additionally, climate effects like forced migration, poor living conditions, health system disruptions, and natural disasters may contribute to increase the health-associated inequities, that mostly effects young population.

Conclusion

To mitigate the current and future effects of climate change in pediatric global health, more research providing high quality data and information is needed; it is necessary to build robust disease surveillance systems that allows a better understanding of the local patterns of transmission to anticipate public health measures. Acquiring that information in a timely manner is key for rapid responses to climatic catastrophes, but also for long-term planning more precise policies and intervention programs (from prevention and diagnosis to treatment). This pathway will

require a broad participation of multiple actors including international organizations, communities, and governments with a decisive role of researchers.

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Authors' contributions

DT, RV, and QB conceptualized the review; DT, RV, JD, and JB performed the literature review and the synthesis of evidence; DT drafted the first manuscript; DT, RV, JD, and JB drafted the following versions of the manuscript; DT, JD, JB, RV, and QB critically reviewed the manuscript and approved the final version.

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