The Impact of Climate Change on Child Health

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Human activity has contributed to climate change. The relationship between climate and child health has not been well investigated. This review discusses the role of climate change on child health and suggests 3 ways in which this relationship may manifest. First, environmental changes associated with anthropogenic greenhouse gases can lead to respiratory diseases, sunburn, melanoma, and immunosuppression. Second, climate change may directly cause heat stroke, drowning, gastrointestinal diseases, and psychosocial maldevelopment. Third, ecologic alterations triggered by climate change can increase rates of malnutrition, allergies and exposure to mycotoxins, vector-borne diseases (malaria, dengue, encephalitides, Lyme disease), and emerging infectious diseases. Further climate change is likely, given global industrial and political realities. Proactive and preventive physician action, research focused on the differential effects of climate change on subpopulations including children, and policy advocacy on the individual and federal levels could contain climate change and inform appropriate prevention and response.

KEY WORDS: child health; children; climate change; environment; global warming

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We live in a world in which greater and more frequent environmental extremes are likely.[1–3] Records since 1860 demonstrate global warming (Figure 1).[4] The 1990s was the hottest decade yet recorded, and the United Nations Intergovernmental Panel on Climate Change (IPCC) predicts a 1.4°C to 5.8°C rise by 2100.[4] Already there is glacier retreat, poleward shifts of animals and plants, and more extreme weather events.[5–8] The IPCC posits that most climate change since 1950 is human induced and will have far-reaching environmental and health effects.[5,9–12]

Global warming results from interactions between greenhouse gases, the Earth's atmosphere, and the sun. The main greenhouse gases are carbon dioxide and methane. These, along with nitrogen oxides, sulfur oxides, ozone, and halocarbons, are produced by fuel combustion and agricultural activities.[8,13] To achieve thermal balance, energy reradiated from the Earth must equal energy absorbed from the sun. Greenhouse gases trap energy in the atmosphere, causing global warming. A baseline level of gases is necessary for a habitable environment, but industrial activities have increased concentrations to levels that induce warming. The upper ranges of carbon dioxide and methane are at the highest levels in 420 000 years.[14] Concentrations of CO_2 are now one third higher than preindustrial levels.[4] Methane concentrations are twice those of the preindustrial era, and ground-level ozone levels are unprecedented.[15,16]

Research on climate change has concentrated on its process and sources. The next phase will be impact assessment. A critical area to address will be the differential vulnerability of subpopulations. To date, there has been little research on climate-health relations that directly addresses children; the available data predominantly concern adult or whole populations.

Children may be an especially vulnerable subpopulation because of their developing physiology and anticipated long-term exposure. Internationally, two thirds of all preventable ill health due to the environment occurs in children.[17] In this paper, we review the available research on the health impacts of climate change, analyze its relevance to children, and propose key areas for action.

The potential associations of climate change and child health can be organized under 3 categories (Figure 2):

1) Environmental change: Anthropogenic changes such as air pollution and altered ultraviolet radiation contribute to climate change.
2) Climate change: An altered climate induces thermal extremes and weather disasters.
3) Ecologic change: Climate change causes longer-term ecologic changes that alter food availability, allergy/mycotoxin and disease exposure, and emerging infectious diseases.

ENVIRONMENTAL CHANGE

Air Pollution: Respiratory Problems

As products of fuel combustion, forest fires, and agricultural activities, air pollutants such as ozone, nitrogen oxides, sulfur oxides, and particulate matter have adverse respiratory effects.[18] Worldwide asthma rates have dou-

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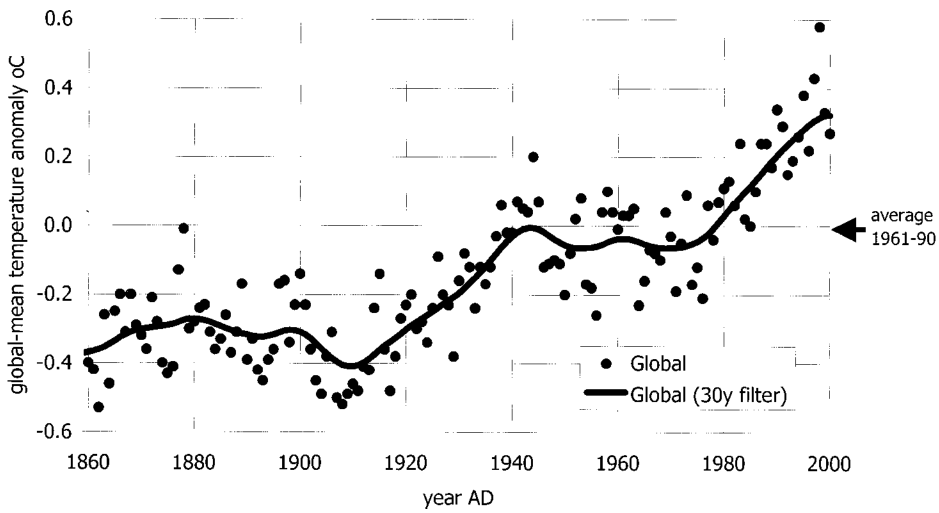

Figure 1. *Observed global average land and sea surface temperatures from 1860 to 2000. Source: Climatic Research Unit, Norwich, United Kingdom.*

bled in the past 15 years, with the greatest rises in children, particularly in African-American populations.[19] Some of this doubling was likely due to increased pollutant concentrations.

Ozone's respiratory effects have been particularly well studied. Cough and asthma are initiated and exacerbated by ozone. Ground-level ozone induces respiratory tract inflammation, reduces lung function, and aggravates chronic respiratory disease.[20] Children exercising in high-ozone environments are 40% more likely to develop asthma,[21] and reductions in ambient ozone concentration are associated with reduced pediatric emergency admissions.[22] Because warming accelerates the reaction that produces ozone, climate change may further increase breathing-zone ozone concentrations.

According to the World Health Organization[17] (WHO), 5 million children die annually from diseases linked to air pollution. Compared with adults, children breathe more rapidly and more often play outdoors, leading to greater exposure to pollutants per unit mass (Figure 3).[23] Their narrower airways result in more tissue exposure per volume inhaled and more inflammation. Further, exercise increases breathing through the mouth rather than the nose, which filters approximately half of pollutants. Polluted air hence goes straight to the lungs, increasing parenchymal damage. Because children's respiratory systems are still developing, this damage can have longer-term impacts. Because children have less self-awareness than adults, they also often do not stop playing when they experience respiratory difficulty.[24]

UV Exposure: Sunburn, Malignant Melanoma, and Immunosuppression

Whereas ground-level ozone is detrimental, stratospheric ozone blocks damaging UV radiation. Solar radiation includes UV rays that cause oxidative damage and immunosuppression. A layer of ozone at an altitude of 15–40 km absorbs and reflects much of the UV radiation. Unfortunately, industrial activity and biomass burning emit halogenated compounds that destroy stratospheric ozone. The ozone layer is consequently thinning, and a seasonal hole has developed over Antarctica. Ozone layer depletion has been observed since 1970 and has caused a 5%–10% seasonal increase in UV exposure at mid to high latitudes. Although ozone depletion is not part of climate change per se, certain gaseous emissions contribute to the causation of both phenomena,[25] and continued fossil fuel emissions are expected to preclude repair of the ozone hole and lead to further thinning.[8,26]

Ozone depletion will lead to greater rates of UV exposure, sunburn, and immunosuppression. Children's skin burns more easily than adult skin. Childhood sunburn significantly increases the risk and accelerates the onset of malignant melanoma later in life.[27] Children sunburned between the ages of 10 and 15 years have a threefold increase in the risk of later developing malignant melanoma.[28,29] Although preliminary data on UV-induced immunosuppression exist, further work is needed to assess its exact impact on child health.[30]

CLIMATE CHANGE

Thermal Extremes: Heat Stroke

Small changes in mean climate trigger large changes in heat wave frequency and severity. The frequency of extremely hot days in temperate zones doubles for every 2°C to 3°C rise in temperature during an average summer.[31] Heat waves cause rash, syncope, cramps, exhaustion, and stroke.[32] Heat stroke is the most serious outcome and results from impaired body thermoregulation. It can lead to fevers above 104°F, tachycardia, mental status changes, and death.[33] Data from US cities show increased death rates during heat waves.[34,35] During the 1995 Chicago heat wave, 514 heat-related deaths occurred in the hottest month, with 485 occurring during the hottest week.[36] Should climate change increase the frequency and intensity of heat waves, rates of death and serious illnesses will rise, particularly in children, the elderly, bedridden, and poor.[37,38] Children are less able to control their local climate, especially if a heat wave is sudden and severe.

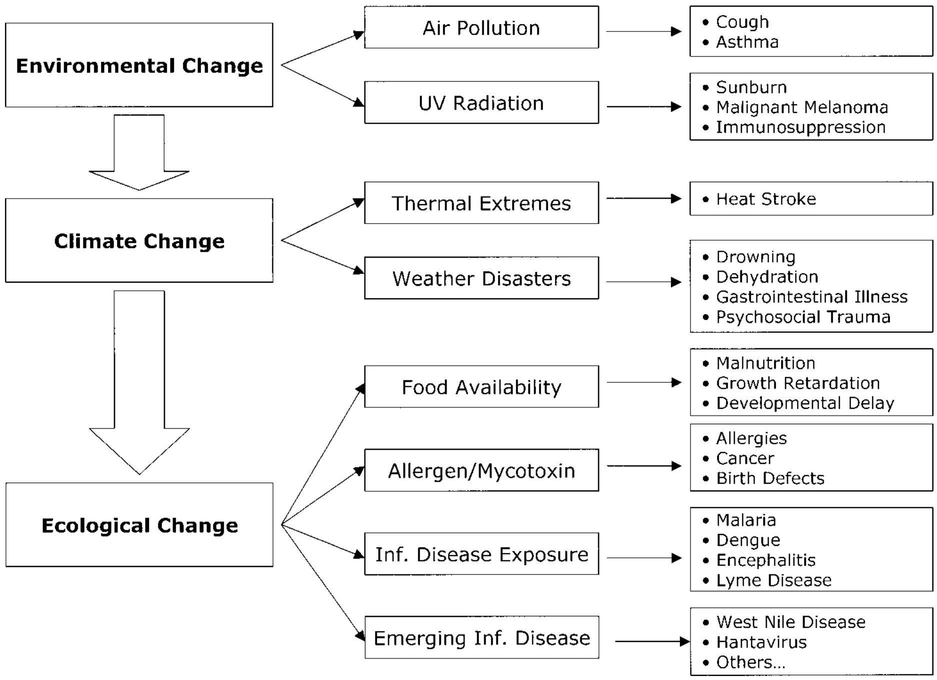

Figure 2. *The relationship between environmental change, climate change, ecologic change, and child health.*

Weather Disasters: Drowning, Dehydration, Gastrointestinal Illness, and Psychological Trauma

Extreme weather events such as heavy precipitation, floods, droughts, and cyclones have increased in frequency, duration, and intensity in some regions over the past century.[5] This trend will continue with climate change.[39,40] In the past decade, climate catastrophes in China, Bangladesh, Europe, Venezuela, Mozambique, and the Caribbean have taken significant tolls.[38]

Global warming accelerates the hydrologic cycle.[41–45] As heat accumulates in the ocean, water evaporates and sea ice melts.[6,7,9] This increases the intensity and frequency of precipitation, leading to more flash floods.[39,46–48] Enhanced evaporation reduces soil moisture elsewhere, inducing longer droughts.[45,49] These extreme climatic processes may undergo positive feedback: a warmer atmosphere holds more water vapor (6% per each 1°C of warming) and better insulates escaping heat, promoting further warming. More evaporation triggers more intense downpours, while warming and parching of the Earth's surface intensifies the pressure gradients that draw in large weather systems, increasing the severity and frequency of further extreme weather events.[40,44,50]

The potential child health impacts of severe weather include drowning, gastrointestinal disease, malnutrition, and psychological trauma. In one model, a 0.5-m increase in sea level by 2100 would double the annual number of people affected by flooding to 92 million.[51,52] Many children would die from drowning.

Floods undermine clean water supplies and spawn gastrointestinal illness. A review of 548 gastrointestinal outbreaks between 1948 and 1994 in the United States showed that 68% of cases were preceded by precipitation above the 80th percentile.[53] Daily hospital admissions for pediatric diarrhea in Peru increased 200% over baseline after the flooding and high temperatures triggered by the 1997–98 El Niño.[54] A total of 30 000 cases of cholera occurred in Honduras after Hurricane Mitch.[55] Morbidity and mortality from *Escherichia coli*, rotavirus, *Cryptosporidium*, *Giardia*, and other water-borne microbes are significant after floods. Mortality is especially high for children; 3 million die each year from waterborne diseases.[17] Children must consume more water per body mass than adults. Greater consumption results in greater exposure to waterborne pathogens. Because children's immune systems are less developed than those of adults, they are less effective in fighting pathogens.[56] Waterborne microbes induce diarrhea and vomiting, which cause children to become dehydrated more quickly than adults.[56] Because children rehydrate less efficiently, they are more likely to die from dehydration. Similarly, children in regions affected by drought experience dehydration.[56,57]

Weather catastrophes destroy homes, prompting refugee camps that harbor infectious diseases. Climate change may also undermine life support systems, including water, forests, and other resources. The resulting social disruption, economic decline, and population displacement will negatively affect the psychosocial development of children, as children are vulnerable to emotional trauma when they experience sudden changes in lifestyle, social networks, or security.

ECOLOGIC ALTERATIONS

Food Availability: Malnutrition, Growth Retardation, and Developmental Delay

Climate change destabilizes agricultural production.[58] Increased evaporation dehydrates soils, and flooding salinates other arable land, diminishing agricultural area and productivity. An estimated 790 million people are presently undernourished in developing countries.[38] Under-

Modality	Mechanism	Increased Exposure
Metabolic	• > Respiratory rate • > Metabolic rate • > Water demand per unit body mass	• Air pollution, allergens • Malnutrition, thermal extremes • Gastrointestinal Diseases, dehydration
Behavioral	• > Outdoor time • > Vigorous activity • < Ability to avoid unhealthy situations • < Swimming capacity	• Infectious diseases, air pollution, UV radiation, thermal extremes, allergens • Weather extremes, UV radiation, thermal extremes • Drowning
Physiology	• > Surface area: volume • < Detoxifying capacity • < Skin development • < Immunity	• Infectious diseases, UV radiation • Air pollution, infectious diseases, thermal extremes • UV radiation • Infectious diseases, allergens/mycotoxins
Time	• > Latency for genetic/long-term effect • > Lifetime exposure time	• UV radiation, malnutrition, allergens
Development	• Undergoing development	• Malnutrition, stunting, psychosocial trauma • Morbidity and quality of life

(> indicates greater, < indicates less)

Figure 3. *Modalities and mechanisms by which children may be more susceptible to climate change than adults.*

nourishment is a well-studied cause of stunted physical and intellectual development and increased disease susceptibility in children.[38,59] Climate change will increase the number of undernourished people in the developing world, particularly in the tropics.[38,60]

Gases that contribute to climate change alter the nutritional content and natural defenses of crops. Carbon dioxide increases plant mass but displaces the nitrogen necessary for protein synthesis, thus reducing protein content.[61] Plants also have a reduced capacity to manufacture nitrogen-based defense compounds, increasing herbivory by as much as 40%.[62]

Herbivores destroy 52% of crops globally, and their distribution is increasing with climate change because they are outpacing their natural hosts and finding new vulnerable crops to destroy.[63,64] Some weeds and exotic species are also spreading because of favorable conditions produced by climate change, further reducing agricultural yields.[60] Climate change may also reduce parasite resistance in livestock.[65]

Forecasts posit that hunger will affect an additional 40 to 300 million people by 2060 due to climate change.[66] Because children require 3 to 4 times more food per unit mass than adults, the majority of this hungry population would be children.[67–69]

Allergies

Exposure and sensitization to pollen cause hay fever, allergenic rhinitis, and allergenic asthma.[70] Aeroallergens also trigger and exacerbate asthma, especially among children.[71–73] Higher atmospheric CO_2 concentrations and warmer temperatures are likely to increase ambient pollen levels.[74–81]

Allergies are associated with increased atopic sensitization. Sensitized individuals are confined indoors during allergy seasons to avoid allergic symptoms. Development of allergies is strongly correlated with allergen exposure in early life.[82] Early atopic sensitization can also lead to asthma. Children therefore have greater susceptibility to and longer-term morbidity from this condition.

The prevalences of hay fever and asthma have increased significantly in recent decades.[72,73] Pollen counts are rising, possibly due to increased CO_2 levels, warmer winters, earlier spring seasons, and/or nitrogen excess.[83] Warming trends in the past 50 years are linked to the amount of pollen released by several European tree species.[84–86] Controlled experiments demonstrate that doubling of the CO_2 concentration increases ragweed production by 61%, with corresponding elevations of pollen dispersal.[83] Climate change could therefore increase the incidence of child allergies and asthma.

Mycotoxins

Warmer temperatures and extreme weather events encourage the growth of mycotoxin-producing fungi, including *Aspergillus*, *Claviceps*, *Stachybotrys*, and *Fusarium* spp. Mycotoxins are implicated in the pathogenesis of cancers, ergotism, and birth defects.[87] Alternating drought and flooding may contribute to mycotoxin production. Drought weakens the seed kernels of plants, allowing greater fungal contamination.[87,88] Flooding causes moist conditions that promote fungal growth. Aflatoxins, produced by *Aspergillus* organisms, are specifically expected to become more prevalent with climate change.[89,90]

Greater Exposure to Infectious Disease: Malaria, Dengue, Encephalitis, and Lyme Disease

Rising temperatures, changing precipitation, and shifting climate variability may alter the distribution of vector-borne infectious diseases.[91–94] Tropical diseases may expand into temperate regions and have longer transmission seasons.[45,95–100] Immunologically naive populations may face novel pathogens.[91] As human settlements move from sparsely settled areas to well-populated areas, vectors will find denser human reservoirs.[45,95,97]

Models suggest that higher global temperatures will enhance the geographic range and transmission rates of vector-borne disease. Greater flooding and precipitation will increase the availability of water breeding sites for mosquitoes.[96–100] Malaria and dengue are the most important vector-borne diseases in the tropics and subtropics, and they rely upon mosquitoes for transmission. Lyme disease, spread by infected ticks, is the most common vector-borne disease in the United States and Europe. An increase in tick- and mosquito-borne encephalitides, prompted by global warming, is a public health concern.[101]

Malaria

Forty percent of the global population lives in areas with malaria.[38] Models of climate change indicate that the exposed population will increase during this century.[38,102–105] Increased temperatures will expand the geographic range of malaria to higher altitudes and latitudes.[93,106–109] Children will be disproportionately affected, as they are more prone to infection and death from the parasite.

Although excessive heat kills mosquitoes, warmer average temperatures within their survival range increase their reproduction, biting, and the rate that pathogens mature within them, including the malaria parasite *Plasmodium*. Warm nights and winters in particular favor insect maturation and survival. This is the specific warming pattern that climate change induces.[48]

The most potent malaria species, *Plasmodium falciparum* and *Plasmodium vivax*, require temperatures of 18°C and 15°C for development, respectively. At least 20°C is needed to initiate a malaria epidemic.[110] The IPCC's predicted 1.4°C to 5.8°C increase in global temperature would increase the proportion of land areas experiencing temperatures of 20°C or higher. At 20°C *P falciparum* takes 26 days to incubate, but it develops in half that time at 25°C. Warmer temperatures will permit *P falciparum* to mature faster and increase its epidemiological outcome.[49]

Global warming may have already exacerbated malaria in areas where *Plasmodium* transmission is limited by low temperatures. Outbreaks of locally transmitted malaria have occurred during temperature rises in Texas, Georgia, Florida, New Jersey, New York, Toronto,[55,108,111] Pakistan,[112] Zimbabwe,[113] the African highlands,[110,114] Rwanda,[93] and Colombia.[115] Malaria has returned to South Korea, the former Soviet Union, and South Africa in association with rising temperatures and changing precipitation.[108]

Of all ages, malaria primarily kills children between 3 months and 5 years of age because they have little specific immunity. They experience yearly attacks of debilitating, potentially fatal disease. Children are also more susceptible to secondary hypoglycemia and cerebral malaria, which can lead to mortality and neurologic sequelae.[116]

Dengue Fever

Mosquitoes also transmit dengue viruses. Like malaria, these viruses have accelerated transmission when their incubation is shortened: a 5-day shortening leads to threefold higher transmission rates.[30] The highly urbanized *Aedes aegypti* is the principal vector. Most dengue affects older children and adults, although children are more likely to manifest overt disease and experience more severe symptoms.[117]

Dengue in urban areas can affect up to 70%–80% of the population. Dengue is currently endemic to tropical Asia, the South Pacific Islands, northern Australia, tropical Africa, the Caribbean, and Central and South America. Increases in its geographic range are expected with global warming, reflecting expanded mosquito habitat range.[118] Already, during a 1988 heat wave in Mexico, *A aegypti* carried dengue fever from 1000 to 1700 m altitude. Dengue fever clusters were associated with extensive flooding and heat along the Colombian coast in August 1995.[119] If climate trends continue, the number and geographic distribution of children affected by dengue will increase.

Encephalitis and Lyme Disease

Climate variability will increase the incidence and geographic distribution of insect-borne encephalitis and Lyme disease. Children are particularly susceptible to mosquito and tick bites because they play outside and are closer to the ground, where these vectors gather. Incidences are highest among children 5 to 10 years of age, twice the incidence among older children and adults.[120]

Because warm winters facilitate the overwintering of ticks, global warming will accelerate the poleward migration of tick-borne encephalitis and Lyme disease.[102] A decade of milder winters and earlier springs in Sweden has been linked to significant increases in rates of tick-borne encephalitis.[121] Replication of the organisms responsible for mosquito-borne encephalitis depends on ambient temperatures exceeding 17°C. Above this threshold, the time from infection to transmission decreases linearly with temperature.[122] A 3°C to 5°C increase in mean monthly ambient temperature in California has been associated with a doubling of the length of the transmission season.[122] The rate of encephalitides is also associated with heavy rain, which would be more frequent with climate change. Mortality rates for the mosquito-borne encephalitides vary from 2% to 75%. Although recovery is usually complete for adults, serious neurologic sequelae have been reported at a prevalence of 30% in infants.[123]

Emerging Infectious Diseases

Thirty new diseases have emerged since the mid 1970s.[124] Old infectious diseases are resurging and appearing in new areas. It is probable that new diseases will emerge in response to climate change.

We have seen significant new infectious diseases in the past decade. Hantavirus pulmonary syndrome appeared suddenly in southwestern United States in 1993. The virus was rodent-borne, carried by the *Peromyscus maniculatus* mouse, whose populations had increased 10-fold after a sequence of extreme weather conditions: years of drought had reduced predators, and heavy winter rains had encouraged growth of food sources.[92] In 1999, West Nile virus emerged for the first time in North America. Its emergence is attributed to warm winters, spring droughts, and stagnant water in the summer. Although most cases involve febrile illnesses, neurologic symptoms, and death among adults, encephalitis has been seen in children.[125–127]

Further temperatures rises, droughts, and heavy rains are anticipated with climate change, and the hantavirus and West Nile virus outbreaks have shown us that new diseases do emerge from ecologic transitions. Their potential differential effects on children remain to be seen.

FUTURE WORK: RESEARCH, PEDIATRICIAN ACTION, AND POLICY CHANGE

The impact of climate change on child health covers a vast spectrum. This review has been limited by a lack of empiric data on the specific effects of climate change on children. To better understand what risks children will face, we need further research, pediatrician action, and policy change.

We need more data on how temperature elevations, weather changes, and ecologic alterations affect the health of age-adjusted populations. Only by delineating affected subpopulations can we accurately assess the differential effects that climate change has on children. This may prompt distinct preventive measures and policy. Ideally, the next phase of research would also focus on subpopulations defined by region, socioeconomic status, and ethnicity. The time to initiate this research is now, as the rate of climate change may be accelerating.[128]

Given our current state of knowledge, pediatricians have an active role to play. A pediatrician should thoroughly understand presentations of illnesses associated with climate change, especially those likely to occur in the immediate term:

1) Asthma. Advise parents to learn about local air quality and to appropriately regulate their child's outdoor activities.
2) Sunburn. Encourage the use of sunblock and protective wear, and discourage midday outdoor activity.
3) Heat stroke. Know how to treat acute heat stroke. Educate parents about appropriate outdoor play and hydration during hot weather.
4) Diarrhea. Provide advice about home management of diarrhea and dehydration, and symptoms that should prompt hospital admission.
5) Allergies. Recognize different presentations and educate families about palliative measures.
6) Malaria, dengue, encephalitis, and Lyme disease. Remain abreast of the signs, symptoms, and management of these illnesses, even if they currently have low incidences. Encourage parents to drain stagnant water, use screens, and dress their children in protective clothing.
7) Emergent diseases. Keep diagnostic possibilities open. Ask appropriate questions about a child's activity and exposures. Consult colleagues with unusual presentations. Report cases to health authorities.

Fully protecting children from the impacts of climate change would require cessation of global environmental change. According to the IPCC, a 60%–70% worldwide reduction in greenhouse gas emissions is necessary to stabilize atmospheric concentrations of greenhouse gases and limit damage to the ecologic and other biophysical systems. This would return emissions to 1920 levels,[129] unlikely given today's global emphasis on productivity. Many nations manifest reluctance, as evidenced by struggles to pass the Kyoto Protocol, an agreement to coordinate international reductions in gas emissions. Even so, any progress toward averting climate change is a step toward health risk reduction, and a step worth taking.

Voting for clean energy resolutions and environmentally aware politicians, reducing energy consumption inside homes and offices and by cars, and recycling are steps that the individual can take. Communities can initiate recycling programs and environmental education campaigns, especially for children. Federal policy should favor economic incentives to lower levels of greenhouse gases, such as emissions trading systems and clean technology subsidies. A national system for climate monitoring and response may merit investment. Even if these measures may seem unprofitable initially, their long-term economic, technologic, environmental, and epidemiologic benefits should not be underestimated. Via voter awareness and advocacy, politicians should be held accountable to their environmental campaign promises, and political action toward international commitments should be applauded.

Through individual, community, and national policy changes, the rate of climate change can be slowed. Further research will elucidate the potential effects of climate change on vulnerable subpopulations, so that we may prepare prevention and care. The physician has a major role as the primary purveyor of health care and health education. This role is even more important for the pediatrician, who cares for an especially vulnerable subpopulation. The committed pediatrician could even play a powerful advocacy role, using his/her understanding of children and health to push for environmental policy change. Combined, these measures in research, policy, and physician actions could contain climate change so that these reviewed impacts on child health could become an estimate of the distant future.

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