Climate Change and Children's Health and Well-Being in the United States

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EPA United States Environmental Protection Agency

Front Matter

ACKNOWLEDGEMENTS

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PEER REVIEW

The methods of the climate change impacts analyses described herein have been peer reviewed in the scientific literature. In addition, this report was peer reviewed by four external and independent experts in a process independently coordinated by Eastern Research Group, Inc. EPA gratefully acknowledges the following peer reviewers for their useful comments and suggestions: Samantha W. Ahdoot, Rupa Basu, Timothy W. Collins, and Kari C. Nadeau. The information and views expressed in this report do not necessarily represent those of the peer reviewers, who also bear no responsibility for any remaining errors or omissions. Appendix G provides more information about the peer review.

RECOMMENDED CITATION

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DATA AVAILABILITY

Data generated from the analyses of this report can be accessed on the following website: http://www.epa.gov/cira/climate-change-and-childrens-health-and-well-being-united-states-report

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Appendices

Appendices with additional analytic details, information on data sources, and supplemental results are provided online at http://www.epa.gov/cira/climate-change-and-childrens-health-and-well-being-united-states-report

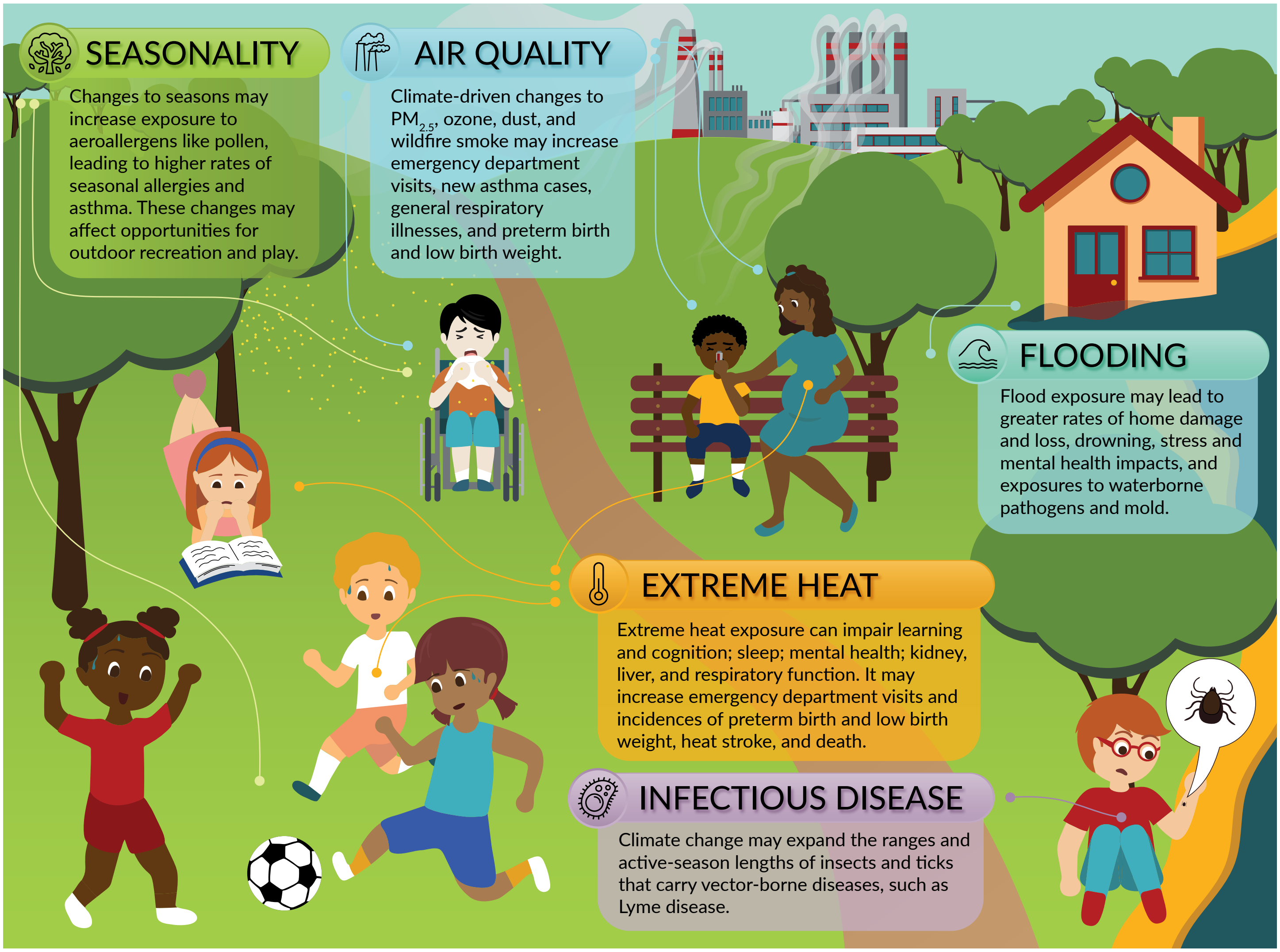
A final appendix covers the peer review process and information quality procedures undertaken.

EXECUTIVE SUMMARY

Introduction

Our climate is changing, and the health and well-being of children will continue to be affected in many ways. Children are uniquely vulnerable to climate change in part because of the natural physiology of developing and growing bodies. Exposures to climate-related stressors can occur in a variety of ways, some of which are distinctive to children, including through outdoor play and at school. Children, and young children especially, have less control over their physical environments, less knowledge about health effects from climate change, and less ability to remove themselves from harm. Climate impacts experienced during childhood can have lifelong consequences stemming from effects on learning, physical development, chronic disease, or other complications.

This report investigates five climate-related environmental hazards associated with children's health and well-being in the contiguous United States (U.S.): extreme heat, poor air quality, changes in seasonality, flooding, and different types of infectious diseases. It provides national-scale quantification of risks to children for a subset of key impacts, in addition to reviewing a broad set of pathways in which climate stressors affect children's health. The analyses presented in this report are part of the EPA's Climate Change Impacts and Risk Analysis (CIRA) project, a framework using consistent inputs to enable comparison of impacts across time and space. The infographic below shows some examples of ways children can be exposed to harmful conditions in a changing climate.



EXECUTIVE SUMMARY

Analysis Approach

The analyses in this report rely on existing evidence establishing links between environmental conditions and impacts on children to project what our changing climate may mean for future generations. Results are summarized by degree of global warming relative to recent conditions. Each detailed analysis follows three main steps:

1 **Establish current risks to children:** Existing literature and data are used to document or model conditions for children during a baseline period of 1986-2005.

2 **Project future environmental conditions:** The rich array of climate data provided in general circulation models (GCMs), or climate models, are employed to project future climate hazards.

3 **Estimate future impacts on children:** Statistical relationships from peer-reviewed, relevant literature are leveraged to project impacts on children's health resulting from exposures to climate change-associated hazards.

Risks are documented for all children in the contiguous U.S., with additional consideration for effects at local and regional scales. The analyses also examine the extent to which certain groups of overburdened children (Black, Indigenous, and people of color, or BIPOC; low income; limited English speaking; and children without health insurance) may be disproportionately exposed to the most severe impacts.

The report also highlights recent literature documenting other pathways in which the five climate stressors of interest may affect children, including potential future magnitudes of each outcome. Finally, some health outcomes from climate change can be prevented or reduced through well-timed and appropriate action; see Chapter 8 of this report for more information on ways to minimize health impacts to children.

FIVE DETAILED ANALYSES

Heat and learning: Heat negatively impacts children through learning, among other pathways. This analysis quantifies how heat experienced during the school year reduces learning, values those learning losses in terms of lost future income, and demonstrates the important role of air conditioning (A/C) in schools and homes in facilitating effective learning.

Air quality and children's health: Existing evidence clearly links poor air quality with various adverse health effects in children, including asthma. This analysis considers how a warming climate will change childhood exposures to particulate matter ($PM_{2.5}$) and ozone (O_3), and then quantifies the related effects on respiratory diseases and related outcomes.

Pollen and children's health: Climate change can increase children's pollen exposures as seasons lengthen and temperatures warm. This analysis examines how changes in oak, birch, and grass pollen may lead to more visits to healthcare facilities, prescriptions filled for allergy medications, and emergency department (ED) visits for asthma among children.

Coastal flooding and children's homes: During flooding events, children experience safety risks, psychological stress associated with displacement and loss, as well as health risks from water-borne pathogens and mold in flooded structures. This analysis estimates the number of children who may experience temporary or permanent displacement from their homes because of coastal flooding.

Lyme disease: Varying temperature and precipitation patterns are likely to alter the habitat, range, and density of pathogens, vectors, and hosts that can cause disease among children. Lyme disease, carried by blacklegged (deer) ticks, is one such disease. This analysis projects the number of new Lyme disease cases in parts of the country.

EXECUTIVE SUMMARY

Key Findings

Results of the detailed analyses are presented for increases in global average temperature of 2°C and 4°C above levels observed in 1986-2005. For the flooding analysis, analogous results for 50 cm and 100 cm of global sea level rise are described. Average impacts across climate models are highlighted, in addition to the minimum and maximum estimates projected by the models. In situations where overburdened children may be disproportionally exposed to the most severe impacts, those findings are provided as well. The summary below also discusses other key pathways through which children are likely to be affected by climate change in the future.

David L. Ryan / The Boston Globe via Getty Images

Temperature increases of 2°C and 4°C of global warming are associated with, on average, 4% and 7% reductions in academic achievement per child, respectively, relative to average learning gains experienced each school year. Across each cohort of graduating students, the total lost future income attributable to these learning losses may reach \$6.9 billion (\$1.9 to \$12.7 billion) at 2°C and \$13.4 billion (\$8.9 to \$18.3 billion) at 4°C. In contrast, installing A/C in schools is less costly, although this action only partially mitigates these effects, and may further induce GHG emissions that contribute to climate impacts. Black, Hispanic or Latino, and low income students report the lowest rates of current A/C in schools, and therefore are likely to experience these impacts disproportionately.

Another way to measure the magnitude of heat's effects on children's health is the number of ED visits associated with high temperature days. Existing evidence suggests the number of ED visits among children are expected to increase between May and September each year as summer temperatures continue to rise.

EXECUTIVE SUMMARY

Key Findings

New diagnoses of asthma associated with $PM_{2.5}$ and O_3 exposure are estimated to increase by 34,500 (27,900 to 42,800) per year at 2°C of global warming up to 89,600 (74,100 to 108,000) at 4°C. On average, this represents a 4% and 11% increase relative to baseline incidence. ED visits and hospital admissions due to general respiratory conditions are projected to increase, as are school days lost because of these effects. The analysis further projects additional premature deaths among newborns. Most impacts stem from climate-induced changes in weather conditions that worsen concentrations of $PM_{2.5}$ and O_3, although wildfires and ground-level dust in the arid Southwest also play a role. BIPOC children are more likely to experience new asthma diagnoses associated with $PM_{2.5}$ exposure, specifically.

Wildfire smoke is comprised of numerous air pollutants that pose significant human health impacts, including adverse birth outcomes. New research documents the association between exposure to wildfire smoke and risk of preterm birth, suggesting a dramatic potential increase in this outcome as wildfire activity continues to increase.

At 2°C of global warming, an additional 5,800 (4,800 to 8,000) asthma-related ED visits in children are anticipated annually from exposures to oak, birch, and grass pollen, increasing to approximately 10,000 (9,500 to 11,000) additional visits annually at 4°C of warming. Less severe outcomes, like visits to healthcare facilities for seasonal allergies (allergic rhinitis) and prescriptions for allergy medications for children, may increase by 41,000 (34,000 to 57,000) visits and 121,000 (101,000 to 167,000) prescriptions annually at 2°C of warming. On average, the health impacts associated with pollen exposure increase 17% and 30% at 2°C and 4°C, respectively. Limited English-speaking, BIPOC, and uninsured children are more likely to experience these impacts stemming from oak pollen exposure, specifically.

Changing seasonality also will alter the ways children play or recreate outside. Overall, new evidence suggests that lengthening warm seasons are expected to result in more time spent on outdoor recreation, especially boating and water sports. On the other hand, the number of trips associated with some recreation types, like skiing and cold-water fishing, is projected to decrease under climate change.

EXECUTIVE SUMMARY

Key Findings

If no additional adaptation actions are taken, approximately 185,000 (159,000 to 437,000) children are estimated to experience complete home loss from coastal flooding at 50 cm of global sea level rise increasing to 1.13 million (477,000 to 3 million) at 100 cm. More than 1 million additional children living in coastal areas may be temporarily displaced from their homes annually due to flooding at both 50 cm and 100 cm. Well-timed adaptation measures, including building sea walls, could delay or prevent many of these impacts; however, they themselves are costly. Children in each of the overburdened groups considered in this report are disproportionally affected by temporary home displacement at 50 cm and complete loss of home at 100 cm.

Inland flooding, also known as riverine flooding, could increase in the future due to climate change. Existing research suggests children will experience damage to their homes from flooding in these areas.

In 21 Eastern states and the District of Columbia, an additional 2,600 (-7,500 to 20,200) new Lyme disease cases per year are projected among children under 2°C of global warming. At 4°C of global warming, the increase is much more extreme: 23,400 (7,800 to 47,000) additional cases per year. These additional cases represent a 31% to 272% increase above baseline infection levels, respectively. States in the northernmost areas of the Northeast and Midwest regions are expected to see most of new cases among children. Research demonstrates that Lyme disease may be under-reported and undertreated among some overburdened populations, increasing the likelihood of more severe outcomes in these communities.

West Nile Virus (WNV) carried by mosquitos is likely to see a change in new cases as temperatures increase, including among children. While existing evidence suggests the estimated increase in new cases of West Nile Neuroinvasive Disease (WNND), a severe outcome associated with WNV, is anticipated to be small in magnitude, growing numbers of cases could be indicative of greater rates of other types of mosquito-borne diseases.

EXECUTIVE SUMMARY

Regional Highlights

Finally, this report documents where climate-induced impacts on children are projected to be most acute. Among the impacts considered, this section identifies the states and regions that are likely to experience the greatest impacts, including emerging areas of interest. The map below summarizes the findings for 2°C of global warning and 50 cm of global sea level rise. By synthesizing results across regions, the map demonstrates how children can experience multiple climate stressors simultaneously. However, the map does not convey the geographic distribution of all climate change impacts on children, or where baseline impacts are high.

NORTHWEST

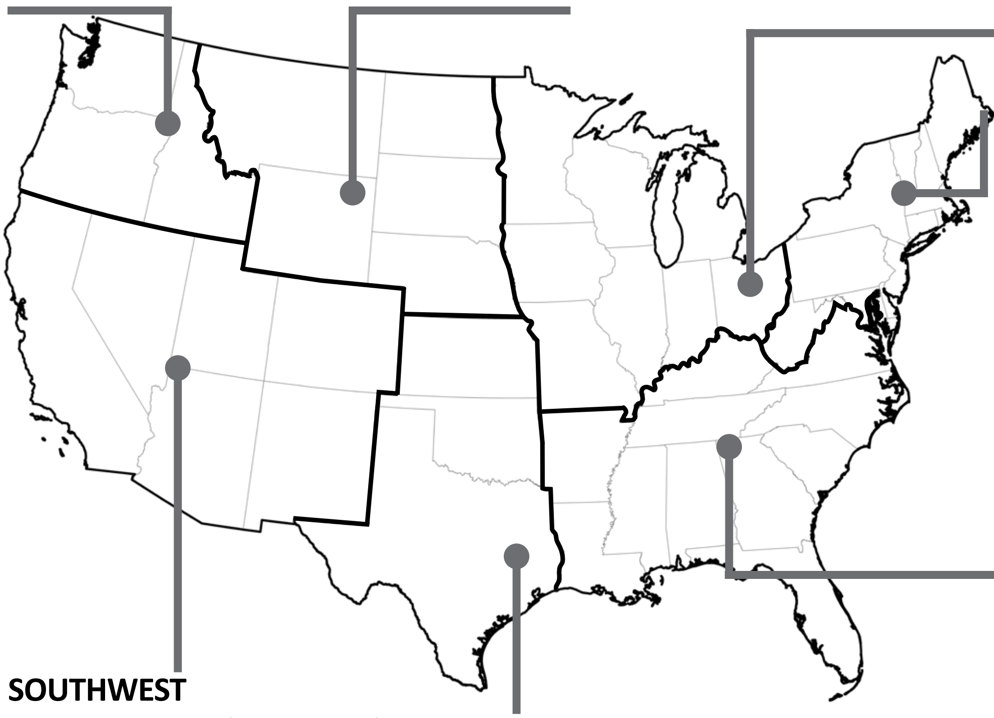
ID and OR are projected to have high concentrations of wildfire smoke, while some of the highest rates of respiratory health impacts among children nationally are projected in WA due to degrading air quality from the climate-induced sources in this analysis. Additionally, increased grass pollen is projected to result in high adverse health effects per capita in OR. Inland flooding effects are among the greatest in the country.

NORTHERN GREAT PLAINS

WY is among the states with the highest projected learning losses per child nationally given high warming and low current A/C coverage. WNND incidence rates may be greatest in ND, NE, and SD, compared to national rates. MT and WY are projected to experience some of the highest rates of health effects to children from wildfire smoke. Inland flooding effects are among the greatest in the country.

MIDWEST

Increasing climate-driven concentrations of O_3 in IL, IN, and OH may contribute to some of the highest rates of air quality health effects on children nationally. MI is projected to experience some of the most considerable learning losses per student due to heat exposure, while MI and MN experience the most extreme per capita increases in Lyme disease cases. IN and OH are projected to see the greatest impacts on children's health of across all included pollen types.



NORTHEAST

ME, NH, and VT are among the states with the highest projected learning losses per child from high temperatures during the school year, as well as low current A/C coverage. These states may also experience the greatest increase in Lyme disease rates. Children in WV and VT are most likely to experience health impacts associated with oak and birch pollen exposures. MD and DC may have some of the highest rates of climate-driven air quality impacts per child, where O_3 is the primary exposure.

SOUTHWEST

Dust in AZ, CO, NM, and UT is projected to adversely impact respiratory health among children. Wildfire smoke stemming from future fire activity in CA is projected to lead to high rates of poor health outcomes, such as asthma. WNND incidence rates are projected to be among the highest in AZ and CO. Inland flooding effects are high in this region.

SOUTHERN GREAT PLAINS

Increases in exposures to grass pollens may lead KS and OK to have some of the highest rates of ED visits for asthma among children. Children in central TX are expected to see considerable per capita health impacts from exposures to oak and grass pollen.

SOUTHEAST

Children in coastal areas of GA, LA, NC, SC, and VA are the most likely to be affected by the impacts of coastal flooding on their homes, assuming no additional protective measures are taken. Inland flooding effects also are high in this region. Climate-driven changes to $PM_{2.5}$ exposure may lead to significant air quality health impacts in AL, GA, NC, and SC. KY may experience among the greatest rates of pollen-related and combined air quality-induced impacts on children nationally.

Glossary

This glossary provides a reference for important terms used throughout the report. For most terms, a technical definition from an external source is provided. For other terms where a specific definition is used in this report, that use case is provided instead of or in addition to a technical definition.

Adaptation – Actions taken to prepare for and/or adjust to climate change impacts.[1] This is complementary to, but separate from, mitigation.[2]

Aeroallergens – Airborne, natural substances such as plant or tree pollen, or mold or fungal spores, that produce an allergic reaction, often presenting as allergic rhinitis (also known as "hay fever"), allergic conjunctivitis, or other respiratory effects like asthma.[3]

Asthma (diagnosis) – A disease that causes inflammation and constriction (narrowing) of the airways to the lungs, limiting or preventing air from entering or exiting the lungs. Asthma is more common in children than adults and is more common in boys than girls.[4]

Asthma attack – A temporary worsening of asthma resulting in difficulty breathing, wheezing, severe cough, or hospitalization, which may be trigged by environmental stressors such as such as aeroallergens, wildfire smoke, or air pollution (triggers discussed in this report).[5]

Baseline – A quantity or scenario (such as of emissions of a pollutant) that is used as a default against which a change is compared. In this report, "baseline" refers to conditions in 1986-2005.

Children – In this report, "children" refers to people younger than 18 years of age. See Chapter 1 for a more detailed definition.

Climate change-related gentrification – The process that leads to the displacement of low-income populations as wealthier residents seek safety from natural, climate change-related hazards to areas that face fewer natural risks or implement hazard mitigation measures.[6]

Climate model – A set of mathematical equations that characterizes how energy and matter interact in different parts of the ocean, atmosphere, and land.[7] Some climate models are referred to as general circulation models or GCMs.

Climate stressor – A condition, event, or trend related to climate that can exacerbate hazards.[8] The climate stressors covered in this report include heat, air quality, flooding, changing seasonality, and infectious diseases.

Coastal flooding – Coastal flooding occurs when water inundates or covers normally dry coastal land as a result of high or rising tides or storm surges.[9] Coastal flooding results from a combination of factors, including waves, tides, storm surges (intense waves of inrushing saltwater which arise during storms), and changes in sea level over time. The most intense storm surges occur during hurricanes and Nor'easters, when low barometric pressures (which temporarily force an increase in ocean levels) and wind-driven water combine to push coastal water landward. The forces behind coastal flooding exhibit natural vulnerability, but sea levels and the intensity and frequency of hurricanes and other coastal storms can be worsened by climate change—as the climate warms, sea levels rise due to the combination of thermal expansion of water volume, melting of glaciers and other ice sheets, and other factors.

Contiguous United States – The 48 adjoining U.S. states and the District of Columbia, which excludes Alaska, Hawai'i, and U.S. territories.

Degree of global warming – A change in the global average surface temperature of one degree above a specific baseline or time period. In this report, degrees of global warming are described relative to averages observed in or modeled for the 1986-2005 period.

Environmental justice – the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income, with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies.[10]

Flash flood – Flooding resulting from heavy rainfall, officially within 6 hours from the start of the precipitation event. Flash floods can occur in rivers and streams, but also in the built environment, such as paved streets.[11]

Greenhouse gas mitigation or emissions mitigation – The process of reducing greenhouse gas (GHG) emissions or strengthening GHG sinks that take GHGs out of the atmosphere. This is complementary to, but separate from, adaptation.[12]

Heat stress – A general term that refers to a variety of health outcomes that result from exposure to heat over a sustained amount of time. The exact temperature and duration of exposure that can lead to illness is dependent upon the person, the activity they are undertaking, their access to drinking water, comorbidities they may have, and other factors. A few examples of severe illnesses that exist under this umbrella term include the following:

- *Heat stroke*, which refers to the inability of a person's body to self-regulate or cool down. This quickly can lead to death.
- *Heat exhaustion*, which presents as a number of symptoms, including headache, nausea, fatigue, and others.
- *Rhabdomyolysis*, which is the breakdown of muscle tissue. This can cause organ failure and death.[13]

Home loss – In this report, "home loss" refers to the loss of physical, home-based space by a person due to some sort of environmental condition, including flooding or wildfire.

Infectious diseases – Illnesses that may be spread from bacteria or viruses.[14]

Lyme disease – Illness caused by the bacterium *Borrelia burgdorferi*, which is spread to humans by tick bites. Most commonly, in the U.S., Lyme is spread by the deer tick, also known as the blacklegged tick (*Ixodes scapularis* Say). It also is spread by the Western blacklegged tick, *I. pacificus* Cooley and Kohls.[15]

Managed retreat – The process by which coastal communities move away from areas endangered by climate change-related hazards.

Ozone (O_3) – A greenhouse gas and air pollutant that occurs naturally (stratospheric ozone) or is created through the release and reaction of volatile organic compounds and nitrogen oxides in the presence of sunlight (ground-level, or tropospheric, ozone)[16]

Particulate matter ($PM_{2.5}$ and PM_{10}) – Airborne particles that are less than 2.5 ($PM_{2.5}$) or 10 (PM_{10}) micrometers in diameter. This report primarily focuses on the health effects from exposure to ambient $PM_{2.5}$, which can contribute to the development of asthma, diabetes, COPD, heart attacks, and other respiratory and cardiac conditions.[17] PM_{10} refers to particles that are 10 micrometers or smaller and may be visible to the naked eye. While these particles are larger, and therefore may not be inhaled as deeply into the lungs, this type of particulate matter can still cause considerable injury to the lungs and airways, leading to chronic effects such as asthma and COPD.[18]

Pathogen – An organism such as a bacteria, virus, fungus, or parasite that harms its host upon exposure. Examples include *Vibrio* spp., Lyme disease via *B. burgdorferi,* and West Nile Virus. They can be spread to humans via food, water, animal vectors, or other humans.[19]

Pluvial flooding – Flooding occurring from excessive precipitation that cannot be immediately absorbed into soil or drained away.[20]

Riverine flooding – Flooding that occurs when a river or stream overflows its banks.[21]

Seasonality – Recurring events or processes that are correlated with seasons, such as rising temperatures at the end of winter or the onset of allergies during ragweed season.

Social vulnerability (also, "socially vulnerable") – Referring to the measure or level of vulnerability of a particular population in the face of different types of environmental stressors and natural hazards.[22] This report includes the following variables as measures of social vulnerability: age (which is a prevailing factor throughout this report), race, ethnicity, poverty status, whether English is a child's first or primary spoken language, and whether a child is covered by health insurance.

Storm surge – A rise in coastal water levels during a weather event (e.g., hurricane, tropical storm), as a consequence of winds propelling ocean water towards the shore. Storm surge can be extremely powerful and cause considerable flooding. It is generally the cause of the majority of injuries, property damage, and deaths during tropical weather events.[23]

Vibriosis – Illness resulting from exposure to non-cholera-causing *Vibrio* species.[24]

West Nile Virus – The most common mosquito-borne illness in the U.S. West Nile does not frequently cause severe illness in children, and typically presents as cold-like symptoms, although it may have extreme health effects on children who are immunocompromised. Such effects may include temporary or permanent paralysis or death.[25]

Chapter 1: Introduction

The goal of this report is to describe and quantify some of the future impacts of climate change on children across the U.S. using the best-available literature and data.

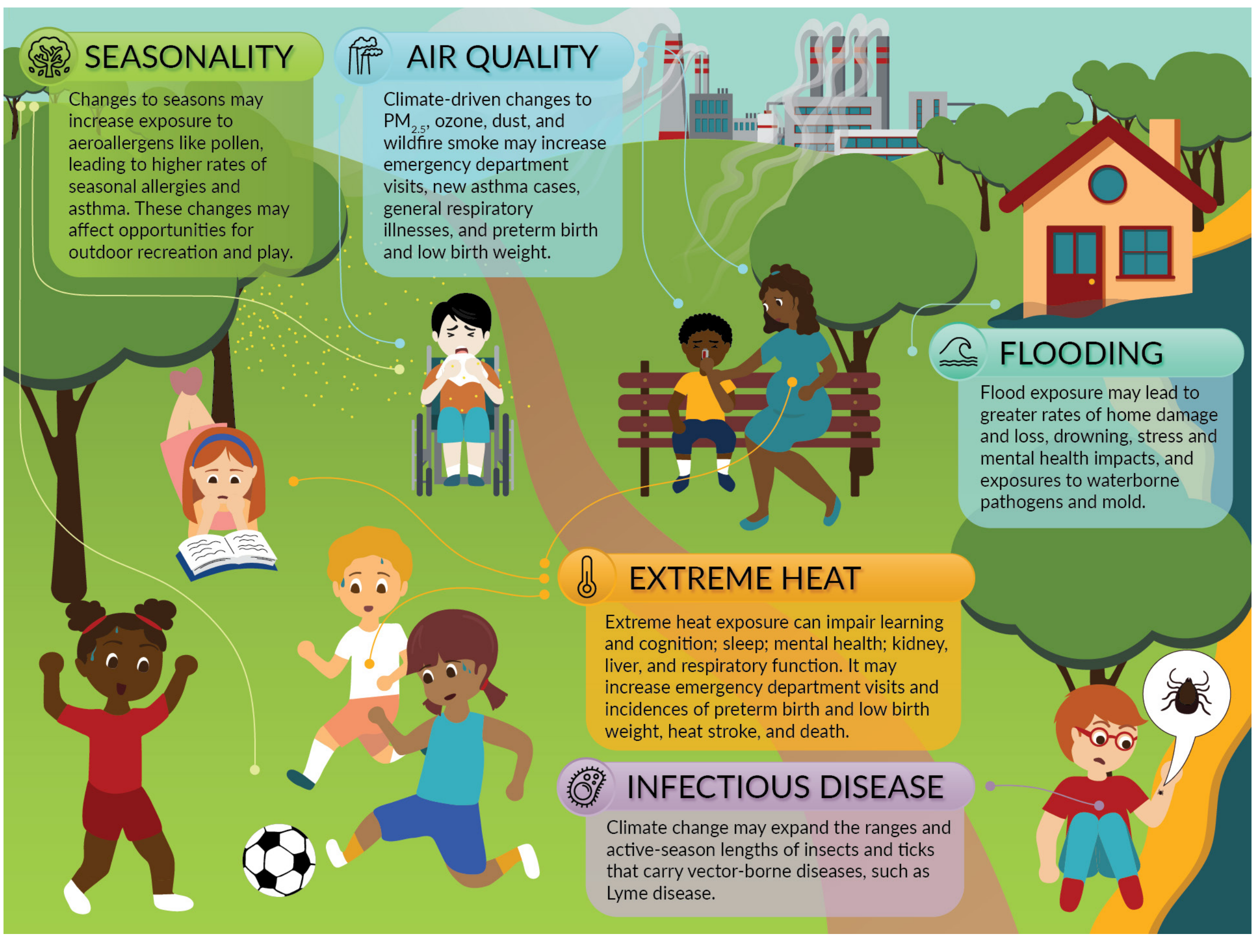
The intended audience includes parents, healthcare providers, researchers, public health practitioners, and decision makers who design and implement strategies and policies to reduce these risks through greenhouse gas mitigation and adaptation.

Our climate is changing, and the health and well-being of children will continue to be affected in many ways.[26] Multiple lines of evidence show risks to children through increasing temperatures, rising sea levels, changing rainfall patterns, more extreme wildfire seasons, and shifting patterns of disease exposure.[27] Children are uniquely vulnerable to climate change in part because of the natural physiology of developing and growing bodies.[28] They physically, psychologically, and socially experience health effects differently from adults.[29]

For example, a baby may be born early and underweight if the pregnant mother experiences a heatwave or is exposed to poor air quality.[30,31] Poor birth outcomes such as these can lead to lifelong effects on behavior and learning.[32] Likewise, children of all ages can develop asthma or cardiac conditions, or be exposed to heat or diseases that can have short- and long-term health consequences.[33,34,35] They also may experience psychological or cognitive effects from exposure to stress or trauma preceding, during, or following severe weather.[36,37] Where possible, a qualitative discussion of the mental health effects of climate change on children is provided throughout the report and in greater depth in Appendix A.

Exposures can occur in a variety of ways, some of which are unique to children. Play – essential to children's healthy physical and emotional development, as well as the very essence of childhood – can change the pathways and extent to which children are exposed to different hazards.[38,39] Outside of play, children can be exposed to hazards by breathing in air pollutants, living in a home or attending a school that is not air conditioned, living in a floodplain, or getting bitten by a tick or mosquito.[40,41,42] Children also have less control over their physical environment than adults. For instance, young children may be unable to open car doors when the inside conditions become unpleasant or dangerous or cannot mask themselves when air quality is noticeably poor. Figure 1 shows some examples of ways in which children can be exposed to harmful conditions in a changing climate via the climate stressors covered in this report.

Figure 1: Examples of Climate Stressors and Impacts on Children



Notes: This figure illustrates the five climate stressors covered in this report as well as some of the ways children are affected by the chosen stressors. See Chapter 2 for details. The figure is not intended to provide a comprehensive accounting of all ways through which children are affected by climate change.

Many health outcomes from climate change can be prevented or minimized through well-timed and appropriate action (see Chapter 8 for more information on ways to minimize health impacts to children). For example, during extreme heat, it is important for children to hydrate often, to play outside earlier or later in the day when temperatures are cooler, and to seek shade to rest and cool off. Monitoring local air quality alerts, especially during wildfire smoke and ash warnings, and limiting children's time outdoors when the air quality is poor, can help reduce exposure and potential health effects. Successful strategies to minimize adverse health outcomes in children depend on a combination of social factors, improved forecasting of weather and climate conditions, and better understanding of how climate change impacts will vary in a changing climate.

This report provides national-scale, multi-sector analyses focused on quantification of projected health risks to children in the contiguous U.S. from climate change. It investigates climate stressors including changes to the frequency and intensity of extreme heat, climate-driven effects on air quality, flooding, changes in seasonality (measured by recreation opportunities and pollen exposures), and different types of infectious diseases. The analyses consider and quantify how children may experience physical harm, and where possible, the extent to which effects disproportionately fall on overburdened children. The report builds on a framework developed by EPA in a 2021 report on climate change and social vulnerability.[43]

Each chapter includes the following components: a discussion of a climate stressor, a literature review of the known attributable health effects, and projections of how risks may change in the U.S. under different levels of future warming. The report concludes with a chapter on actions for addressing and preparing for these risks, through applications of hazard mitigation and adaptation measures, improved risk communication to support healthy choices for children and their parents and caregivers, and recommendations for future research.

The analyses presented in this report are part of the EPA's Climate Change Impacts and Risk Analysis (CIRA) project, a multi-model framework using consistent inputs to enable comparison of climate-driven impacts across time and space.[44] The purpose of CIRA is to quantify the physical effects and economic damages of climate change in the U.S. Using detailed models of sectoral impacts (e.g., human health, infrastructure, and water resources), the project seeks to quantify and monetize how risks, impacts, and damages may change in response to greenhouse gas mitigation and adaptation actions. The data and methods follow this framework and are applied in the detailed analyses in this report. Each underlying study has been peer-reviewed and published in the scientific literature; the corresponding research papers are cited throughout this report and in the appendices.

This report is intended to provide insights about risks to children's health across multiple impacts and future levels of global warming, with consideration for important sources of uncertainty involved with projecting future risks. It is not designed to be a comprehensive assessment of climate change impacts on children. Estimates should not be interpreted as definitive predictions of future impacts at a particular time or place. Instead, the intention is to produce estimates using the best available data and methods, identified by extensive literature reviews and prior analyses. The analyses can be revisited and updated as science and modeling capabilities continue to advance. Finally, there are many potential effects of climate change that are not explored in this report due to limitations of available data and robust methodologies. Therefore, the results capture only a portion of the potential risks to children's health.

The analyses presented in this report focus on how children experience the impacts of climate change *as children* (see definition below). Another important dimension of how climate change will affect children is through the increasing intensity of impacts they may experience *as future adults*. For instance, a child born the year this report was published may live to see the effects of a changing climate into the 22nd century, which are projected to be even more extreme than the impacts experienced by adults today. Projections of the cumulative effects of climate change on current and future generations of children is beyond the scope of this report.

How are children defined in this report?

U.S. EPA's Policy on Children's Health defines children's environmental health as the effect of environmental exposure during early life: from conception, infancy, early childhood, and through adolescence until 21 years of age. In this report, the term "children" encompasses individuals aged 0-17, or the period immediately postpartum (newborn) through the age customarily acknowledged in the U.S. as the end of childhood. Specific analyses may use narrower age ranges in which the underlying studies and methods indicate specific age groups. For instance, several studies are specific to school-aged children (aged 5-17) or infants only (aged less than one year). When possible, the report accounts for fetal effects, including preterm birth and low birth weight.

Chapter 2: Approach

This report takes an expansive approach to documenting climate risks to children, including both qualitative descriptions of the pathways by which climate affects children's health and quantified health impacts for key endpoints. The quantified impacts are summarized using an "impacts by degree of global warming" framework used in this and other EPA reports on climate change impacts.

This chapter describes the analytic approaches used throughout this report to assess the impacts of climate change on children's health and well-being in the contiguous U.S. It first explains the selection of the five specific climate stressors assessed in this report and then describes the three types of analyses conducted for each: a literature summary identifying impacts of climate change in children, a detailed analysis of one key impact pathway, and a discussion of emerging climate change impacts.

Lastly, this chapter provides an overview of the standard analytic approach used for the detailed analysis of each of the five climate stressors, including details on the impacts by degree approach, adaptation assumptions, how uncertainty is conveyed, geographic considerations, and how disproportionate risks to overburdened children are assessed.

CLIMATE STRESSORS

This report focuses on five climate stressors that are likely to impact children in unique ways: *extreme heat, air quality, changing seasons, flooding,* and *infectious diseases*. The selection of these specific climate stressors was guided by findings from recent research synthesizing the current state of understanding about how climate change affects children,[45] along with the availability of methodologies to quantify future risks for each. Many other types of climate stressors can and do interfere with the health and well-being of children in the U.S. beyond what is covered in this report.

IMPACT ANALYSIS TYPES

Each of the following chapters explores three types of evidence pertaining to the risk of impacts on child health for a particular climate stressor. Figure 2 summarizes the specific analyses for the five climate stressors covered in the report.

- Literature reviews summarize evidence that establishes pathways between climate stressors and various health outcomes among all children, with consideration for environmental justice concerns.
- Detailed analyses provide quantitative assessments of ways in which changing environmental conditions could affect children via a well-established impact pathway also known to be of substantial magnitude. Following the CIRA approach, results are summarized by degree of global warming relative to baseline conditions in 1986-2005. Analyses convey changes in risks to children, discuss geographies where impacts are concentrated, and when possible, determine whether already overburdened populations are more likely to be disproportionately affected than other groups.
- Emerging climate impact discussions highlight new literature quantifying other key climate-impact pathways of harm to children's health. These discussions indicate where deeper analysis is needed to further characterize future impacts.

Figure 2: Summary of Climate Stressors, Analyses, and Emerging Impacts Included in this Report

Climate Stressors	Detailed Analyses*	Emerging Climate Impacts
Extreme heat	Learning losses	Emergency department (ED) visits
Air quality	$PM_{2.5}$ and O_3 and children's health	Wildfire smoke and fetal health
Changing seasons	Pollen and children's health	Outdoor recreation
Flooding	Coastal flooding and children's homes	Inland flooding and children's homes
Infectious diseases	Lyme disease	West Nile Virus

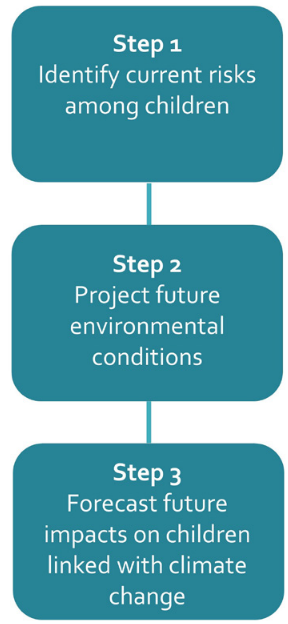
**Specific impacts (endpoints) associated with each detailed analysis are summarized in the following section.*

ANALYTIC APPROACH IN DETAILED ANALYSES

Detailed analyses in each chapter follow a standard analytic approach, which is summarized in this section and described in more detail in Appendix A. Individual analyses rely on specific data sources, methods, and assumptions that are explained in the relevant chapters and accompanying appendices.

STEPWISE ANALYTIC APPROACH

Figure 3: Overarching Stepwise Analytic Approach



Each detailed analysis follows a three-step approach to estimate future impacts on children (see Figure 3). Step 1 identifies current risks among children using literature and quantitative data to document or model conditions in 1986-2005. This baseline represents the reference point for understanding future changes. Step 2 draws on existing climate data provided by six general circulation models (GCMs), or climate models, to project future climate hazards, including temperatures, rainfall, and sea level rise. To provide a simple and common climate change metric for all analyses, the climate projections are indexed to changes in global temperature per degree Celsius from the baseline. The detailed climate scenarios are drawn from the fifth phase of the Coupled Model Intercomparison Project (CMIP5) and represent a recent, well-established understanding of how climatic conditions may change in the future.[46] The climate scenarios in Step 2 also enable projections of other environmental conditions associated with climate change, such as changes in air quality and pollen exposure. Finally, Step 3 uses the climate data generated in Step 2 as an input to a variety of models that estimate the impacts on children's health from changes in climate variables and compares the outcomes to a future without climate change, while accounting for changes in population. The analyses leverage existing statistical relationships from peer-reviewed literature to make the connections between climate and impacts.

The detailed analyses in this report focus on the following endpoints:

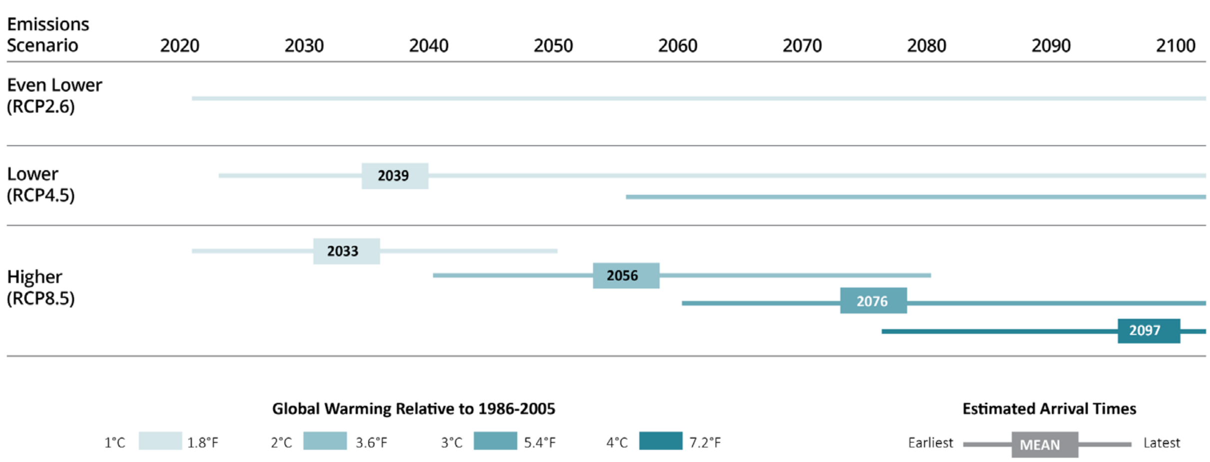
- Heat and learning: Learning losses per child relative to a normal year of learning and future lost income associated with learning losses across each graduating student cohort.
- Air quality and children's health: Cases of asthma, incidence of hay fever, lost school days, ED visits for asthma, hospital admissions for respiratory illness, and infant deaths.
- Pollen and children's health: Prescriptions filled for allergy medications, first doctor visit for hay fever, and ED visits for asthma.
- Coastal flooding and children's homes: Children at risk of temporary or total home loss with consideration for different protective adaptation scenarios.
- Lyme disease: Cases of Lyme disease in 21 states and the District of Columbia caused by changes in extent and range of the blacklegged tick and Lyme-disease causing bacteria.

IMPACTS BY DEGREE OF WARMING

Climate impacts are generally expected to become worse as the Earth continues to warm. To synthesize results across impacts, each analysis presents results for incremental increases in global warming relative to mean conditions in 1986-2005 (baseline). As described in Sarofim et al.,[47] this approach eliminates confusing scenario jargon and aids comparability across analyses. Impacts in this report are presented for global average temperature increases of 2°C and 4°C (equivalent to 3.6°F and 7.2°F; see accompanying appendices for results at other degrees of warming).

Figure 4 shows that under a "higher GHG emissions" scenario, climate models on average project that global temperature increases of 2°C and 4°C could be reached by the years 2056 and 2097, respectively, but the uncertainty range around this central estimate spans several decades. For "lower emissions" futures, which are considered more likely as of the writing of this report, the arrival of these temperatures could be pushed back further into the future. The "even lower emissions" scenario reflects emissions reduction action that is generally sooner and more aggressive than is considered likely as of the writing of this report.[48]

Figure 4: Projected Timing for Global Average Temperature Changes



Notes: This figure describes the range (lines) and mean (boxes) estimated arrival times for each degree of global warming above mean levels observed in 1986-2005 across global climate models and emissions scenarios.

SEA LEVEL RISE PROJECTIONS

The coastal flooding analysis in Chapter 6 summarizes results associated with changes in global average sea level rise in 25 cm increments relative to a baseline sea level period from the year 2000. To compare the baseline with the impacts summarized by degree of warming, the analysis highlights impacts at 50 cm (equivalent to 19.7 inches) and 100 cm (equivalent to 39.4 inches) of global sea level rise, which are commonly used index values for this metric (see Appendix A for details).[49] The projected changes in global average sea level generally correspond to higher changes in sea level in the U.S. For instance, U.S. sea level rise may be more than 50% greater than global sea level rise, particularly along the Atlantic and Gulf coasts, where land levels are falling as sea levels rise.[50]

What is 1°C of global warming?

The "degrees of warming" considered in this report are relative to temperature levels in 1986-2005, the baseline considered in the CIRA project. Care should be taken when viewing these results in relation to other analyses that use different baselines, like the targets under the Paris Agreement that consider degrees of warming relative to pre-industrial times. After adjusting for the differences in baselines, 2°C of warming relative to 1986-2005 would translate to 2.45°C of warming relative to pre-industrial times. For context, by 2020, global mean temperatures had risen roughly 0.5°C above the 1986-2005 baseline mean temperature.[51]

Additionally, the "degrees of warming" referred to throughout this report relate to changes in *global* mean temperatures. Warming across the planet is not uniform because the oceans, which comprise a majority of Earth's surface, are slower to warm than the land. 1°C of global warming results in more than 1°C of warming in areas that largely comprise land surfaces. At 2°C of global warming, large areas of the contiguous U.S. are projected to experience average annual temperature increases between 3°C and 4°C (5.4°F and 7.2°F). At 4°C of global warming, most of the contiguous U.S. is projected to experience temperature increases between 5°C and 6°C (10.8°F and 12.6°F). See Appendix A for details.

FUTURE POPULATIONS OF CHILDREN

The detailed analyses incorporate projections of the future population of children. The analyses rely on U.S. Census data for 2010 as well as future projections published in EPA's Integrated Climate and Land Use Scenarios version 2 (ICLUSv2) model through 2100.[52] Populations for a given future year are matched with the "arrival year" for each climate scenario, as described in Figure 4. Appendix A provides more details on the methods and data sources used to model both baseline and future populations of children expected to experience the impacts described in this report.

ADAPTATION ASSUMPTIONS

Populations may adapt to climate change in many ways, with some actions limiting the impact of climatic exposure, and other actions potentially exacerbating impacts. The detailed analyses of this report treat adaptation in two different ways. The coastal flooding analysis directly models a baseline "no additional adaptation" scenario as well as a "with adaptation" scenario that incorporates specific assumptions, using a simplified cost-benefit analysis, about future investments in coastal flood risk management. All other analyses assume no additional adaptation beyond the extent to which populations have already adapted to recent climatic changes or weather variations.

These treatments reflect the current state of the underlying impacts literature, where only a few studies of children's health and well-being currently incorporate the efficacy of future adaptation actions which might be undertaken to reduce children's health risks. For instance, the air quality, pollen, and Lyme disease analyses do not account for potential technological advancements or changes in behavior that may result in more- or less-severe health impacts on children in the future. The "with adaptation" scenario in the coastal flood risk analysis is intended to be illustrative and does not represent a specific policy at national or regional levels; no specific programs, authorities, or policy mechanisms were considered or evaluated.

UNCERTAINTY AND PRECISION CONSIDERATIONS

There are important sources of uncertainty involved with estimating the future impact of climate change on children's health. The underlying peer-reviewed health studies used in the extreme heat, air quality, changing seasons, and infectious disease chapters include statistical analyses which incorporate confidence intervals to characterize estimation uncertainty – the flooding analyses, however, rely on process-based simulation modeling approaches that do not include statistical representations of the uncertainty in flood response to changes in climate. The technical appendices that accompany this main report provide some insight into the uncertainty ranges associated with the estimates employed for projection purposes, where applicable.

There is also uncertainty about how the climate will change in the future. This uncertainty is reflected, in part, in the differences in outputs across available global climate models. The detailed analyses presented in this report use the findings from up to six global climate models; the impacts presented reflect averages across those models (with ranges reflecting the low and high estimates from among the suite of global climate models employed in these analyses). For coastal impacts, which are connected to specific index values for future sea-level rise (50 and 100 cm), uncertainty in the estimates is characterized by uncertainty bounds reported in a recent NOAA report that provides global mean projections as well as the 17th and 83rd percentiles.[53] We use these bounds to estimate the number of children impacted in contiguous U.S. for each increment from 25 cm to 100 cm. There is also uncertainty regarding future population, as well as how people may adapt to climate change in the future. Combining these various sources of uncertainty was not attempted in this report.

GEOGRAPHIC CONSIDERATIONS

In addition to describing total impacts across all children in the contiguous U.S., the report showcases the spatial distribution of those impacts, building on the spatial granularity inherent in the underlying climate models, as well as population projections incorporated into the analysis. To accomplish this, total impacts on children's health are mapped at the census block group, census tract, or county levels, consistent with the underlying input data. Further, each detailed analysis identifies the five states where the impacts per child are projected to be highest. The accompanying technical appendices provide additional detail on the concentration of total impacts, taking into account the influence of population projections as well.

DISPROPORTIONATE RISKS TO OVERBURDENED POPULATIONS

Where possible, the detailed analyses examine the degree to which children within several demographics living in the contiguous U.S. (Black, Indigenous, and people of color (BIPOC); low income; limited English speaking; and children without health insurance) may be disproportionately exposed to the most severe impacts of climate change, building on an approach in a 2021 EPA report.[54] The detailed analyses conclude by estimating the likelihood that these groups of concern live in geographic areas with the highest projected climate change effects. This likelihood is based on current demographic distributions and projected changes in climate conditions. The estimated risks for each demographic group are presented relative to each group's reference population, defined as all individuals other than those in the group analyzed. Due to data limitations, this report does not consider all possible dimensions of social vulnerability that children may experience, although it includes summaries of existing literature within each chapter that discuss potential impacts that may affect these individuals.

While differential risks to children can be linked to specific physiological differences between children and adults, the disproportionate risks to overburdened populations tend to be associated with social, historical, healthcare, and institutional disparities between groups. Climate change will continue to exacerbate existing inequities in children's health. Due to a deeply rooted system of discrimination and oppression (i.e., structural racism), Black, Indigenous, and other communities in the U.S. are often particularly vulnerable to environmental hazards, including the effects of climate change. For example, historic practices of redlining have created lasting effects and are correlated with low-income neighborhoods and communities of color in urban areas being disproportionately exposed to heat islands (e.g., lower vegetative cover and greater blacktop coverage leading to higher temperatures).[55]

Which overburdened populations of children are considered?

Black, Indigenous, and people of color (or BIPOC): This report uses the term BIPOC to refer to individuals identifying as Black or African American; American Indian or Alaska Native; Asian; Native Hawaiian or Other Pacific Islander; and/or Hispanic or Latino. It is acknowledged that there is no "one size fits all" language when it comes to talking about race and ethnicity, and that no one term is going to be embraced by every member of a population or community. The use of BIPOC is intended to reinforce the fact that not all people of color have the same experience and cultural identity. This report therefore includes, where possible, results for individual racial and ethnic groups.

Low income: Children living in households with income that is at or below twice the Federal poverty threshold for their household size.

Limited English speaking: Children living in households where all members 14 years and over older have at least some difficulty with speaking English.

No health insurance: Children without health insurance.

Notes: 1) These definitions rely on standard variables in the U.S. Census Bureau's American Community Survey.[56] 2) Due to data limitations, this report does not analyze the impacts of climate change in Hawai'i, Alaska, or U.S. territories. However, the analyses use demographic data from the U.S. Census which includes individuals living in the contiguous U.S. who identify as "American Indian or Alaska Native" and "Native Hawaiian or Other Pacific Islander." For more information, please see Appendix A.

Chapter 3: Extreme Heat

David L. Ryan / The Boston Globe via Getty Images

Chapter highlights

This chapter describes examples of how heat affects children's health and well-being, and how those risks are expected to increase in a warming climate. Children's physical, cognitive, and mental health may be affected by climate-induced temperature increases, extreme heat, and increased frequency of heat waves.

One key way that heat negatively impacts children is through learning. This chapter first quantifies how heat experienced during the school year reduces learning and then monetizes those losses in terms of lost future income. Holding constant current levels of school and home A/C availability, temperature increases of 2°C and 4°C of global warming are associated with 4% and 7% reductions in average academic achievement per child, respectively, relative to average learning gains experienced each school year. The lost annual future income across each cohort of graduating students may reach $6.9 billion ($1.9 to $12.7 billion) at 2°C of global warming and $13.4 billion at 4°C ($8.9 to $18.3 billion). Installing A/C in schools is less costly, although it only partially mitigates these effects, and will exacerbate climate impacts if the electricity used is not from renewable sources. Black, Hispanic, and low-income students are likely to experience these impacts disproportionately.

This chapter also documents the relationship between increased summer temperatures and ED visits at children's hospitals in the U.S. For each 1°F (equivalent to 0.6°C) increase between May and September, the number of ED visits at U.S. children's hospitals could increase by 113 visits per day, or over 17,000 visits over the five-month period.

HOW CLIMATE CHANGE AFFECTS HEAT AND CHILDREN

Heat is one of the most apparent indicators of climate change. Increasing average surface temperature will generally lead to both less cold weather and more hot weather: the hottest temperatures in the future may be warmer than any experienced in recent decades.[57] In addition to overall warming, climate change is intensifying heat waves and extreme heat events. In particular, the U.S. is seeing higher temperatures year-round, with hotter summers and longer heatwaves.[58] Heat can have a wide range of health impacts, regardless of location.[59,60,61] Many of these effects are especially pronounced on the young and old, pregnant women, people who have certain preexisting health conditions, and outdoor workers.[62,63,64]

IMPACTS OF HEAT ON CHILDREN

Heat can affect children in many ways, in part because children's bodies respond differently to heat than adults; this also is true for pregnant women and fetuses.[65,66,67] Thermoregulation, which refers to how the body maintains a normal internal temperature despite changing external temperatures,[68] is at the core of the physiological response to excess heat. If the body is unable to properly cool itself, excess heat can lead to dehydration and organ damage. This can manifest as lightheadedness, fainting, muscle breakdown, renal (i.e., kidney) failure, seizure, coma, or death in extreme cases.[69,70,71]

Children are particularly susceptible to heat-induced adverse health outcomes because their bodies are not as efficient at thermoregulation as adults. For example, children also do not sweat as much as adults, limiting a key method the body uses to cool itself. This is especially true for the youngest children (including infants) and girls more than boys.[72,73] Research shows that children with preexisting health conditions—including asthma, other respiratory conditions, impaired kidney function, and endocrine disruption (e.g., diabetes[74,75,76])—are also more vulnerable to the effects of heat.

Exposures to heat can take several forms. Tragically, one of the best-known metrics is the number of children who die each year after being

Heat effects on children

- Excess heat in children can lead to fainting, muscle breakdown, organ failure, seizure, coma, or death in extreme cases.
- Heat is linked to poor cognitive function and reduced ability to concentrate or learn.
- Children are at greater risk of developing anxiety or depression due to high heat.
- Heat can affect children in utero.
- "Heat islands" and lack of access to A/C exacerbate these effects among overburdened populations.
- Increasing humidity may also impact children's health, although it is not explored in this report.

left in hot cars.[77,78] Another unfortunate example is children collapsing during sporting activities in hot weather.[79] A child playing in heavy sports equipment or participating in other types of exerting activities in hot weather may find it very difficult to maintain sufficient fluid levels. Children may not receive enough encouragement to drink water or may be susceptible to pressure not to take breaks when they feel heat-related discomfort.[80] While there are recommendations for how to adapt to increased heat exposure—such as guidelines for sports practices and games,[81,82] car-based alert systems that remind parents about a child in the backseat,[83] and communications messaging around risk[84]—children remain vulnerable in these settings.

Other heat effects may occur in the home or at school, especially in spaces that lack A/C. Heat is linked to poor cognitive function and the ability to concentrate or learn, reducing learning outcomes. One reason for this effect is that cognitive function declines during excessive heat, leading to slower reaction times on assessments.[85] A second reason is that heat affects the ability to have a "good night's sleep," which can lead to cognitive disruption and learning difficulties.[86,87,88] Further, hot classrooms may be distracting and unmotivating. Finally, on extremely hot days, students may miss or intentionally avoid school, particularly if the school is not air-conditioned.[89] Emerging evidence also suggests that extreme heat experienced in utero can have long-term cognition impacts on children and are linked to losses in income and earning potential.[90]

Play is a fundamental component of childhood, and research suggests that children's activity levels may vary due to high heat during outside play, including recess. This is especially true in areas that historically have had cooler average temperatures;[91] thus, children in these areas may be less able to adapt (acclimatize) to hotter temperatures.[92] While seemingly less severe, this can have implications for children's physical and mental health.[93,94]

Adverse mental health impacts are also associated with rising temperatures. Children are at greater risk of developing anxiety or depression due to high heat.[95] Adolescents especially may respond to heat with irrational and aggressive behaviors. Extreme heat linked to climate change has been connected to increases in violent behavior and crime,[96,97,98] all of which may impact children directly.[99] Additionally, research shows that climate change is likely to increase suicide rates in adults and children.[100]

Children from overburdened households are at particular risk of experiencing harm due to high temperatures.[101] Poverty can leave children at greater risk of harm from heat exposure; race and other demographics are correlated with high exposure and risk of heat-related impacts.[102] A 2016 scientific assessment found that children—especially non-White, economically disadvantaged individuals (among other characteristics)—are more vulnerable to adverse health outcomes such as death due to heat exposure.[103] Poverty is linked with adverse health outcomes, stress, and poor cognition, and heat compounds these effects for children.[104] Heatwaves also have been linked to preterm labor,[105] especially in non-White, less-affluent populations.[106] This, consequently, can result in low birth weight,[107] as well as subsequent developmental effects.[108]

Urban heat islands often are found in lower-income, predominantly BIPOC communities, exposing residents to greater concentrations of higher temperatures.[109] Additionally, many vulnerable households do not have A/C due to cost or because the home was built when A/C was not common or necessary.[110] Research shows connections between poverty and race with exposure to both higher temperatures in an area as well as A/C access.[111] The combination of exposure to high heat plus poor health outcomes has been linked to the socioeconomic demographics of a given area, along with access to A/C.[112]

Finally, a changing climate will moderate average cold temperatures across most of the contiguous U.S. While this chapter focuses on heat, changes in cold temperatures likely will benefit some aspects of children's health. For instance, mortality associated with extreme cold is projected to decrease as the climate warms.[113] Children are particularly susceptible to mortality associated with extreme cold as they are less able to regulate their body temperature than adults.[114] However, several studies have shown that the adverse effects of heat outweigh any potential benefits from reductions in cold-related effects and, therefore, this chapter focuses on quantifying the former.[115,116]

HEAT AND LEARNING LOSSES

This section analyzes the connection between heat experienced during the school year and learning losses among children. As described in the previous section, heat is linked with poor cognitive function and reduced ability to concentrate or learn. This report leverages national-level findings from Park et al. to model adverse education effects among high school students, the cohort examined in the study.[117] Park et al. investigated how heat inhibits learning among students in the contiguous U.S. and how A/C in schools and homes reduces those effects. The analysis presented in this report uses that historical relationship to assess how students may suffer from heat during future school years.

Figure 5: Heat and Learning Analysis Steps

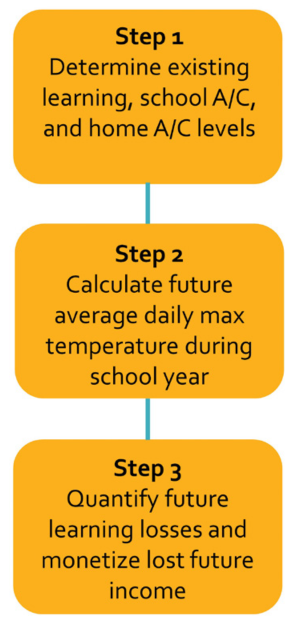
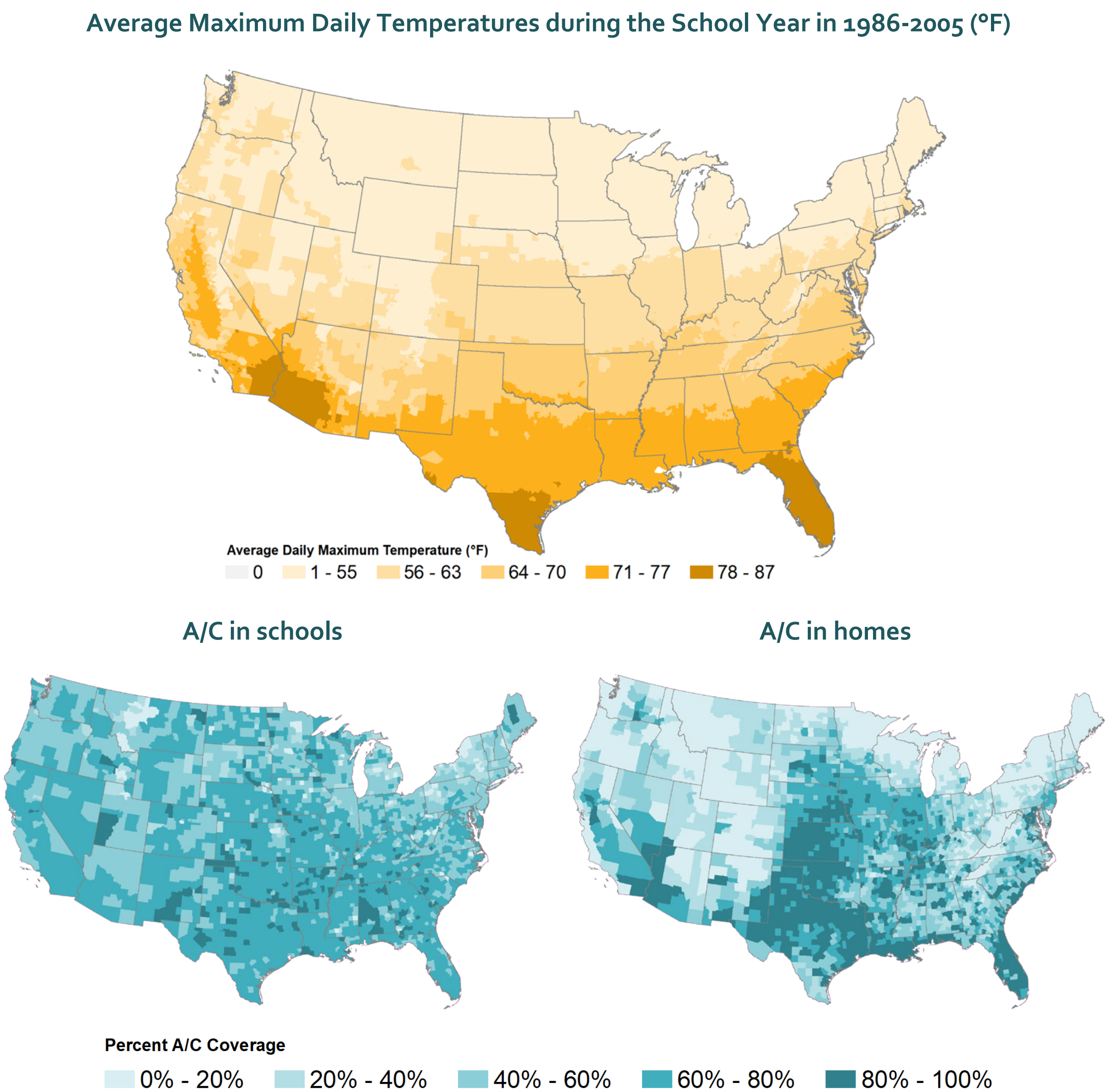


Figure 5 summarizes the three overarching steps of the analysis, with more details about the methods and underlying data sources in Appendix B. First, several data sources are assembled to determine existing learning gains each academic year as well as current levels of A/C in schools and homes. Then, because school calendars vary considerably across the county, this analysis considers local start and end dates for the school year to determine how future temperatures will rise during that time by census tract (for instance, states in the South generally start in early to mid-August whereas states in the North and Midwest often begin in late August or early September). Finally, the analysis quantifies learning losses in terms of percent reduction in learning relative to average gains per school year, then values those losses in terms of lost future income using findings from Chetty et al.[118] By valuing learning losses, the analysis can compare findings to the total projected cost of installing A/C in schools as an adaptation strategy, using estimates presented in LeRoy et al.[119]

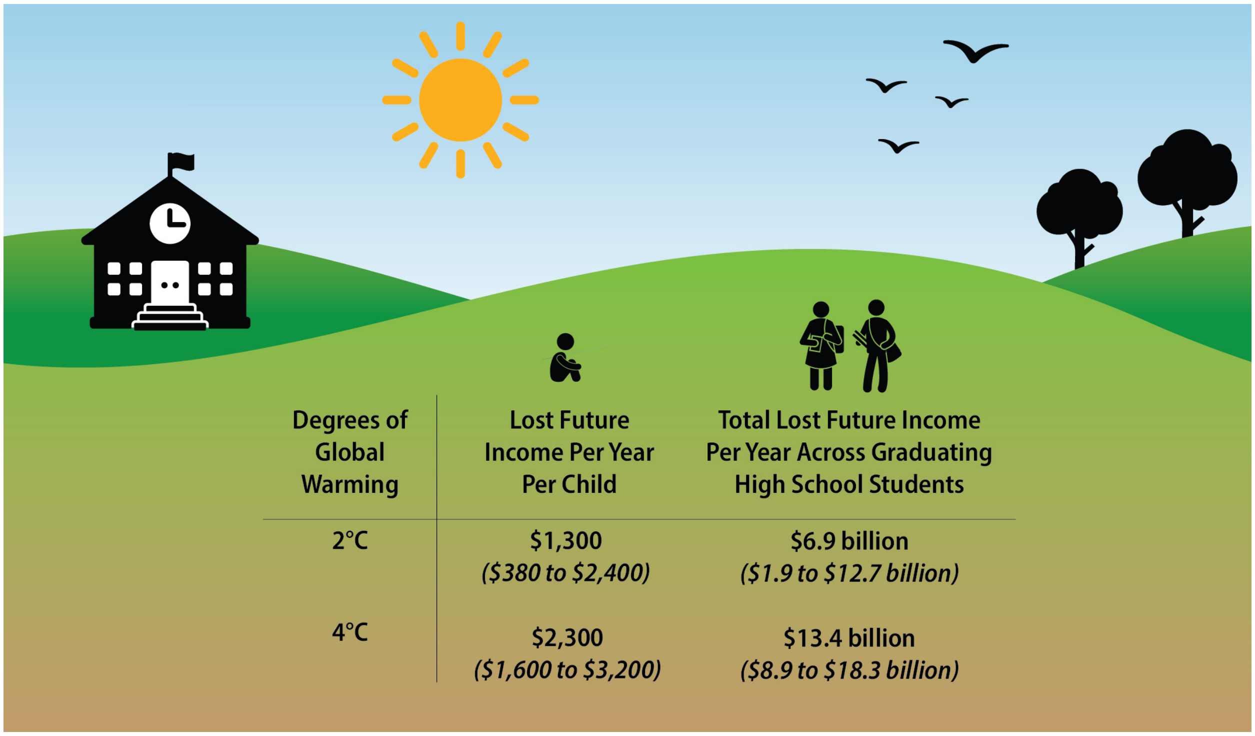
Figure 6 demonstrates why accounting for local A/C coverage is important to accurately project learning losses associated with heat. The top map presents baseline average maximum daily temperatures during the local school year (1986-2005), while the middle and bottom maps describe the current distribution of A/C in schools and homes, respectively. As shown, the regions that currently experience the warmest academic years (the South and Great Plains) already have the most protection from existing A/C. On the other hand, regions historically characterized by milder temperatures during the school year have less school and home A/C coverage, particularly in the Northeast, Midwest, and across the Rocky Mountains. This analysis highlights where future infrastructure investments are most needed as temperatures warm.

Figure 6: Baseline Average Maximum Daily Temperatures During School Years in °F (Top), A/C Coverage in Schools (Bottom Left), and A/C Coverage in Homes (Bottom Right)



Notes: The top map shows average daily maximum temperatures (°F) at the county level during state-specific school calendar years in the baseline considered across this analysis (1986-2005). The middle and bottom maps show the current coverage of A/C at the county level, assembled from various sources described in Appendix B.

Figure 7: Projected Additional Impacts of Heat on Learning Among Children



Degrees of Global Warming	Lost Future Income Per Year Per Child	Total Lost Future Income Per Year Across Graduating High School Students
2°C	$1,300 *($380 to $2,400)*	$6.9 billion *($1.9 to $12.7 billion)*
4°C	$2,300 *($1,600 to $3,200)*	$13.4 billion *($8.9 to $18.3 billion)*

Notes: This graphic presents the results of the heat and learning losses analysis at 2°C (equivalent to 3.6°F) and 4°C (equivalent to 7.2°F) of global warming, expressed in 2021 dollars. The results describe additional impacts relative to the baseline (1986-2005) and assume populations of children will increase over the 21st century (see Chapter 2, Appendix A). The table displays the average and range across climate models. Average lost future income per child is population-weighted (see Figure 9 for variation across the country). Total lost income per year considers learning losses experienced by each cohort of graduating high school students. Figure 8 compares these results with baseline levels. Appendix B provides results for additional degrees of global warming.

Across the contiguous U.S., the average maximum daily temperatures during the school year are projected to reach 69.7°F by the time global temperatures have increased by 2°C and 73.9°F by the time of 4°C of global warming (see Appendix B for details). These temperature levels correspond to temperature increases of 5.8°F and 10°F relative to baseline school year temperatures at 2°C and 4°C of global warming, respectively. While baseline high temperatures are concentrated in the South (see Figure 6), increases in temperatures relative to baseline school-year temperatures are found throughout the contiguous U.S., including in parts of the Midwest and Northeast (see Appendix B for details). Importantly, Park et al. do not find evidence that cold weather affects learning, so all increases in temperatures are anticipated to contribute to learning losses.

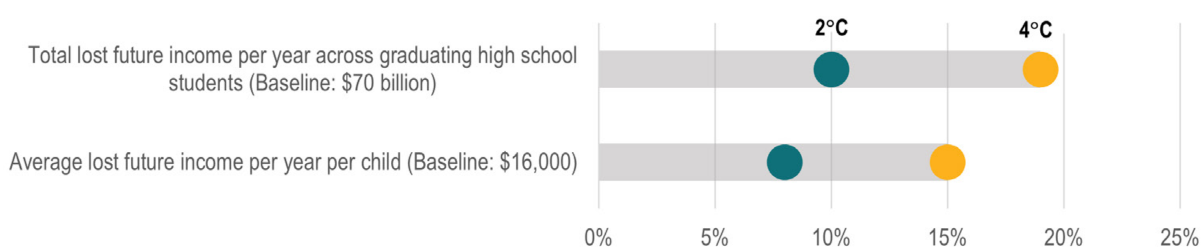
Holding current market penetration of school and home A/C constant (see Figure 6), these temperature increases are associated with approximately 4% and 7% reductions in learning relative to average learning gains experienced each academic year at 2°C and 4°C of global warming, respectively. Applying a valuation approach used by Park et al. that relies on information from Chetty et al., these learning losses are projected to translate into future lost annual income per student on the order of $1,300 (ranging from $380 to $2,400 across climate models) and $2,300 ($1,600 to $3,200) at the same temperature thresholds (2021 dollars). To put these numbers in context, the median weekly earnings reported by the U.S. Bureau of Labor Statistics for 25- to 35-year-old workers translates to roughly $48,000 in annual income in 2021.[120] The average income losses associated with heat experienced as a student are equivalent to between 3% and 5% of annual earnings for the median worker in that age cohort.

Considering lost future income across all graduating high school students each year is a way to demonstrate the magnitude of learning losses across the contiguous U.S. Applying this approach, the total lost future income related to learning shortfalls could reach $6.9 billion per year at 2°C of global warming ($1.9 to $12.7 billion) and $13.4 billion per year at 4°C ($8.9 to $18.3 billion). Relative to temperature-related achievement impacts experienced during the baseline period (1986-2005), future total earnings gaps are projected to increase by 10% and 19% at 2°C and 4°C of global warming, respectively (see Figure 8).

These estimates are large in magnitude and suggest that heat can have long-term negative impacts on academic performance and income gains when experienced during childhood. Further, these projected impacts only consider the effects of heat exposure on learning during high school, and research is mounting that heat experienced by elementary and middle school students also contributes to learning losses.[121] This newer research suggests the potential for cumulative impacts not accounted for in the projections presented in this report. In other words, the impacts presented here are likely to underestimate the total impact of heat on accumulated learning throughout childhood.

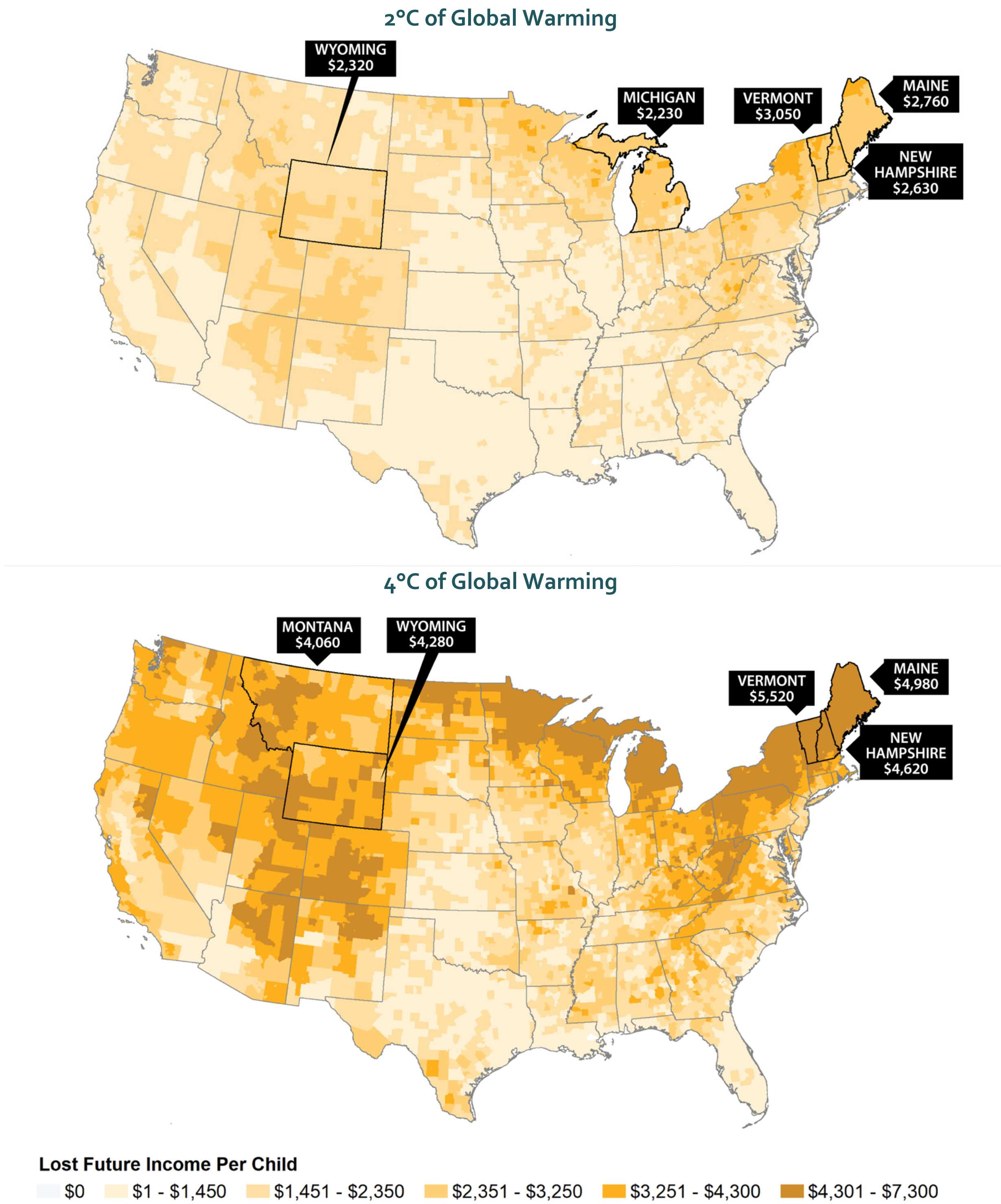
As shown in Figure 9, not all students experience these impacts uniformly. At 2°C of global warming, the states with the highest projected learning losses per student are Maine, Michigan, New Hampshire, Vermont, and Wyoming. Once temperatures reach 4°C of global warming, Montana is another state with among the highest impacts per student, nationally. These and other states in the Northeast, upper Midwest, and mountainous areas experience a confluence of relatively high warming during future school years compared with baseline temperatures and relatively low current A/C coverage. While the Southeast and Southwest regions are expected to warm considerably, and to levels greater than in the cooler states, learning losses are partially mitigated by the existing availability of A/C in these areas.

Figure 8: Estimated Percent Change in Heat and Learning Loss Impacts Relative to Baseline



Note: This graphic describes how the student achievement impacts associated with heat increase relative to baseline conditions (1986-2005), as listed in the figure and under assumptions described in Appendix B. The teal circles show increases between baseline and 2°C of global warming; the orange circles convey increases at 4°C.

Figure 9: Estimated Distribution of Lost Future Income Per Student Per Year from Heat



Notes: These maps present lost future income per child attributable to learning losses from heat exposure during school years. Areas with darker shading have higher rates of learning losses. The five states with the highest learning losses per child are outlined in black. See Appendix C for more details on the distribution of impacts.

These findings can be compared to the cost of installing A/C in schools. LeRoy et al. estimate the cost of furnishing all public schools in the contiguous U.S. with A/C to be $42.4 billion, including $40.5 billion in new installations, $414.8 million in upgrades to existing HVAC technology, and $1.5 billion in annual operating and maintenance costs.[122] Assuming HVAC systems have a 20-year lifespan and applying a 3% discount rate, this would equate to an annualized cost of installing and maintaining HVAC systems in U.S. public schools of approximately $4.2 billion. In other words, the annualized cost of installing and maintaining A/C systems in schools is less than the projected annual lost income associated with learning losses from heat at both 2°C and 4°C of global warming. Holding aside the fact that many school systems would be challenged to find resources to pay for these investments, having A/C in school does not mitigate the potential for learning losses entirely. Park et al. show that learning losses are erased only with A/C in school *and* at home. This suggests that additional investments in home A/C infrastructure are also necessary to eliminate these risks. Analogous estimates of the cost of installing, upgrading, and maintaining A/C in all homes are not available for comparison. While Park et al. focus on the role of A/C in mitigating the adverse heat-indued learning impacts, relying on A/C to reduce these impacts also poses other climate-related challenges, including the increase in energy use that could contribute to further GHG emissions that worsen climate change.[123] Chapter 8 of this report explores other ways of protecting children from these effects.

Appendix B explores how average learning losses per student decrease under different school A/C coverage scenarios. Even when increasing A/C in schools by 10 percentage points across the contiguous U.S., students still experience learning losses relative to baseline at 4°C of global warming.

Park et al. use student-level data to reveal that hot school days disproportionately impact learning among BIPOC students and students living in low-income households. The authors found that the negative impact of prior year heat on Black and Hispanic students was three times larger than the impact on white students. Similarly, the impact of prior year heat on students in lower-income zip codes was twice as large as those from higher-income zip codes.

The results from Park et al. reflect the fact that Black, Hispanic, and low-income students generally experience differential ambient heat exposure *and* have less access to A/C in their schools and at home. Even in places where all students are exposed to the same levels of heat, the learning losses to wealthier students may be offset via supplementary enrichment and instruction. The analysis by Park et al. relies on highly granular data that can explore important variations among students within the same general location; however, the student-level data were not available for this report. The text below describes the current understanding of how overburdened communities may experience the most significant learning impacts associated with heat.

What do we know about the disproportionate impacts of heat on learning?

Disproportionate exposure to heat: Vulnerable communities, especially those living within urban areas, are disproportionately exposed to extreme heat in part because of residential segregation caused by historical housing policies.[124] Hoffman et al. found that land surface temperatures in historically redlined areas were warmer than in non-redlined areas in 108 urban areas across the U.S., increasing the burden of heat on BIPOC and low-income residents, including children. Similarly, another study found that people of color were more likely to live in census tracts with higher surface urban heat island intensity compared to White people in 97% of the largest urbanized areas in the U.S., further emphasizing the disparities in exposure to heat among subpopulations.[125] Park et al. also described mean temperature by race and income, finding that Black and Hispanic children were exposed to higher ambient temperatures (68.8°F on average) than White children (64.2°F on average). Average temperatures in this study during the school year did not vary by income.

Disproportionate access to A/C in homes: Literature and data describing A/C availability in households by demographic group is minimal. Park et al. noted that Black and Hispanic households were 7% and 6% less likely to have access to A/C compared to White households, respectively. Across urban areas specifically, recent research shows that intra-city variation in A/C coverage in homes is considerable, and that the prevalence is much lower in areas with multiple indicators of social vulnerability.[126] A survey administered in 2009 by the California Energy Commission (CEC) shed light on potential disparities in access to A/C in homes by race and income in one state. CEC found that 56% of American Indian households, 57% of Black households, 58% of Hispanic households, and 62% of Asian households had air conditioning statewide.[127] In comparison, 68% of White households were air-conditioned. Additionally, 61% of California households with income below $30,000 had air conditioning, compared to 69% of households with income between $75,000 and $150,000.

Disproportionate access to A/C in schools: Access to A/C in schools varies by demographic group as well. Park et al. found that Black and Hispanic students were 1.6% more likely to be in schools with inadequate A/C than White students. Lower-income students were 6.2% more likely to be in schools with inadequate A/C than higher-income students.

HEAT AND EMERGENCY DEPARTMENT VISITS

Another way to measure the magnitude of heat's effects on children's health and well-being is the number of emergency department (ED) visits associated with high temperature days. Bernstein et al. offer an assessment of the relationship between daily maximum temperature and the incidence of ED visits among a sample of 47 children's hospitals across the U.S.[128] The authors find that location-specific high heat days in May through September are associated with a 17% greater likelihood of an ED visit. Information presented in the study suggests each degree above 62°F is associated with a 0.5% increase in daily incidence of ED visits at the children's hospitals in the study sample.

Extrapolating these findings specifically to all 222 children's hospitals with EDs in the contiguous U.S. indicates what the future may mean for serious health impacts on high-temperature days. Children's hospitals are within 80 miles of 92% of children in the country,[129] and thus can provide services to the most acute cases of heat-related illness. Data from the Healthcare Cost and Utilization Project's Kids' Inpatient Database (HCUP-KID, 2016 and 2019) documents approximately 22,000 ED visits per day between May and September at children's hospitals, equivalent to 3.4 million per summer. Temperature increases of 1°F between May and September would increase the number of ED visits at children's hospitals by 113 visits per day, or over 17,000 visits over the five-month period. A more detailed assessment of these future risks across all hospitals with EDs would better inform planning among healthcare providers.

Chapter 4. Air Quality

Chapter highlights

Climate change is likely to worsen air quality and cause or exacerbate air quality-related negative health outcomes among children. Existing evidence clearly links exposure to air pollutants with various adverse health effects in children, including asthma and other respiratory diseases. Exposure to poor air quality is also associated with limiting brain development. Many of these impacts emerge in childhood and affect people throughout their lives.

This chapter includes a quantitative analysis of long- and short-term childhood exposures to climate-driven changes in outdoor particulate matter ($PM_{2.5}$) and ground-level ozone (O_3) as well as related effects on respiratory diseases such as asthma. Results show that new annual cases of asthma could increase by 4% to 11% at 2°C and 4°C of global warming, respectively. ED visits and hospital admissions from respiratory conditions also are expected to increase, as are school days lost as a result of these effects. Most impacts stem from climate-induced changes in O_3 and $PM_{2.5}$, although wildfires and ground-level dust in the arid Southwest also play a role. Low-income and BIPOC children are more likely than others to experience new asthma diagnoses associated specifically with $PM_{2.5}$ exposure.

Fetal health effects can occur when pregnant women are exposed to poor air quality during pregnancy. Projected increases in wildfire activity are associated with heightened levels of $PM_{2.5}$ and PM_{10} and could result in more adverse birth outcomes. An additional 7,700 and 13,600 premature births may be attributable to wildfire annually at 2°C and 4°C of warming, respectively. At 4°C, this represents a 92% increase in premature births relative to the baseline level of births affected by wildfire smoke.

HOW CLIMATE CHANGE DEGRADES AIR QUALITY AND IMPACTS CHILDREN

Climate change is likely to worsen air quality at the national level primarily due to changes in environmental conditions, such as changes in temperature, precipitation, and wind patterns, that can lead to increases in ambient particulate matter and ground-level (or tropospheric) O_3.[130,131,132,133] Wildfire smoke, dry and dusty conditions due to drought, and changes in agricultural activities can also lead to increases in ambient concentrations of O_3, particulate matter, and other harmful pollutants like carbon monoxide and nitrogen oxides, which can damage the health of children.[134,135,136,137,138,139,140] In addition, wildfires can also burn manmade structures such as homes and vehicles that release toxic chemicals into the air when they combust.[141,142] The resulting smoke can travel far from the immediate area, impacting children and adults at considerable distances from the original location for weeks or even months after an event occurs.[143] Exposures to fine and coarse dust are also projected to increase as climate change progresses, particularly in the arid Southwest.

IMPACTS OF AIR QUALITY ON CHILDREN

Children are particularly vulnerable to the effects of air pollution for a variety of reasons.[144,145,146] Infants and children have more immature lungs compared to adults; as a result, their lungs can be more susceptible than those of adults to harm following exposures to toxins and hazards.[147] They also generally breathe faster than adults and take in more air relative to their size and body weight, thus increasing their relative exposure to air pollution compared to adults.[148] As a result, short-term and long-term (i.e., annual) exposures to air pollution have been shown to have significant effects on child lung function and development, as well as impacts on brain development.[149,150,151]

Short-term exposure to air pollution can cause or worsen asthma, one of the most common childhood diseases, and among the most common reasons for child ED and hospital visits nationwide.[152] Particulate matter from wildfire smoke has been shown to trigger asthma attacks in children more than other sources of

Poor air quality and children

- Worsening air quality is linked with asthma and other respiratory diseases, cancer, and dermatitis in children.
- Decreased lung function in childhood may lead to chronic, severe respiratory conditions in adulthood.
- Preterm birth, low birth weight, and birth defects are associated with *in utero* exposures.
- Poor air quality can affect brain development and mental health.
- Children in many overburdened populations are more likely to live in areas with poor air quality and therefore often suffer these health effects more acutely.

PM.[153] In addition, children have the highest rate of coarse dust-related asthma visits to EDs relative to all age groups, an important consideration for those living in the dry and dusty conditions of the Southwest.[154] Air pollution is also linked with lung injury and inflammation, school loss days, rhinitis, upper and lower respiratory symptoms, cancer, dermatitis, autism spectrum disorder, and even infant death, among others.[155,156,157,158,159,160]

Long-term exposure of pregnant women to air pollution can also have serious implications for fetuses, leading to lifelong health effects. Pollutants are transferred to the fetus from the mother's bloodstream when she breathes them in and can reduce blood flow and oxygen to the fetus due to inflammation. In turn, reduced blood flow and oxygen levels can lead to adverse birth outcomes including preterm birth (i.e., earlier than 37 weeks) and low birth weight (i.e., <2500 grams, or approximately 5.5 pounds), limited fetal growth, birth defects, or stillbirth.[161,162,163,164,165,166,167,168] Exposure to poor air quality can also lead to smaller head circumference, which is associated with memory, learning, and concentration challenges in childhood; and abnormal abdominal (stomach/midsection) circumference, an indicator of a propensity for obesity and other types of metabolic conditions.[169,170] Exposure to particulate matter can also lead to a greater likelihood of pregnancy complications, including blood clots, dangerously high maternal and fetal blood pressure, preeclampsia, gestational diabetes, and childhood diabetes.[171,172,173,174,175,176,177] Studies have shown that increased exposure to any amount of air pollution during the first 14-16 weeks of pregnancy, even at levels below national standards, are associated with abnormal fetal development.[178,179,180]

Changes in lung function in children—measured using a spirometer, often when individuals have respiratory illness or are being tested for asthma—can have lifelong impacts, as this can be indicative of the potential quality of respiratory health in adults.[181] Poor childhood lung function has been linked to chronic, severe respiratory conditions such as chronic obstructive pulmonary disease (COPD) and other types of degenerative lung ailments later in life.[182,183] Impaired lung function from air pollution can continue into adulthood, even if an individual's exposure decreases;[184] however, it is unclear whether effects are reversible.[185]

Long-term exposure to air pollution can also affect brain development and mental health.[186,187,188] Infants and children younger than five years old experience rapid growth, particularly of the brain.[189] The brain is among the fastest developing organs in a child's body and can be greatly impacted by inhaled toxins and particulate matter, leading to cognitive effects.[190] Some evidence suggests that poor air quality can contribute to the development of neurocognitive disorders such as autism and attention deficit/hyperactivity disorder.[191,192] School-aged children may experience poor academic performance if they live in areas with higher air pollution.[193] Poor air quality may affect sleep patterns, which also has mental health implications.[194]

Certain social factors make children more vulnerable to the health effects of poor air quality, including race, ethnicity, and income.[195] Overall, research indicates that increased air pollution-related health risks associated with race and ethnicity are linked to social, historical, healthcare, and institutional disparities between groups. In general, infants born to racial and ethnic minorities are at greatest risk of adverse health outcomes related to air pollution exposure.[196] Black and Hispanic mothers have been shown to be especially at risk for preterm birth and low birth weight related to air pollution.[197,198] Children in lower-income households are more likely to live in areas with poor air quality and are more likely to have worse health outcomes.[199] For instance, BIPOC children are more likely to live in areas closer to a factory or road with heavy traffic, exposing them to more pollution,[200] and are less likely to have an adequate air filtration system in their home.[201] Wildfires are known to increase particulate matter and toxic gas concentrations far above national standards,[202] and these elevated exposures have been shown to be disproportionately higher among children in lower-income households.[203,204] Race appears to play a significant role in making some children more vulnerable to harm from poor air quality. Black children, especially, are more likely to live in areas with expected increases in childhood asthma cases related to climate-driven changes in air pollution.[205,206,207] Similarly, Black individuals—including children—have been shown to face greater health effects from air quality, which may result from a wide range of factors including systemic social inequalities, a historical lack of social capital, and/or baseline health status and ability to avoid and mitigate harmful climate-related air pollution exposures.[208]

AIR QUALITY AND CHILDREN'S HEALTH

The health outcomes associated with long- and short-term exposure to poor air quality are numerous. To convey the magnitude of impacts associated with respiratory conditions specifically, this detailed analysis uses existing evidence from several epidemiological studies to project changes in health and health-related effects among children associated with heightened levels of outdoor $PM_{2.5}$ and O_3. These include:

- New diagnoses of asthma (Tetreault et al.[209])
- Incidence of hay fever (Parker et al.[210])
- School days lost from respiratory issues (Gilliland et al.[211])
- ED visits associated with asthma (Alhanti et al.[212] and Mar and Koenig[213])
- Hospital admissions for respiratory issues (Ostro et al.[214])
- Infant mortality (Woodruff et al.[215])

While ambient concentrations of $PM_{2.5}$ and O_3 have many sources, this analysis targets the changes in annual ambient concentrations expected from climate-induced changes in environmental conditions (Fann et al.[216]) (i.e., the climate penalty), ambient dust concentrations in the Southwestern U.S. (Achakulwisut et al.[217]), and wildfire activity in the West (Neumann et al.[218]). These studies address the impact of climate change on $PM_{2.5}$ and O_3 air quality, but other studies have focused on how greenhouse gas emission reduction policies can reduce air pollutant emissions and have a positive effect on air quality and, by extension, children's health.[219]

Figure 10 describes the steps of the analysis, with further details on the methodology available in Appendix C. This analysis considers all areas of the contiguous U.S. except for changes in southwest dust exposure, which is restricted to four states in the Southwestern U.S. where these impacts are particularly substantial. Future impacts are quantified using U.S. EPA's Benefits Mapping and Analysis Program (BenMAP),[220] a tool that estimates the human health impacts of air quality changes using air quality data, spatially resolved baseline incidence data, and concentration-response functions for short-term and long-term exposure, derived from epidemiology studies. BenMAP applies the relationship between these components to the population experiencing the change in pollution exposure to calculate the resulting health impacts. For presentation purposes, impacts are summed across pollutants and pollutant sources.

Figure 10: Analytic Steps in Air Quality Analysis

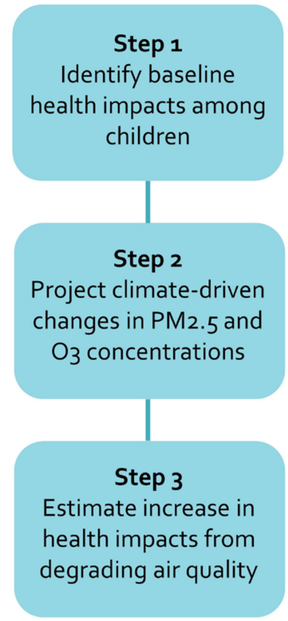


Figure 11 summarizes the analysis findings. An additional 34,500 (ranging from 27,900 to 42,800 across climate models) asthma cases per year among children are projected across the contiguous U.S. at 2°C of global warming, increasing to 89,600 (74,100 to 108,000) additional cases annually at 4°C. These impacts are fueled predominantly by climate-driven changes in ambient $PM_{2.5}$ and O_3. At 4°C of warming, 98% of new cases of asthma are attributable to climate-driven changes in ambient $PM_{2.5}$ and O_3 concentrations, 82% of which are from O_3 alone. In contrast, 1.5% and 0.5% of total cases are attributable to southwestern dust and western wildfires, respectively.

Other respiratory impacts are projected to be substantial, as well. The analysis estimates 6,240 (5,210 to 7,300) additional ED visits for asthma per year at 2°C of global warming, increasing to 15,800 (14,500 to 17,200) additional visits annually at 4°C, representing a considerable reaction to air pollution in children with asthma. Additional cases of hay fever per year among children are estimated to increase by 228,000 (179,000 to 276,000) at 2°C of global warming and 554,000 (447,000 to 662,000) at 4°C. Among the more severe effects, 332 (230 to 430) additional respiratory hospitalizations among children per year are estimated at 2°C, increasing to 785 (353 to 1,220) per year at 4°C. Finally, this analysis also projects additional deaths among newborns. At 2°C of global warming, an estimated 7 (4 to 10) additional newborn deaths annually attributable to climate change, increasing to 15 (6 to 25) additional deaths at 4°C.

What about other air pollutants?

This analysis specifically considers the relationships between children's health and changes in $PM_{2.5}$ and O_3 associated with climate change. The association between human health impacts and long-term exposure to these pollutants is widely studied and documented in epidemiological literature, and projected future pollutant concentrations were available for use in the detailed analysis portion of this chapter. Beyond the pollutants considered here, children will also be negatively affected by various other pollutants that degrade air quality, including ambient dust with particle size larger than $PM_{2.5}$ (called the PM coarse fraction), carbon monoxide, nitrogen dioxide, sulfur dioxide, and the complex mixtures of particulates and organic compounds that make up wildfire smoke.[221,222] Children's exposure to these pollutants may change in the future, leading to changes in the incidence of various health effects, including respiratory symptoms in children and long-term health outcomes when the children become adults. In other words, the health outcomes projected in this section are only a subset of all health impacts to children which could result from climate-induced changes in air quality.

Figure 11: Projected Additional Annual Impacts of Air Quality on Children's Health

Degrees of Global Warming	New Asthma Cases	Incidence of Hay Fever/ Rhinitis	ED Visits for Asthma	School Days Lost	Infant Deaths	Hospital Admissions for Respiratory Illness
2°C	34,500 *(27,900 to 42,800)*	228,000 *(179,000 to 276,000)*	6,240 *(5,210 to 7,330)*	2,240,000 *(1,850,000 to 2,630,000)*	7 *(4 to 10)*	332 *(230 to 430)*
4°C	89,600 *(74,100 to 108,000)*	554,000 *(447,000 to 662,000)*	15,800 *(14,500 to 17,200)*	5,480,000 *(5,170,000 to 5,790,000)*	15 *(6 to 25)*	785 *(353 to 1,220)*

Notes: This graphic presents the results of the air quality analysis at 2°C (equivalent to 3.6°F) and 4°C (equivalent to 7.2°F) of global warming. The results describe additional impacts per year, conditions relative to baseline (1986-2005), and assume populations of children will increase over the 21st century (see Chapter 2, Appendix A). The table displays the average and range across climate models. Figure 12 provides baseline levels and age ranges for each health outcome included. Appendix C provides results for additional degrees of global warming.

The direct medical costs and indirect productivity losses associated with these health impacts may be substantial. For instance, research documents that the lifetime medical and productivity costs associated with new asthma diagnoses are approximately $49,600 per case,[223] while the one-year medical costs stemming from hay fever incidence are about $670 per case,[224] with the potential for further costs over a lifetime if symptoms persist (2021 dollars). ED visits for asthma may result in medical costs of approximately $550 per visit,[225,226] while hospitalizations can cost approximately $10,000 per inpatient visit.[227]

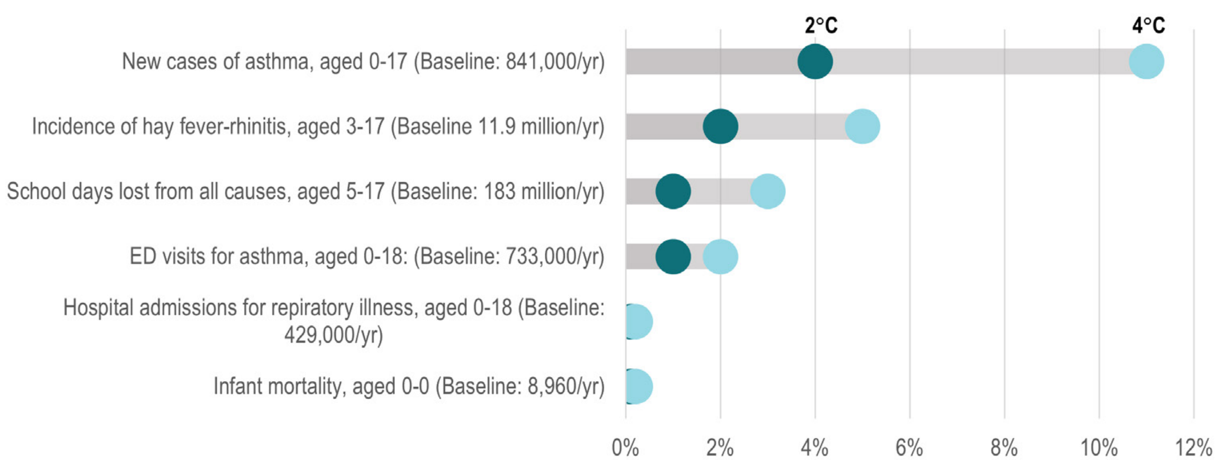
To demonstrate how children's schedules and learning may be interrupted by these health impacts, the analysis projects how climate-driven changes in air pollution will affect school attendance specifically. Across the school-age population (aged 5-17), an additional 2.24 million (1.85 to 2.63 million) school days lost per year are projected at 2°C of warming, increasing to an additional 5.48 million (5.17 to 5.79 million) annually at 4°C. To put these numbers in context, the projected absences at 4°C of warning translate to 0.1 lost days per child per school year. These absences are likely to disproportionately affect children with preexisting conditions, such as asthma.[228] If the population is restricted to children with asthma, each child is expected to miss an additional 1 day of school each year due to climate-driven changes in air pollution levels at 4°C of global warming. Currently, students with asthma miss an average of 4.5 days per school year, amounting to a total of 164 million lost school days nationally.[229]

Research is not available to project what lost school days may mean in terms of current and future costs to children. For example, missing school and after school enrichment or play may affect a child's quality of life, and frequent absences from school may contribute to reduced academic performance and affect cognition and future income. However, available research does translate sick days for children to lost productivity for their parents and caregivers. The health impact valuation literature often assumes approximately $120 per day in lost productivity for adults for each day spent tending to illness for themselves or their dependents.[230]

Finally, the pain and suffering associated with losing an infant is immeasurable. Current practice in health valuation suggests applying a value of approximately $10 million per adult death to account for how much people are willing to pay to reduce their risks of a fatality. Research is limited on how much parents and caregivers value reducing fatal risks to their children, although evidence suggests society may value the health and well-being of children more than adults.[231]

Figure 12 depicts how these various impact measures change relative to their baseline levels (1986-2005) as climate change progresses. Over 4.2 million children across the nation currently have asthma, and over 840,000 new cases are diagnosed annually.[232,233] Relative to these levels, new cases of asthma attributable to climate increase by 4% and 11% at 2°C and 4°C of global warming, respectively—the largest percent increases across the impact measures assessed. The percent change in incidence of hay fever, school days lost, and ED visits from asthma all increase between 1% and 5%. Hospitalizations from respiratory illnesses and infant mortality linked to climate-induced changes in air quality are projected to increase by up to 0.2% at 4°C of global warming.

Figure 12: Estimated Percent Change in Air Quality Impacts Relative to Baseline



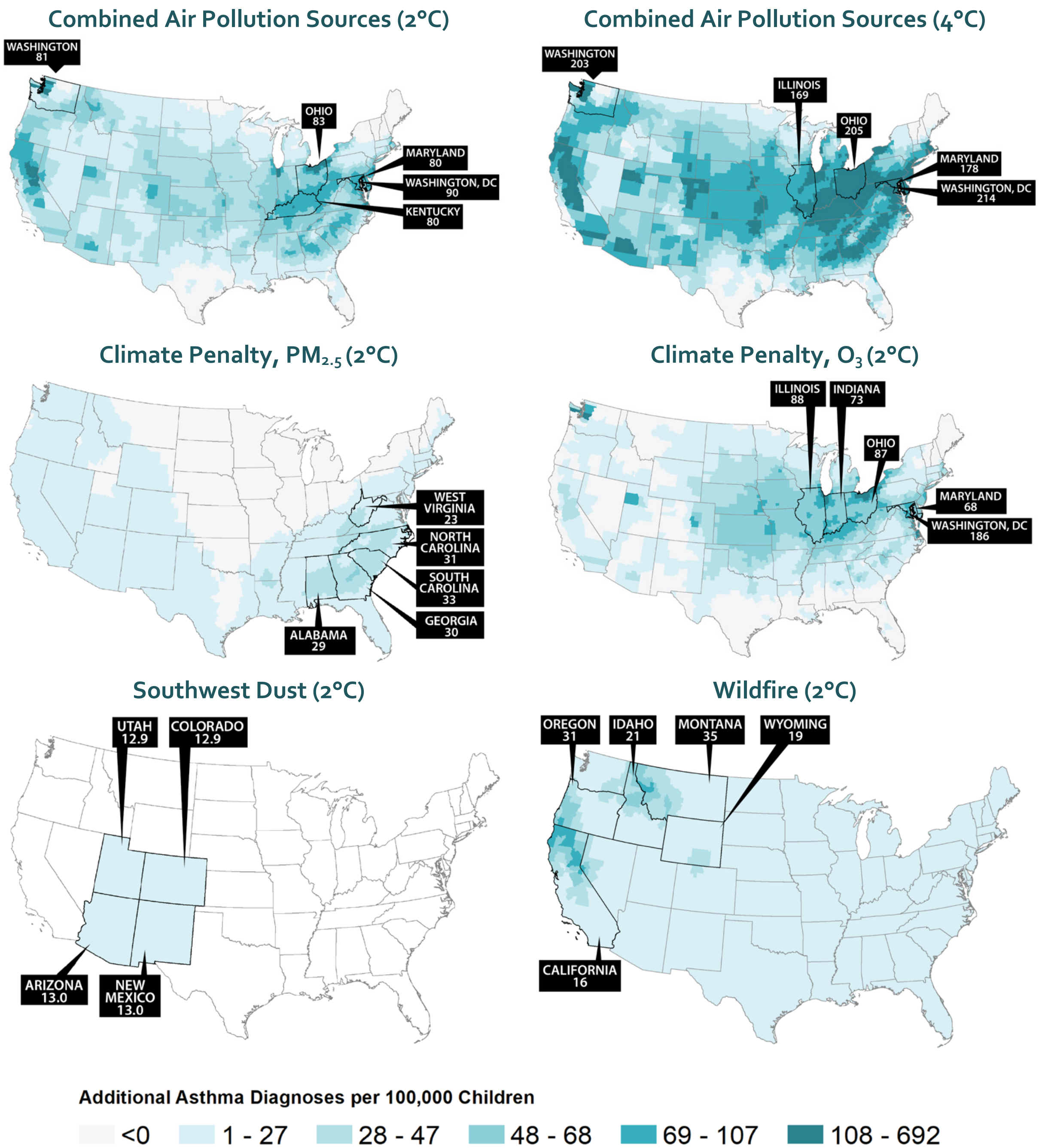
Note: This graphic describes how the health impacts associated with climate-driven changes in air quality increase relative to baseline conditions (1986-2005), as listed in the figure and under assumptions described in Appendix C. The teal circles describe increases between baseline and 2°C of global warming; the light blue circles convey increases at 4°C.

Figure 13 shows the geographic distribution of children aged 0-17 (per 100,000) experiencing new diagnoses of asthma due to climate-driven changes in air quality at 2°C and 4°C of global warming combined across all air pollutant sources and by specific air pollutant type and source. These maps clearly show that the spatial distribution of changes in air quality varies significantly by air pollutant type and source. For instance, the climate-induced changes in $PM_{2.5}$ are concentrated in the Southeast, while related changes in O_3 are highest in some parts of the Midwest and Northwest. Changes to air quality from climate-induced wildfire activity are most acute in the Northwest. Finally, as the name implies and given the spatial scope of the underlying analyses, the impacts associated with ambient dust are confined to four states in the Southwest.

Combined, the greatest impacts are observed in the inner Midwest and Appalachian regions, where O_3 concentrations are expected to increase, and on the West Coast where wildfire activity degrades air quality. Rates are also high across several states in the Southeast where climate-induced increases in $PM_{2.5}$ levels are greatest. The maps identify the five states with the highest number of affected children per 100,000 across air pollutant sources, including the District of Columbia, Kentucky, Maryland, Ohio, and Washington State at 2°C of global warming; Illinois also is among the top states nationally at 4°C. Wildfire $PM_{2.5}$ drives new cases in Washington, while climate-induced increases in O_3 concentrations drive the majority of impacts in the other top states.

Other impacts quantified in this analysis follow similar spatial patterns (see Appendix C). For instance, the increase in school days lost per 100,000 individuals at 2°C of global warming is highest across the Midwest and Mid-Atlantic (the District of Columbia, Illinois, Indiana, Ohio, and Maryland) where O_3 levels associated with changing temperature and precipitation patterns are expected to be most pronounced. Following that, climate-driven changes in precipitation and temperature may also lead to decreased air pollution in some locations. This analysis shows that children in some parts of the contiguous U.S.—such as parts of Maine, New Hampshire, Vermont, Florida, and Texas—are expected to experience decreases in respiratory impacts as conditions change in the future.

Figure 13: Estimated Distribution of Additional Asthma Diagnoses from Air Quality Changes

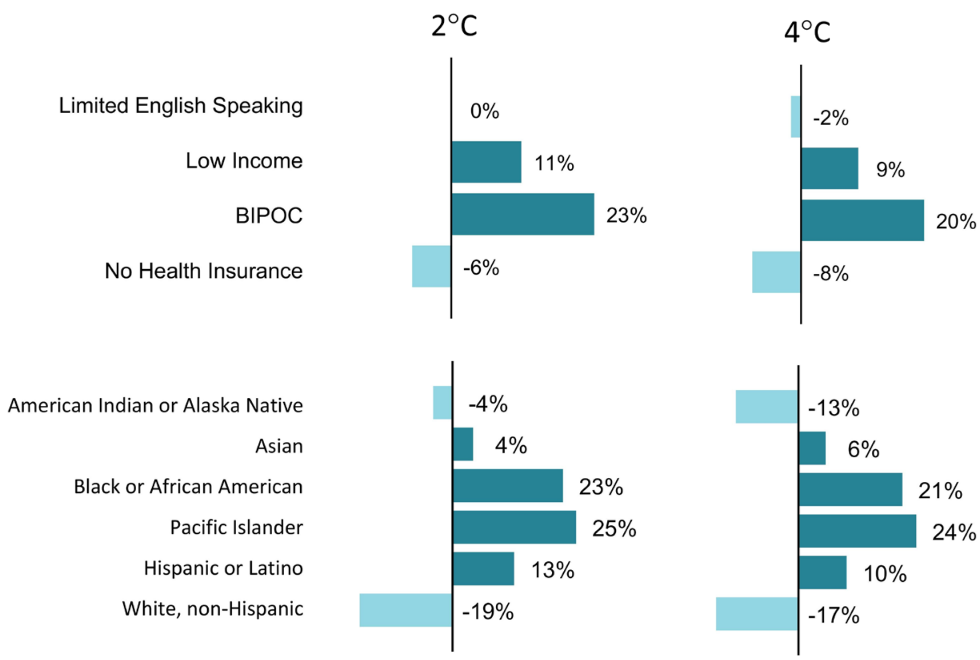


Notes: The maps present new asthma diagnoses attributable to climate-driven changes in air quality per 100,000 children per year. Areas with darker shading have higher rates of affected children. The five states with the highest rates of affected children relative to the county populations are outlined in black. The top two maps show the additional impacts combined across pollution sources for both 2°C and 4°C of global warming. The remaining four maps show the contributions from specific pollutant sources at 2°C specifically. See Appendix C for more details.

Finally, Figure 14 presents the results of the analysis describing the likelihood that certain groups of overburdened children live in areas with the greatest projected number of new asthma diagnoses annually per 100,000 children, following methods described in Chapter 2 and Appendix A. The analysis considers $PM_{2.5}$ and O_3 separately, as the pollutants' contributions to health effects vary across space. Low-income children are 11% and 9% more likely to experience the highest incidence of new asthma diagnoses attributable to climate-driven changes in short-term $PM_{2.5}$ exposure at 2°C and 4°C of global warming, respectively. Similarly, BIPOC children are 23% and 20%, respectively, more likely to experience these effects at the same temperature thresholds. When exploring these same measures by racial and ethnic group, the analysis finds that Asian, Black or African American, Pacific Islander, and Hispanic or Latino children are all more likely than their reference populations to experience the highest likelihood of new asthma cases linked with climate-driven changes in $PM_{2.5}$ exposure.

The analysis does not identify that the socially vulnerable groups of children considered in this report are more likely to be diagnosed with asthma attributable to climate-driven changes in short-term O_3 exposure, specifically. However, among BIPOC children, Asian and Black or African American children are more likely to experience impacts than their reference population, and at levels similar to the $PM_{2.5}$ assessment. More details of the O_3 results are available in Appendix C.

Figure 14: Likelihood of Disproportionate Asthma Impacts Attributable to $PM_{2.5}$ Exposure on Overburdened Children



Notes: These graphics present the results of the social vulnerability analysis of new asthma diagnoses among children attributable to $PM_{2.5}$ exposure linked with climate change, following the methods described in Chapter 2 and Appendix A. The estimated risks for each socially vulnerable group are presented relative to each group's reference population, defined as all individuals other than those in the group analyzed. Populations represent those living in the contiguous U.S. but identifying as a particular race/ethnicity. Analogous results related to O_3 exposure are included in Appendix C.

WILDFIRE SMOKE AND FETAL HEALTH

Wildfire activity across the western U.S. is increasing due to hotter temperatures, more lightning strikes, and more variable precipitation. Wildfire smoke is comprised of numerous air pollutants, notably $PM_{2.5}$ and PM_{10}, which pose a threat to human health, including adverse birth outcomes. For instance, Amjad et al.[234] assessed the impacts of wildfire exposure during pregnancy, finding evidence of association between maternal smoke exposure and low birth weight, particularly when smoke exposure occurred late during pregnancy. Similarly, Heft-Neal et al.[235] evaluated the association between wildfire smoke exposure and risk of preterm birth (<37 weeks) in California, finding that 3.7% of observed premature births were attributable to wildfire during the study period.

This report extrapolates the findings from Heft-Neal et al. to consider what these adverse health impacts might look like nationwide, given future warming conditions and associated wildfire activity. The percentage of premature deaths attributable to wildfire activity from Heft-Neal et al., baseline data on premature births from CDC,[236] and average future $PM_{2.5}$ concentrations associated with wildfires from Neumann et al.[237] are used to estimate additional premature births attributable to wildfire at 2°C and 4°C of global warming (see Appendix C for further details). Nationwide, this analysis suggests an additional 7,700 and 13,600 premature births per year at 2°C and 4°C of global warming, respectively, attributable to wildfire annually relative to a 2010 baseline of 14,700 annual premature births. At 4°C, this represents a 92% increase in premature births relative to the baseline number of births affected by wildfire smoke. Additional research by Childs et al. found that population exposure to moderately high wildfire smoke levels in California has increased four-fold in the last decade, suggesting that estimates of a doubling of wildfire exposure and of wildfire-induced premature births may be conservative.[238] Premature births are associated with $38,600 per case in direct health care costs throughout the first five years of life and $2,300 in costs in subsequent years (2021 dollars).[239]

Chapter 5. Changing Seasons

Chapter highlights

Climate change is altering seasonality in numerous ways, leading to longer warm seasons and shorter cool seasons. While seasonality-related changes have a myriad of health and well-being effects on children, this chapter focuses on the effect of seasonality changes on pollen exposure as well as opportunities for participation in outdoor recreation.

This chapter provides a detailed assessment of how children's health may suffer from pollen exposure as seasons lengthen and temperatures warm. At 2°C of global warming, the analysis projects an additional 5,800 (4,800 to 8,000) asthma-related ED visits per year in children from oak, birch, and grass pollen exposures, increasing to approximately 10,000 (9,500 to 10,700) additional asthma-related ED visits at 4°C of warming. Far larger impacts are expected on outcomes like physicians' visits for allergic rhinitis and prescriptions filled for allergy medications, which are projected to increase by 72,000 (68,000 to 77,000) and 211,000 (199,000 to 224,000) visits per year, respectively, at 4°C of warming. These impacts are associated with 17% and 30% increases above baseline at 2°C and 4°C. Some groups of overburdened children are more likely to experience the most severe impacts associated with oak pollen exposure specifically.

The chapter concludes by highlighting several studies that estimate how the number of outdoor recreation trips may change with climate. Overall, lengthening warm seasons are expected to result in more time spent on outdoor recreation, especially boating and water sports. On the other hand, the number of trips associated with some recreation types, like winter recreation and cold-water fishing, will decrease under climate change.

HOW CLIMATE CHANGE AFFECTS SEASONALITY AND IMPACTS CHILDREN'S HEALTH

Climate change is altering seasons in the U.S., leading to longer warm seasons, decreases in natural snow cover, and shorter periods of prolonged cold weather.[240,241,242,243] Increasing temperatures and changing rainfall patterns are extending the growing season, resulting in longer and more intense pollen and allergy seasons.[244,245,246] Warming ambient air temperatures translate into warming water temperatures, which in turn may increase growth of bacteria and harmful algae, leading to increased potential for exposure to waterborne toxins and pathogens.[247,248] Additionally, longer warm seasons and decreased rainfall increase the potential for more frequent and severe wildfires and droughts, particularly in the western U.S. Shorter cold seasons reduce snowpack melt, thus affecting snow-based recreational activities as well as water supply.

IMPACTS OF CHANGING SEASONALITY ON CHILDREN

This chapter explores health impacts from lengthening and intensifying pollen seasons and effects on opportunities for participation in outdoor recreation and play stemming from changes in various weather conditions (temperatures, precipitation, and, subsequently, snowpack).

There are many health effects that can occur from exposure to plant-, fungi-, and tree-based aeroallergens, all of which could be more abundant in a warmer climate. These include conditions such as allergic conjunctivitis, atopic dermatitis of the skin (eczema), and allergic rhinitis (commonly known as hay fever).[249,250] Some research suggests that there may be correlations between hay fever or eczema and attention deficit/hyperactivity disorder (ADHD) in children.[251,252,253] Most diagnosed cases of hay fever in the U.S. are in children, with the highest rates in southern and southeastern states.[254,255] Studies show that historically, states with higher pollen counts and greater rates of pediatric hay fever have sustained either higher temperatures, with drier conditions and a greater number of sunny days, or wetter weather.[256] Pollen particles in the respiratory tract also may weaken the ability of children's immune

Seasonal changes and children

- This chapter explores the effects of changing seasons associated with airborne allergens (like pollen) and on outdoor recreation participation.
- Asthma and other respiratory conditions associated with pollen exposures are likely to become more common and severe as seasons lengthen.
- Overburdened children are more susceptible than other children to adverse health outcomes associated with pollen exposure.
- Recreation types that benefit from an extended warm season will likely see an increase in participation among children, whereas winter recreation will see a decrease in participation.

systems to respond to common viruses, thus putting children at risk of developing more respiratory infections during high pollen seasons.[257] Finally, mold is another source of environmental aeroallergens, releasing spores into the air. Studies have shown that areas with warmer temperatures and higher precipitation rates have more outdoor mold aeroallergens, which can cause allergic and respiratory diseases, particularly in children.[258,259]

Asthma is among the most common childhood respiratory diseases. It is triggered or exacerbated by plant- and fungi-based aeroallergens.[260,261] This can pose health risks to children who are sensitive to these types of allergens and can lead to sickness, missed school days, or worsened performance in school.[262,263] Exposures to tree and other plant pollen also increase the risk of asthma-related ED visits in children.[264,265] Furthermore, research has shown increases in the volume of prescriptions filled for allergies and ED visits for asthma attacks in young children during times of peak pollen counts in the atmosphere in urban and rural environments.[266,267,268,269] This has environmental justice and equity implications as childhood asthma cases occur disproportionately in children belonging to Tribes or children of color living in urban areas that often have worse air quality and poorer health outcomes.[270,271,272,273,274]

Additionally, climate change increasingly will affect personal choices that children and their families make about spending time outdoors, as well as the quality of outdoor recreational spaces.[275,276] Outdoor recreation is important to maintaining general well-being, particularly for children's behavioral, social, and mental health benefits.[277,278,279] As children interact more with nature, they are shown to have decreased stress and improved mental health, and are likelier to maintain a healthier body weight.[280,281]

Recreational activities that benefit from longer warm seasons may see an increase in future participation among children. This increased time spent outdoors is likely to be beneficial to children given the positive physical and mental health associations. However, not all children have equal access to outdoor recreation, particularly children living in poverty and BIPOC children.[282] These children may miss out on the benefits of outdoor recreation opportunities. Children who live in socioeconomically disadvantaged areas often have fewer opportunities to engage in outdoor recreation for multiple reasons, including limited availability of transportation to wilderness areas, financial limitations, or a general lack of access to green spaces and safe areas to play in their neighborhoods.[283,284,285,286,287]

Winter recreation—including skiing and snowmobiling—is one example of where climate change might *decrease* participation among children.[288,289,290] In addition to the reduction in access to these activities, children in communities that rely on the revenue brought in by winter activities may experience decreased financial security when jobs disappear, which can have myriad downstream effects such as food insecurity, mental health challenges, difficulty concentrating and learning, and limited access to healthcare.[291,292,293] While climate change may also contribute to an increase in cold snaps, primarily through changes in circulation patterns, winter recreation impact research indicates that cold periods will be reduced as the climate warms overall.

Extended warm seasons will increase exposure to waterborne hazards such as harmful algal blooms (HABs) or pathogens like *Cryptosporidium*.[294,295,296,297,298] HABs subsequently can limit recreational activities such as fishing, swimming, or playing on the beach;[299,300] additionally, Tribal communities' use of water bodies for subsistence fishing and as sacred resources may be disrupted by these hazards.[301,302] Waterborne hazards can also affect children indirectly when the hazards result in fisheries closures, reductions in tourism dollars, or other effects to their parents' or caregivers' livelihoods.[303,304,305,306,307]

POLLEN AND CHILDREN'S HEALTH

This analysis projects increases in adverse health outcomes among children from more frequent and greater exposure to pollen resulting from climate change. It relies on findings from Neumann et al.,[308] which studied the relationship between increasing season length attributable to climate change for various pollen sources (oak, birch, and grass) and the projected number of future ED visits associated with asthma. Because ED visits represent a relatively rare outcome resulting from pollen exposure, the analysis also considers how the number of physicians' visits associated with allergic rhinitis and prescription fills for allergies may increase in the future. The analysis is guided by findings from Saha et al.[309] that link these health outcomes to intensity of exposure to a broader selection of tree, grass, and weed pollen, including ragweed.

Figure 15: Pollen Analysis Steps

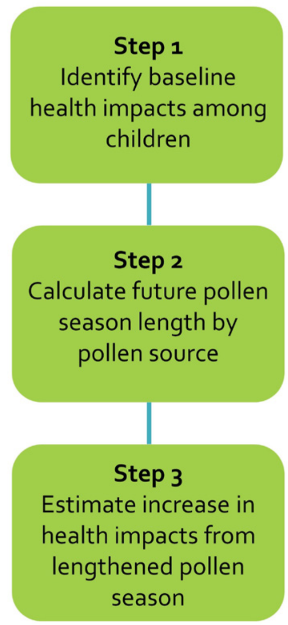


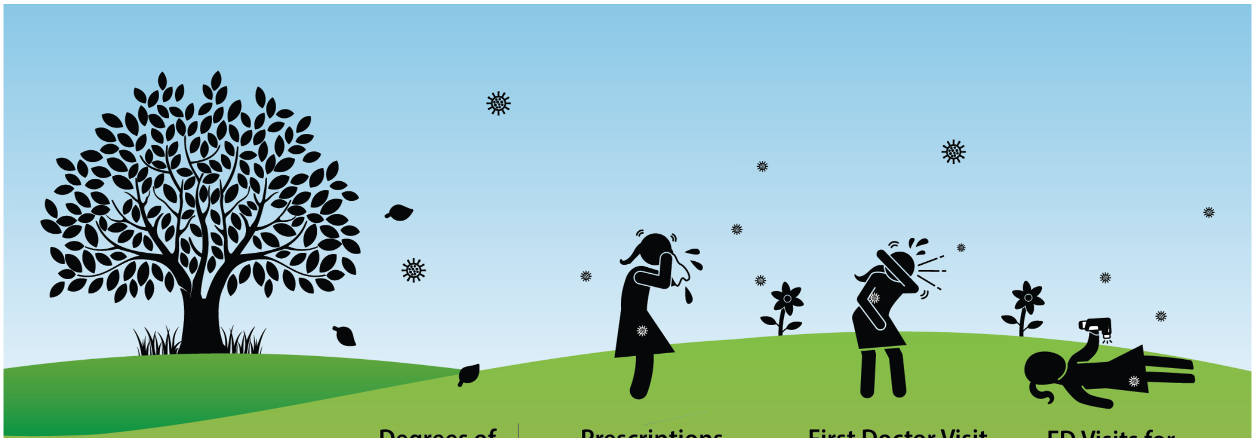
Figure 15 summarizes the analysis steps; more detail about data sources and assumptions is provided in Appendix D. Like the air quality analysis presented in Chapter 4, future health effects associated with climate-driven changes in seasonal conditions are quantified using U.S. EPA's BenMAP[310] model (see Chapter 4 for details). To forecast health impacts, the analysis starts with data from a study projecting future ED visits for asthma. Then, estimates of future physicians' visits and prescription fills associated with a lengthening pollen season are scaled by the rate of change in projected ED visits, for each degree of global warming.

What are the sources of pollen and aeroallergens that affect children?

Different types of plants and trees produce different types of pollen or other aeroallergens. Ragweed is a common type of allergen-producing plant that grows across the U.S.,[311] including in urban areas,[312] and is known to cause irritation and inflammation of the respiratory tracts of sensitive individuals.[313] One ragweed plant can release up to a billion pollen grains into the air over the course of a season.[314] Oak tree pollen is another allergen that has been implicated in increased numbers of ED visits related to asthma.[315,316,317,318]

Finally, while mold is not a plant, molds release spores, another type of environmental allergen. Studies have shown that areas with warmer temperatures and higher precipitation rates can lead to increases in outdoor mold aeroallergens that can cause allergic and respiratory diseases, particularly in children.[319,320] The same types of increases in outdoor mold spore production have been seen after extreme weather events.[321]

Figure 16: Projected Additional Annual Impacts of Pollen on Children's Health



Degrees of Global Warming	Prescriptions Filled for Allergies	First Doctor Visit for Allergic Rhinitis	ED Visits for Asthma
2°C	121,000 *(101,000 to 167,000)*	41,000 *(34,000 to 57,000)*	5,800 *(4,800 to 8,000)*
4°C	211,000 *(198,000 to 224,000)*	72,000 *(68,000 to 77,000)*	10,000 *(9,500 to 11,000)*

Notes: This graphic presents the results of the pollen exposure analysis at 2°C (equivalent to 3.6°F) and 4°C (equivalent to 7.2°F) of global warming. The results describe additional impacts per year for children, conditions relative to baseline (1986-2005), and assume populations of children will increase over the 21st century (see Chapter 2, Appendix A). The table displays the average and range across climate models. Figure 17 provides baseline levels for each included health impact. Appendix D provides results for additional degrees of global warming.

At 2°C of global warning, the analysis projects an average of 5,800 (ranging from 4,800 to 8,000 across climate models) additional asthma-related ED visits per year among children from pollen exposure (Figure 16). Once global temperatures reach 4°C above baseline levels, there are projected to be an additional 10,000 (9,500 to 11,000) ED visits per year associated with asthma exacerbations among children. First-time pediatric visits to physicians for allergic rhinitis are projected to increase by 41,000 (34,000 to 57,000) and 72,000 (68,000 to 77,000) annually at 2°C and 4°C of warming, respectively. Pollen exposure could also result in an estimated 121,000 (101,000 to 167,000) to 211,000 (198,000 to 224,000) additional prescriptions filled for allergies each year at the same temperature thresholds.

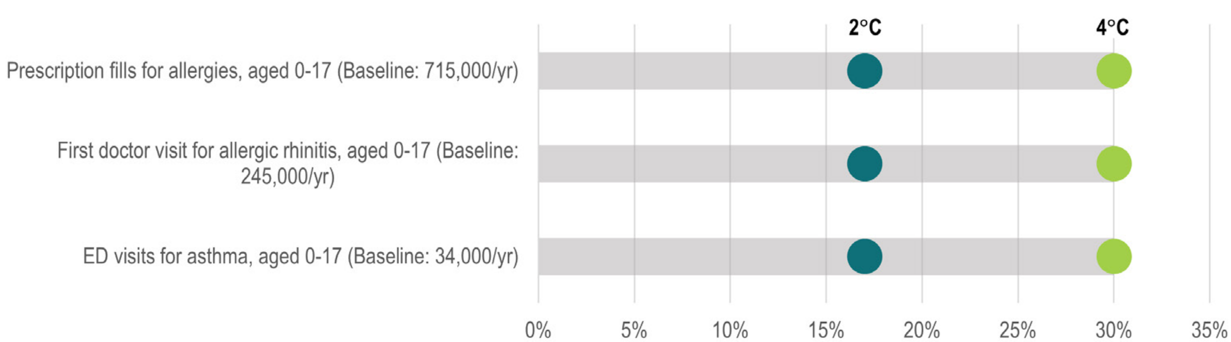
Relative contributions of oak, birch, and grass pollen to these total health impacts are also explored. At 2°C of warming, 45% of cases are associated with birch pollen, 31% with oak pollen, and 24% with grass pollen. Likewise at 4°C of warming, the contributions are 41% from birch pollen, 35% from oak, and 24% from grass. Taken together, birch pollen is expected to be the largest contributor to future climate-induced ED visits for asthma among the three sources explored in this analysis.

Figure 17 provides additional information about how these health impacts are projected to increase in the future relative to levels observed in the baseline. Neumann et al. estimated ED visits would increase by 17% at 2°C of global warming and by 30% at 4°C. The analysis presented in this chapter directly relies on these percent changes to estimate the future total number of doctors' visits for allergic rhinitis and prescription fills for allergies. Therefore, Figure 17 conveys that these two less severe health impacts will increase by the same percent. Further research is needed to more definitively predict if these health measures are likely to increase at the same future rate.

There are several key reasons these results might represent a lower bound of the potential magnitude of allergen-induced suffering among children in the future. First, Neumann et al. consider only the effects associated with *lengthening* pollen seasons, although *intensifying* pollen seasons also are linked with climate change and may result in more illnesses among children. These links to climate change include changes to seasonality but are also connected to changes in pollen production and allergenicity associated with elevated carbon dioxide in the atmosphere because plants use carbon dioxide as an input to photosynthesis.[322] In addition, the health outcomes in the Neumann et al. study stem only from oak, birch, and grass pollen exposures, although pollen from all species of trees, grass, and weeds, especially ragweed, will affect children.[323,324,325] Finally, beyond pollen, childhood exposures to other allergen sources such as mold could increase under climate change and result in additional adverse health effects on children.[326,327]

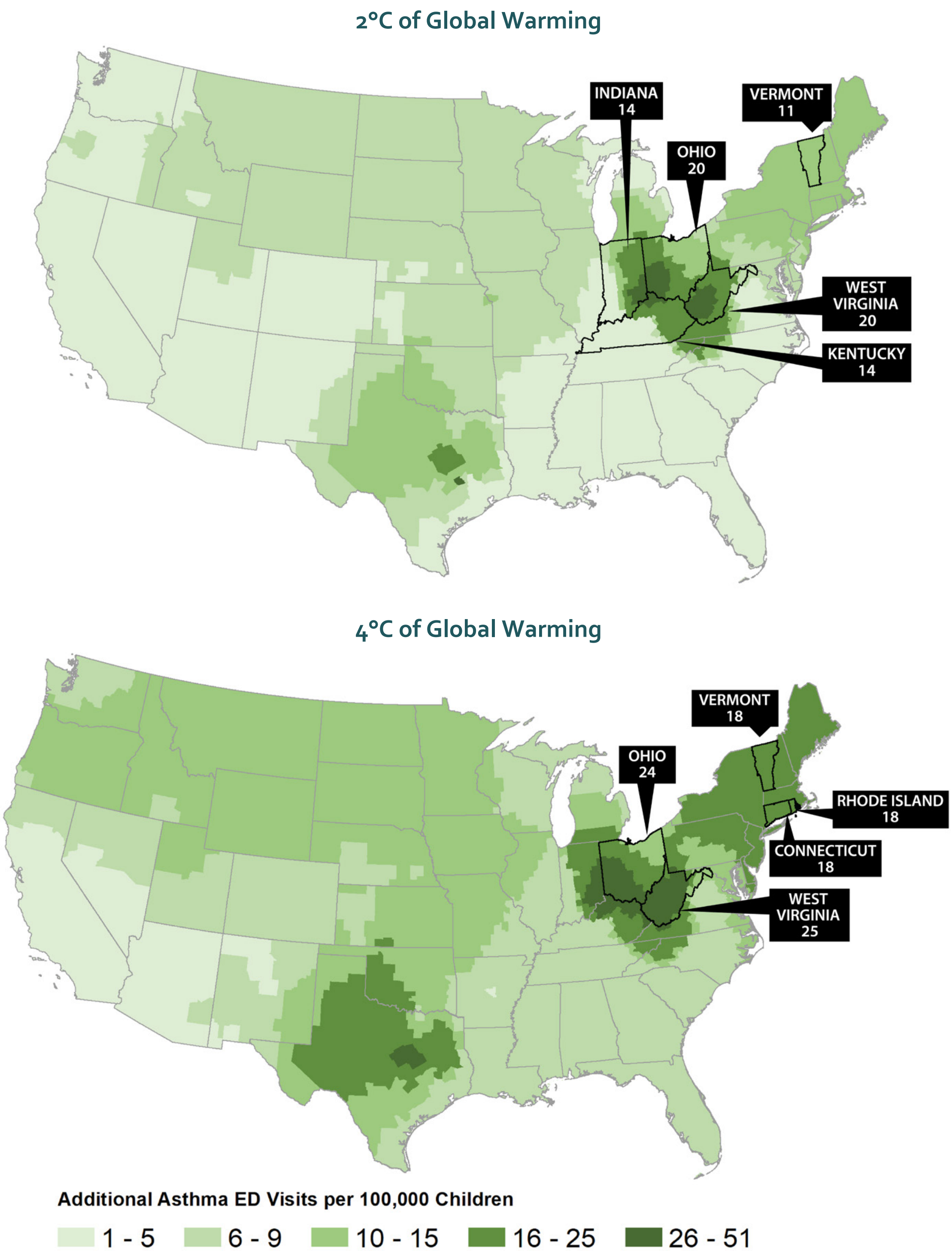
The health burdens associated with pollen exposure can impose costs on children, their caregivers, and society more generally. ED visits are typically associated with direct medical costs of approximately $550 per case (2021 dollars).[328,329] The costs of prescriptions for allergic rhinitis are approximately $130 per year, where patients may need one or more prescriptions filled annually.[330] Visits to physicians are often valued at approximately $150 per visit. Experiencing both mild and serious symptoms from exacerbations of allergies and asthma may result in child absences from school or other enjoyable activities, as well as lost productivity for their parents and caregivers. Even when children attend school, the discomfort and distraction associated with experiencing pollen allergy symptoms can significantly diminish school performance.[331]

Figure 17: Estimated Percent Change in Pollen Health Impacts Relative to Baseline



Note: This graphic describes how the health impacts associated with pollen exposure linked to climate change increase relative to baseline conditions (1986-2005), as listed in the figure and under assumptions described in Appendix D. The teal circles describe increases between baseline and 2°C of global warming; the green circles convey increases at 4°C.

Figure 18: Estimated Distribution of Additional Asthma-Related ED Visits Per 100,000 Children



Notes: These maps present additional asthma-related ED visits attributable to exposure to oak, birch, and grass pollens at the county level. Areas with darker shading have higher rates of affected children. The five states with the highest rates of affected children relative to the county populations are outlined in black. See Appendix D for more details on the spatial distribution as well as impacts by pollen source (oak, birch, and grass).

Figure 18 highlights the regional distribution of these future pollen-induced health impacts. As shown, the incidence of asthma-related ED visits per 100,000 children is highest in parts of the Northeast, Midwest, and Mid-Atlantic regions. The five states with the highest impacts per 100,000 children at 2°C of global warning are Indiana, Kentucky, Ohio, Vermont, and West Virginia. At 4°C of warming, Connecticut and Rhode Island experience among the highest per capita rates nationally. Children are also impacted at a higher rate in central Texas. California and the Southwest region are among the areas projected to experience the lowest pollen-related pediatric health impacts per capita.

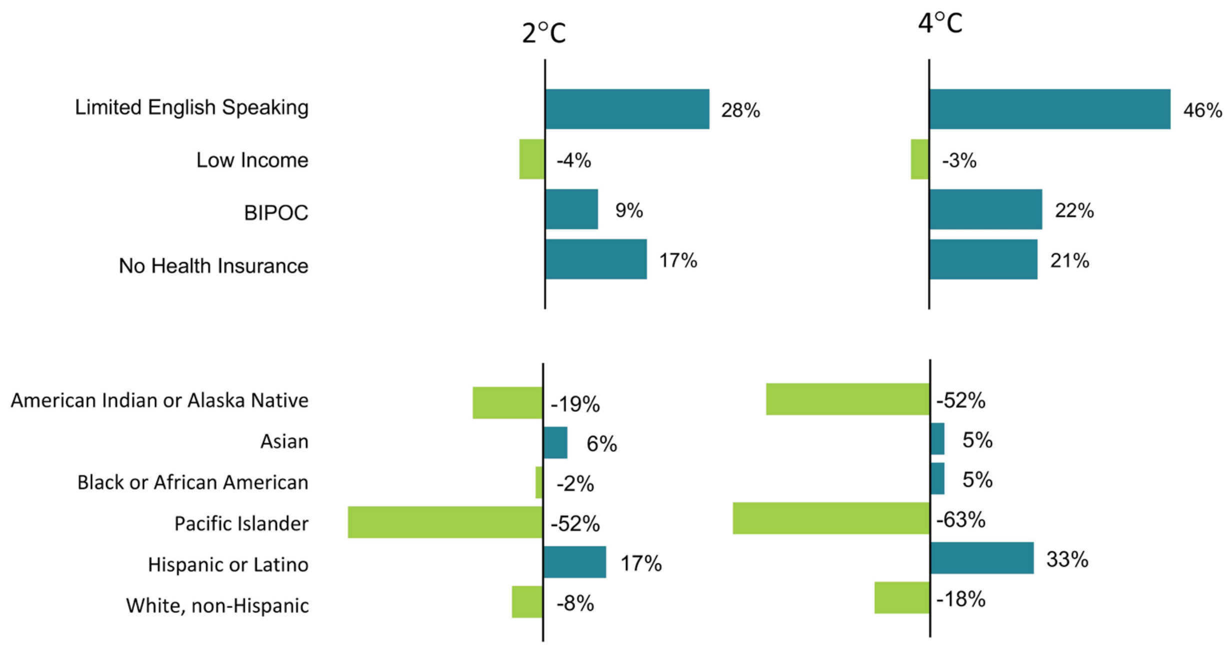
Appendix D provides more detail on the spatial distribution of future asthma-related ED visits linked to each pollen source considered in Neumann et al. As shown, birch pollen is the main contributor to these health impacts experienced throughout Indiana, Kentucky, Ohio, and West Virginia. ED visits associated with oak pollen are more common throughout the Northeast region, whereas grass pollen contributes to higher concentrations of cases in the Northwest region as well as Utah and Kansas. Both oak and grass pollen contribute to the higher rates in central Texas.

Finally, Figure 19 presents the results of the analysis describing the likelihood that overburdened populations of children live in areas with the greatest projected number of asthma-related ED visits from pollen exposure per 100,000 children, following methods described in Chapter 2 and Appendix A. The analysis does not identify that the overburdened populations of children are more likely to experience the greatest impacts associated with combined effects of oak, birch, and grass pollen. White, non-Hispanic children are most likely to experience pollen-related health impacts (see Appendix D). It should be noted that vulnerability to pollen-related morbidity depends only in part on pollen exposures. Equally important are underlying rates of allergies and asthma, which numerous studies have shown are disproportionally high among BIPOC children.[332,333]

However, when disaggregating the analysis by pollen type, the health impacts associated with oak pollen are shown to be concentrated among some of the groups assessed. The underlying pollen exposure data suggest that the higher exposures to birch and grass pollen tend to occur in suburban and rural areas, while exposure to oak pollen is at least as prevalent and perhaps somewhat higher in urban areas – and urban areas tend to be better correlated with the locations of overburdened children.

For instance, children living in limited English-speaking households are 28% and 46% more likely to experience the highest incidence of ED cases for asthma attributable to oak pollen exposure at 2°C and 4°C of global warming, respectively. Further, children not covered by health insurance are 17% and 21% more likely to experience these effects at the same temperature thresholds. Across groups, BIPOC children also experience these effects disproportionately. When evaluating by racial and ethnic group, the analysis finds Hispanic or Latino and Asian children are the groups driving these measures at 2°C of global warming; Black or African American children are also among the groups experiencing the highest likelihood of ED visits from oak pollen exposure at 4°C of global warming.

Figure 19: Likelihood of Disproportionate ED Visits for Asthma Impacts Attributable to Oak Pollen Exposure on Overburdened Children



Notes: These graphics present the results of the social vulnerability analysis of asthma-related ED visits among children attributable to oak pollen exposure linked with climate change, following the methods described in Chapter 2 and Appendix A. The estimated risks for each group are presented relative to each group's reference population, defined as all individuals other than those in the group analyzed. Populations represent those living in the contiguous U.S. but identifying as a particular race/ethnicity. Analogous results related to birch and grass pollen are included in Appendix D.

OUTDOOR RECREATION

Research demonstrates that climate change will alter recreational access, opportunities, and preferences through changes in seasonality. This section highlights several studies that project future recreation access under climate change. While none of these studies are specific to children, they provide suggestive evidence for how recreational opportunities will change for children in the future.

All Outdoor Recreation

Willwerth et al. predicted the future number of outdoor recreation trips for Americans aged 15 and older resulting from changes in temperature and precipitation.[334] The authors find that participation in outdoor recreation increases as weather warms, driven by time spent on water sports and boating, and that individuals in the northern and southern regions respond differently to the warmest days. If individuals continue to respond to temperature as they have between 2003 and 2019, the authors project a net increase of 157 million outdoor recreation trips across all types annually at 2°C of warming in the contiguous U.S. (not global), and up to 288 million trips at 4°C of warming.

Winter Recreation

Wobus et al. assessed how winter recreation, including skiing and snowmobiling, will decrease without reliable snow in the future.[335] The authors project that by 2050, the U.S. will see a net decrease of 17.4 million winter recreation trips annually under a lower emissions scenario (RCP4.5) and 21.5 million trips annually under a higher emissions scenario (RCP8.5). Children currently represent the majority of skiers and snowboarders in the U.S.[336]

Freshwater Fishing

Jones et al. document how increases in ambient temperatures are likely to raise stream temperatures and decrease the areas suitable for cold-water fishing (e.g., fly-fishing for trout).[337] They estimate that annual cold-water fishing days will decline by 1.25 million days by 2030, to 6.42 million days by 2100. Instead, anglers will spend more time fishing in warm-water habitats. This is notable as the largest share of fishing participants in the U.S. are between ages 6 and 12.[338]

Recreation at Reservoirs

Chapra et al. model how increasing temperatures and changing precipitation levels will affect the frequency of HABs in large reservoirs, and how closures will impact recreation, including swimming and boating.[339] They estimate that the 279 reservoirs and lakes covered in the study will experience a projected 1.2 million to 5.3 million visitor-days lost per year by 2090.

Chapter 6. Flooding

Chapter highlights

This chapter describes how flooding affects children and how those impacts are expected to increase as the climate changes. Evidence shows that children experience increased safety risks—including drowning—during flooding events, as well as mental stress associated with displacement from their homes and communities. Exposures to waterborne pathogens and mold in flooded structures also pose health risks. Stress can affect birth outcomes.

This report quantifies the number of children who may experience adverse effects due to flooding in coastal areas; specifically, children who may experience short-term displacement from their home as well as those at risk of losing their homes completely. If no additional adaptation measures are taken, approximately 185,000 (159,000 to 437,000) children are projected to lose their homes from coastal flooding at 50 cm of global sea level rise, increasing to 1.13 million (477,000 to 3 million) at 100 cm. More than 1 million additional children may be temporarily displaced from their homes due to coastal flooding at both 50 cm and 100 cm. Adaptation, including building sea walls, could prevent these impacts for many children. The greatest flooding impacts are concentrated along the Atlantic and Gulf coastlines. Children in overburdened households are projected to experience these impacts disproportionately.

Inland (or riverine) flooding will increase in many areas due to climate change, although fewer children are projected to experience these impacts relative to coastal flooding. For instance, at 4°C, an estimated 560,000 children could be temporarily or permanently displaced from their homes.

HOW CLIMATE CHANGE EXACERBATES FLOODING AND IMPACTS CHILDREN

The frequency of flooding events due to sea level rise will continue to worsen as the climate changes.[340] This includes **inland flooding**, which is the type seen following heavy rainfalls or snowmelt, when flash-flooding occurs during a severe storm, or when rivers or other water bodies overrun their banks,[341] and **coastal flooding**, which refers to nuisance or high-tide flooding, storm surge, high waves that occur during coastal storms, and inundation related to sea level rise.[342] Storm surge is a particular concern; it is the most common cause of physical injury and death during hurricanes, and it also can flood large coastal areas, causing property damage and persistent health risks.[343] The impacts of storm surge can be compounded when surges coincide with high tides, making the flooding that much more extreme and destructive to life and property.[344] Scientific assessments and indicators developed over the past decade have demonstrated a high likelihood of climate change exacerbating or causing coastal flooding, inundation, and inland flooding.[345,346]

IMPACTS OF FLOODING ON CHILDREN

Children face myriad threats from flooding. The physical health impacts of flooding can include cuts, bruises, sprains, and broken bones, which may have short- or long-term health effects.[347] However, tragically, drownings are among the most common types of reported injuries.[348] According to data from the National Oceanic and Atmospheric Administration, between 2017 and 2021, 92 individuals who were 19 and younger were reported to have died from flood-related drownings, representing 16% of all flood-related drownings.[349] Child drownings often are associated with falling into swimming pools or other similar circumstances; however, flood-related injuries and fatalities involving children often occur from slips and falls into or near flooded waterbodies.[350] Additionally, children may be injured or killed if a car they are riding in becomes swept away or overwhelmed by flash-flooding.[351] Research shows that as precipitation amounts have increased in parts of the country, so too have flooding events,

Flooding and children

- Children are susceptible to increased safety risks during floods, including drownings.
- Flooding increases children's exposure to waterborne pathogens, as well as mold in damaged structures.
- Temporary or permanent displacement from homes and communities can create mental health challenges for children.
- Stress experienced by pregnant women during a flooding event can negatively impact birth outcomes.
- Overburdened populations often live in flood-prone areas and are more likely to experience flood impacts.

including flash-flooding.[352] This is especially significant as flash-flooding is responsible for the highest number of flooding-related deaths.[353,354]

The risk of disease may increase during or after flooding events. For example, children may be exposed to pathogens like the norovirus or bacteria of the genus *Vibrio*, either through open wounds in their skin[355] or ingesting drinking water. Depending upon the species, pathogens can cause a range of health effects, including ear infections, flu-like symptoms, or death.[356] Such health effects may become a greater issue in the future as increased cases of vibriosis[357] (any infection resulting from exposure to non-cholera-causing *Vibrio* genus bacteria) and norovirus[358] (the latter due largely to effluent and increased sewage runoff)[359] have been linked to climate change.[360] While many children may not suffer long-term effects from pathogens, immunocompromised children are at greater risk of severe illness or death.[361] Children can be exposed to different types of chemical and biological pollutants or pathogens if they ingest contaminated water either accidentally, by water splashing into their mouths, or from contaminated drinking water sources caused by infrastructure failures during flood events.[362]

Homes that experience flooding are more likely to have dangerous levels of mold, which is linked to increased incidence of asthma in children.[363] Research also shows that mold-related asthma diagnoses and incidences are likely to increase with climate change.[364,365] There are demonstrated correlations between childhood asthma, race, and socioeconomic status, meaning that exposure to flooding could worsen health equity concerns.[366,367]

Pregnant women and fetuses are also at increased risk of experiencing harm associated with flooding. Psychological stress experienced by mothers can be imparted to fetuses during pregnancy, which in turn can lead to adverse pregnancy and birth outcomes, such as preterm birth, low birth weight, and stillbirths, among other effects.[368,369] Limited studies point to ways in which prenatal stress incurred during flooding conditions can lead to cognitive effects in offspring or a failure to thrive.[370,371] Additional ways in which pregnant women may experience harm during flooding include gastrointestinal issues linked to exposures to pathogens or dehydration due to lack of clean water,[372] which can impact the health of the fetus.

Flooding can also impact children's mental health. For example, children may experience post-traumatic stress disorder (PTSD) upon exposure to climate change-related trauma from extreme weather events, such as destructive flooding, or after physical injury or loss of their home.[373,374] PTSD may be short-term or chronic and can manifest in a variety of ways in children, including regressions in toilet-training and communications skills, panic attacks, and a propensity for aggressive behavior.[375,376,377] Stress in childhood, and especially in adolescence, that is related to climate change or exposure to extreme events can contribute to lifelong mental illness, including depression or attachment disorders. It also may contribute to the development of substance misuse disorders.[378,379]

Flooding can disproportionately affect low-income and BIPOC populations. Many flood-prone areas in the U.S. are predominantly disadvantaged, non-White communities.[380] Furthermore, residents within these same demographics are at risk of experiencing "worse" or exacerbated short- or long-term impacts (e.g., displacement or chronic health conditions) of severe tropical weather-related flooding, such as hurricanes, compared to White and/or wealthier communities.[381] As an example, Hurricane Harvey and its documented impacts on the residents of the Greater Houston area have fallen disproportionately on a broad range of disadvantaged, non-White communities.[382,383,384,385,386]

Managed retreat, as well as climate change-related gentrification (see "Glossary" for definitions), are felt most acutely by low-income and BIPOC populations that are more likely to have limited resources or fewer options to move.[387,388] Additionally, leaving a particular area of land or body of water that has cultural or historic significance to communities, including BIPOC individuals, can cause psychological and emotional trauma.[389] As sea level rise increases due to climate change, coastal housing in many parts of the country is losing its value, while inland areas are becoming more and more expensive. This minimizes the flexibility of many coastal inhabitants to relocate.[390] Additionally, groups with strong personal and cultural ties to an area may experience heightened levels of trauma if moving becomes a necessity.[391] Experiencing or exposure to gentrification, loss of housing or housing uncertainty, or observing stress among trusted parents or caregivers may affect children's mental health.[392]

COASTAL FLOODING AND CHILDREN'S HOMES

This section describes an analysis of coastal flooding risks to children through impacts on their homes. The analysis leverages the National Coastal Property Model (NCPM), including recent evidence from Neumann et al.,[393] to model the number of children likely to be temporarily displaced from or lose their home because of coastal flooding. The following two measures of risk are proxies for a larger set of risks to children associated with coastal flooding:

1. *Number of children likely to be temporarily displaced:* This scenario is associated with a high likelihood of temporary home displacement, such as relocation while minor flooding subsides and structures are repaired. This scenario results in various risks to children, including financial and mental stress or loss of schooling opportunities. When children return to their homes following the flooding event, the structures may contain levels of mold that pose health risks to children. Temporary displacement is triggered by damages to residences associated with storm surge, a coastal hazard amplified by sea level rise.

2. *Number of children likely to lose their home:* This scenario considers the high likelihood of permanent home loss through repeated flooding episodes causing damage or permanent inundation and serves as an indicator of the most severe impacts of coastal flooding. For instance, children forced to abandon their homes may experience the financial stress that is placed on families that require new housing. This may be worsened by the mental stress associated with displacement from a community and sites of personal and cultural importance, as well as the threat of housing uncertainty. Concurrent or subsequent disrupted school attendance may also lead to lower educational attainment. Home loss can be triggered by intense and repeated damage from storm surge or by permanent inundation from sea level rise.

Figure 20 summarizes the steps in the coastal flooding analysis, with more details in Appendix E. First, children living in structures experiencing flooding damage under current conditions are identified for the entire contiguous U.S. coastline. Next, the analysis forecasts future coastal flooding from sea level rise and storm surge resulting from climate change. The NCPM then identifies the annual expected damages to residential structures within a 150 m grid. The temporary home displacement scenario evaluates homes with minor damage (2% annual expected damages). The home loss scenario considers properties once annual expected damages reach 10%. Finally, to approximate the number of children who may experience these flooding risks, the analysis maps the 150 m grids to census block groups to calculate the number of children living in those areas. Across all 302 coastal counties, the 2010 U.S. Census identifies over 17.2 million children, equivalent to 23% of all children in the contiguous U.S. By the end of the century, this is expected to grow to 24.5 million children across coastal counties. To show how flooding impacts may progress over the 21st century, results showcase both 50 cm and 100 cm of global mean sea level rise (see Chapter 2).

Figure 20: Coastal Flooding Analysis Steps

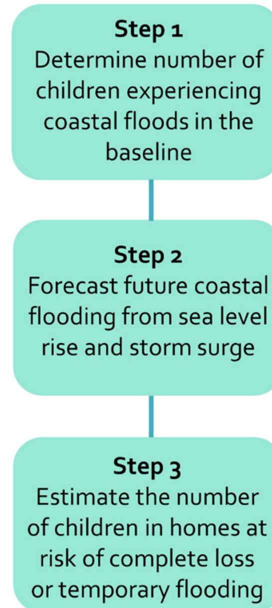
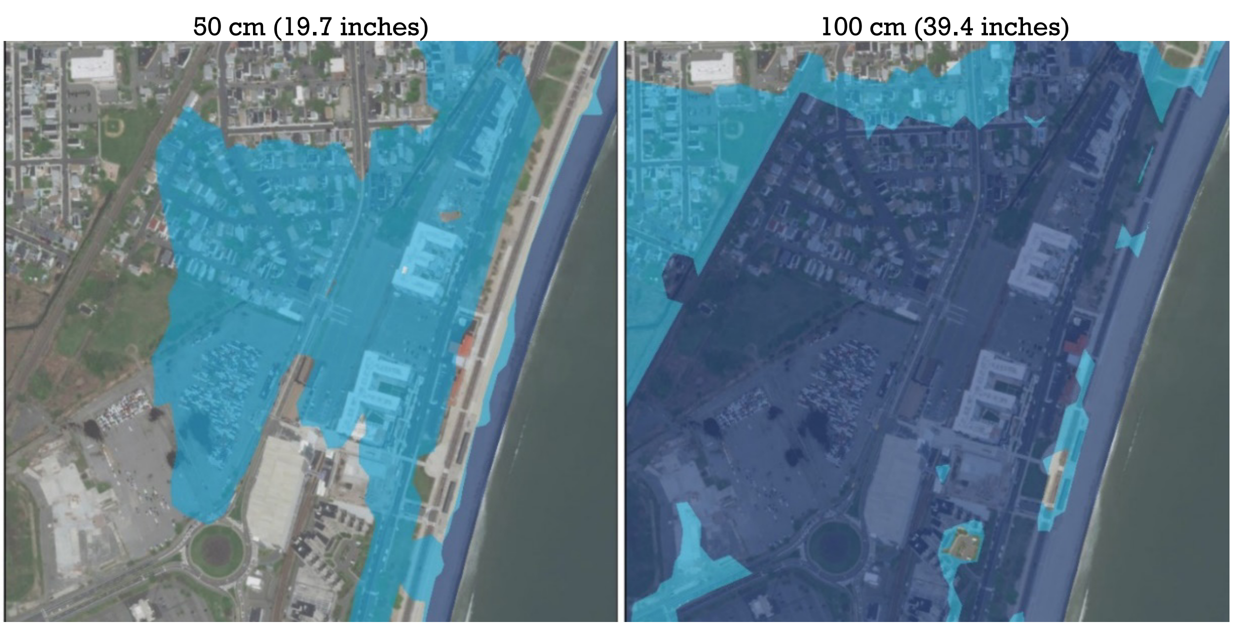


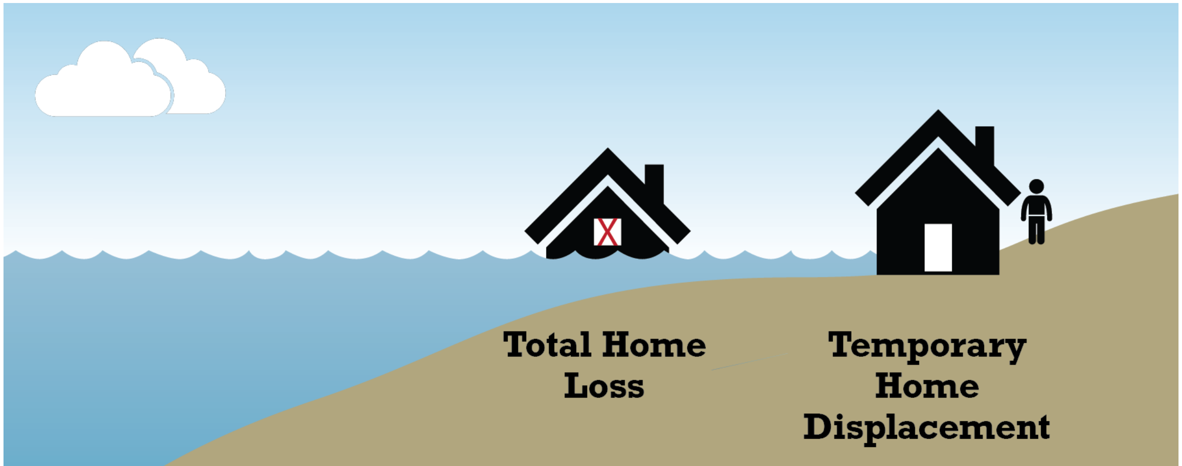
Figure 21 provides an example of the flooding risk severity and global sea level rise scenarios included in this analysis. As shown in the lefthand graphic, the 50 cm scenario generally projects more homes with some amount of flooding that likely results in temporary displacement of families, with fewer homes completely lost. Then, at 100 cm, many more homes are permanently lost, including homes that experienced temporary damage at 50 cm. In other words, homes change from the temporary damage category to the more severe home loss category as sea level rise progresses.

Figure 21: Flooding Scenarios in One Coastal Area



Notes: These maps present an illustrative example of how coastal flooding progresses between 50 cm and 100 cm.

Figure 22: Projected Additional Coastal Flooding Impacts on Children Assuming No Additional Adaptation



Global Mean Sea Level Rise	Number of additional children living in these homes in coastal areas	
	Total Home Loss	Temporary Home Displacement
50 cm	185,000 *(159,000 to 437,000)*	1.01 million
100 cm	1.13 million *(477,000 to 3.0 million)*	1.08 million

Notes: This graphic presents the results of the coastal flooding analysis at 50 cm (equivalent to 19.7 inches) and 100 cm (equivalent to 39.4 inches) of global sea level rise. The impacts assume populations of children will increase over the 21st century (see Chapter 2, Appendix A) and convey the impacts to children under the "no additional adaptation" scenario. The results describe additional coastal flooding impacts on children relative to baseline conditions (see Figure 23). Temporary home displacement refers to the number of children affected each year, whereas the number of children affected by home loss is cumulative (i.e., all children affected by home loss at or before the sea level rise threshold). The table displays the average and a statistically derived range of uncertainty for sea level rise for the 50 and 100 cm projections. Chapter 2 and Appendix E provide additional detail on the specific basis for estimating uncertainty in sea level risk and the Appendix provides results for additional global sea level rise thresholds and assuming "with adaptation."

In addition to the severity scenarios and global mean sea level rise projections, the NCPM models two different assumptions about how communities adapt to the threat of coastal flooding by building levees or sea walls, investing in beach nourishment, and elevating properties. The "no additional adaptation" scenario assumes properties maintain the current level of protection, even in cases where some building codes may require it in the future, while the "with adaptation" scenario assumes properties are protected when the benefits of protection outweigh the financial costs of implementing the protection measures.

Figure 22 summarizes the findings of the coastal flooding risk analysis assuming "no additional adaptation" conditions. As indicated in the figure caption, the count of children experiencing home loss considers all homes lost up to and including the time when sea level reaches the indicated sea level rise threshold. The analysis finds that temporary home displacement would affect an additional

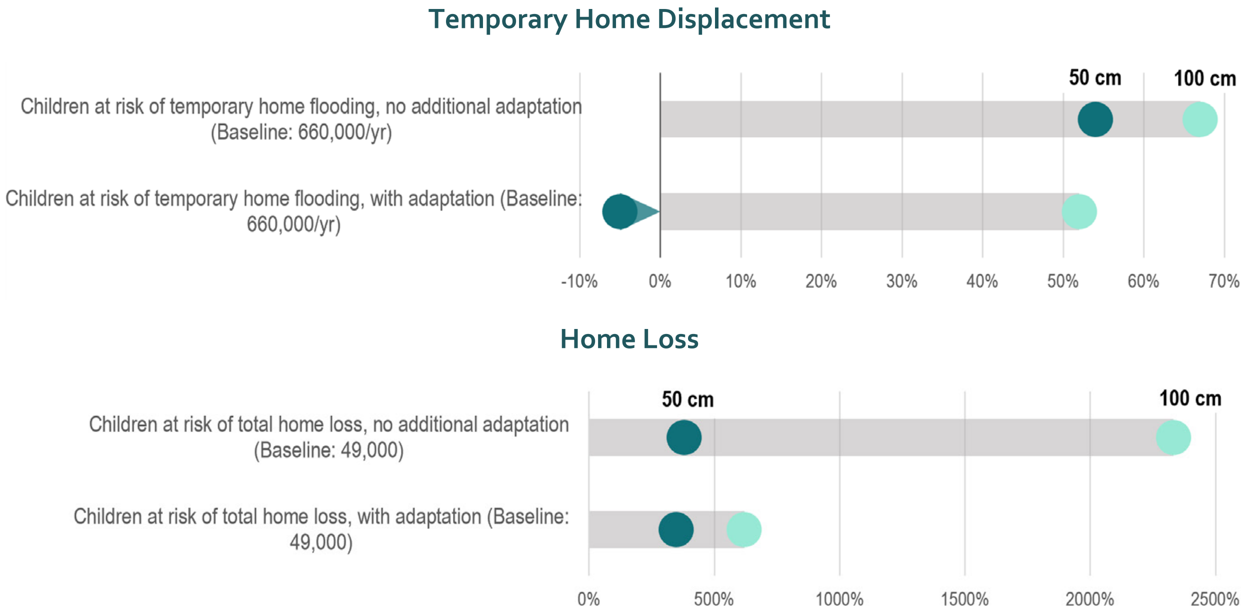
1.01 million children per year at 50 cm and 1.08 million children per year at 100 cm. Complete home loss is projected to affect 185,000 (ranging from 159,000 to 437,000 across climate models) children cumulatively as sea levels rise to 50 cm above current levels. The number of children cumulatively affected by home loss increases to 1.13 million (477,000 to 2.96 million) at 100 cm of sea level rise.

The "with adaptation" scenario projects that the number of children affected by coastal flooding is less widespread, but the effects of adaptation are site- and context-specific. Home loss is projected to affect an estimated 170,000 (149,000 to 216,000) additional children and 300,000 (223,000 to 603,000) additional children at 50 cm and 100 cm of global mean sea level rise, respectively. Relative to the "no additional adaptation" scenario, adaptation prevents home loss for an estimated 16,000 children at 50 cm on average across models. By the time global mean sea level rise reaches 100 cm, adaptation could prevent home loss for 830,000 children on average, suggesting that well-timed adaptation is especially effective at reducing risks under more significant global sea level rise levels. The maps of impacts by state in Appendix E show that this substantial benefit of cost-effective adaptation, where adopted, is uneven across states. For example, for 100 cm, adaptation reduced the number of children experiencing total home loss in Florida by more than a factor of 10, and in California by a factor of 2, but in North Carolina by less than 15 percent.

Adaptation prevents temporary home displacement for an estimated 380,000 children per year at 50 cm on average but only 124,000 children per year at 100 cm, since protection in response to coastal flooding risks tends to prioritize areas that are at the highest risk of significant damage. While the risk reduction benefits of coastal adaptation are apparent, the financial and time investments necessary to implement such protection will be large (on the order of at least several billions of dollars annually, and hundreds of billions through the end of the century) and are an important consideration for the interpretation of these results.

The relatively high number of children still likely to be affected by coastal flooding under the "with adaptation" scenario implies that there are limits to adaptation. Adaptation is a complex process and is difficult to forecast. Many adaptation response decisions in coastal zones are not made with strict cost-benefit decision rules, particularly at the local level. Other factors may include local zoning bylaws, future land use plans, the presence of development-supporting infrastructure, or proximity to sites of high cultural value. The analytical framework of the NCPM provides a simple, benefit-cost decision framework that can be consistently applied for regional and national-scale analysis, but the exact areas where adaptation is implemented may be more or less extensive than reported here.

Figure 23: Estimated Percent Change in Coastal Flooding Impacts Relative to Baseline Conditions



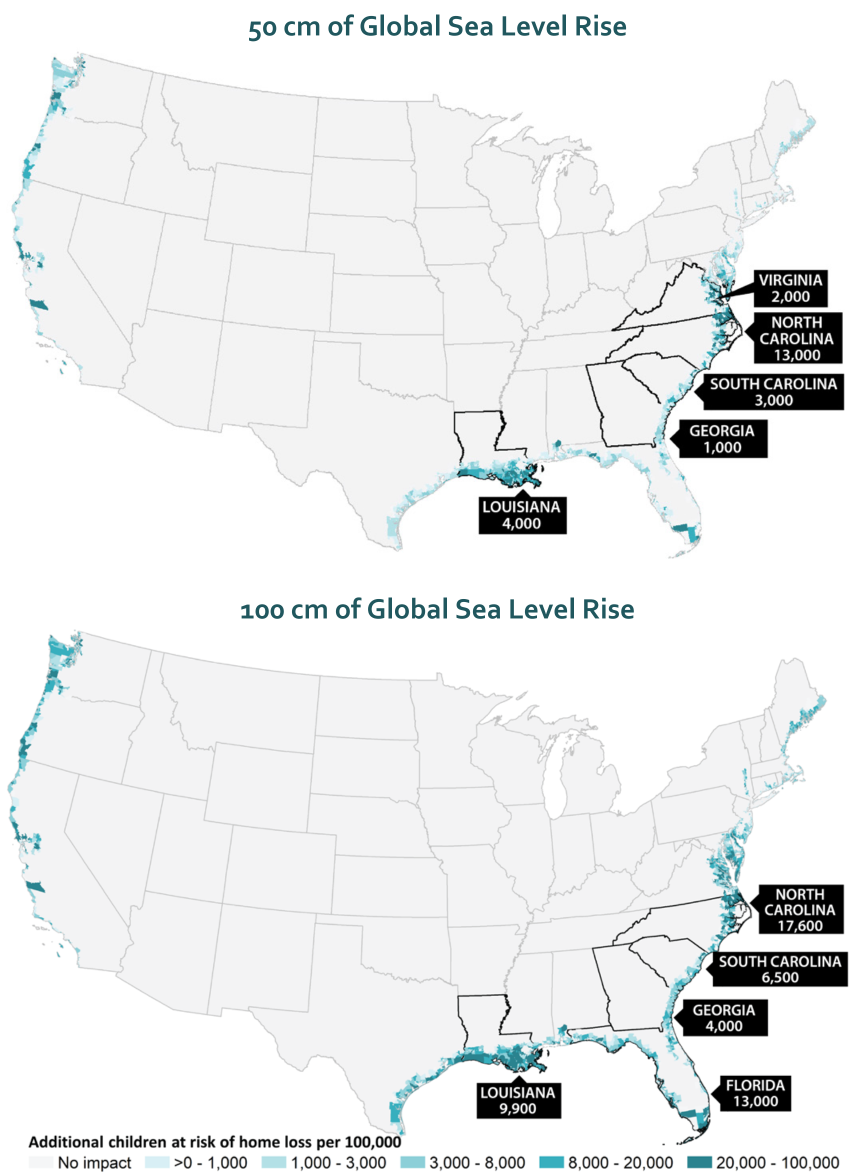
Notes: This graphic describes how the number of children affected by coastal flooding damage to their homes will increase relative to baseline (1986-2005) under assumptions described in Appendix E. The teal (darker) circles describe increases between baseline and 50 cm of global sea level rise; the light blue circles convey increases at 100 cm. "Comets" highlight leftward movement and therefore decreases relative to baseline. The graphic includes temporary displacement and home loss (with different axes) under the "no additional adaptation" and "with adaptation" scenarios.

Figure 23 compares these various future flooding impacts to current conditions, further demonstrating how conditions will change over time. While children currently experience the effects of coastal flooding in many areas, families in homes that have sustained significant damage are likely to have already moved elsewhere, meaning the number of children observed in damaged structures currently is very low. Using various techniques and assumptions to approximate the number of children in previously flooded structures, this analysis identifies around 49,000 children in homes lost to flooding and 660,000 in temporarily damaged homes.

This means that the number of children temporarily displaced by flooding will increase between 47% and 67% under the analysis's "with adaptation" and "no additional adaptation" scenarios at 100 cm. Children experiencing complete home loss increases far more dramatically, in part because the measure captures *cumulative* home loss. Even at 50 cm, the additional children who may sustain home loss increases 3.5 times "with adaptation" and 3.8 times assuming "no additional adaptation." At 100 cm, up to 23 times the number of children could experience total home loss if there is "no additional adaptation" —even with adaptation, the estimated number of children who may lose their home is 6.2 times the current number of children at risk from this type of loss.

Figure 24 describes the geographic distribution of children affected by home loss at 50 cm and 100 cm of global mean sea level rise assuming "no additional adaptation." Regionally, the affected children are concentrated along the Mid-Atlantic and the Gulf coastlines. At 50 cm, the five states with the highest number of affected children living in coastal counties per 100,000 are Georgia, Louisiana, North Carolina, South Carolina, and Virginia. Florida also is among the states with the highest impacts nationally at 100 cm of sea level rise. As shown, children on the Pacific and the upper-Atlantic coasts of the U.S., including the Northern New Jersey and Long Island geographies that were severely affected by Superstorm Sandy, may be spared the worst of future coastal flooding impacts. These results reflect, in part, the coastal protection infrastructure deployed given the known coastal floodplain risks in these areas. Future adaptation to these threats also may alter the geographies with the highest concentrations of children affected.

Figure 24: Estimated Distribution of Additional Children's Home Loss from Coastal Flooding

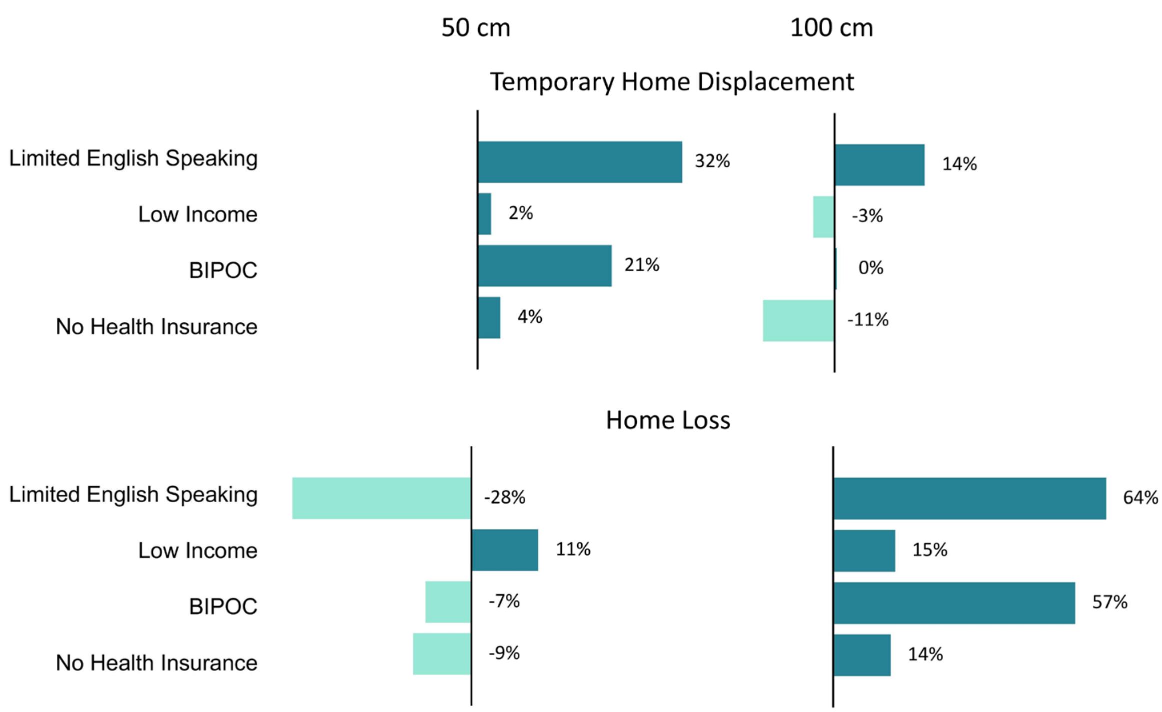


Notes: These maps present the children living in coastal counties at risk of home loss from coastal flooding impacts. Areas with darker shading have higher rates of affected children. The five states with the highest rates of affected children relative to the coastal county populations are outlined in black. The risks assume "no additional adaptation" (see Appendix E for the "with adaptation" scenario).

Finally, Figure 25 explores the social vulnerability dimensions of the impacts predicted in the "no additional adaptation" scenario, implementing the methods described in Chapter 2 and Appendix A. Overall, children in the demographic groups assessed are more likely to be disproportionately impacted by temporary home displacement at 50 cm and complete loss of home at 100 cm. These results may be reflective of the fact that the same child's home may be temporarily damaged at 50 cm but completely lost at 100 cm.

For instance, children in limited English-speaking households are 32% more likely to be affected by temporary home displacement at 50 cm of global sea level rise, decreasing to 14% at 100 cm respectively because a different group of homes and set of children are affected under the two scenarios. At 100 cm, children in limited English-speaking households are 64% more likely to experience home loss, representing a significant increase in disproportionate impacts relative to 50 cm. BIPOC children are 21% more likely to experience effects at 50 cm; these households generally are Hispanic or Latino. At 100 cm, BIPOC children are 57% more likely to suffer home loss, although these effects are concentrated among Asian and Pacific Islander children. Low-income children and children not covered by health insurance also experience disproportionate impacts from temporary flooding at 50 cm and complete home loss at 100 cm, although to a lesser extent than the other groups.

Figure 25: Likelihood of Disproportionate Coastal Flooding Impacts on Overburdened Children



Notes: These graphics present the results of the social vulnerability analysis of coastal flooding impacts on children, following the methods described in Chapter 2 and Appendix A. The differences in risk are measured for the "no additional adaptation" scenario specifically (see Appendix E for other analysis details). The estimated risks for each socially vulnerable group are presented relative to each group's reference population, defined as all individuals other than those in the group analyzed. Populations represent those living in the contiguous U.S. but identifying as a particular race/ethnicity.

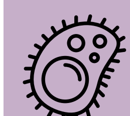
INLAND FLOODING AND CHILDREN'S HOMES

Inland flooding, including riverine flooding ("fluvial flooding") and flash floods associated with extraordinary precipitation events ("pluvial flooding"), will impact children through damages to their homes and the potential for displacement. Riverine flooding occurs when excessive rainfall over an extended period collects across a watershed and causes a river to exceed its capacity. Because a warmer atmosphere can hold more moisture than a cooler atmosphere, climate change is expected to change the frequency and magnitude of precipitation and flooding across the country.[394] Flood risk from high excessive riverine flow is widespread in the contiguous U.S. and growing because of climate change, as well as changes in housing and population density.[395,396] Flood risks associated with high rainfall events are widespread nationally and appear to be increasing in frequency, particularly as a result of hurricane-induced rainfall, but are only beginning to be understood comprehensively as a serious flood risk and a source of inequitable flood risk exposure.[397]

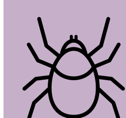
A recent study that connects the frequency and severity of inland flooding events to climate change also provides insights on how children may be affected.[398] The analysis considers annual expected property damages from flooding, the same metric as the coastal flooding analysis presented earlier in this chapter. With 2°C and 4°C of global warming, the greatest impacts are projected to occur in the Northern Great Plains and Northwest regions, with a significant and large burden of damage also seen in the Southwest and Southeast. At 2°C of global warming, nearly 200,000 additional children may live in areas where flood damage could cause a temporary evacuation. At 4°C, the estimate of children affected grows to more than 550,000 individuals. Using a metric of more severe flood damage, including permanent home loss, nearly 17,000 children might be affected at 2°C of warming, and more than 55,000 at 4°C. These results are informative about the number of children that may be affected by climate-induced riverine floods and offer a useful comparison to the coastal flooding results presented earlier in the chapter, where far more children will be impacted. Note that flood-proofing or other adaptation was not considered in this study. Appendix E provides more details on the methods used for this analysis.

Chapter 7: Infectious Diseases

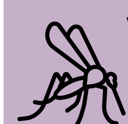
Chapter highlights



This chapter describes how varying temperature and precipitation patterns linked with climate change are likely to alter the habitat, range, and density of pathogens, vectors, and hosts that result in disease among children. Similarly, as people spend more time outdoors as temperatures warm, especially in the "shoulder seasons" of spring and fall, children are more exposed to ticks and mosquitos that carry vector-borne diseases.



Lyme disease, carried by blacklegged ticks, is one such disease that will be influenced by changing temperatures and rainfall patterns. Across the 21 states and the District of Columbia in which Lyme disease is currently prevalent, the detailed analysis presented in this chapter projects an additional 2,600 (-7,500 to 20,200) new cases of Lyme per year among children at 2°C of global warming (31% increase relative to baseline). At 4°C of global warming, the increase relative to baseline is much more extreme: 23,400 (7,800 to 47,000) additional cases per year among children (272% increase). States in the northernmost areas of the Northeast and Midwest regions are expected to see the majority of new cases among children.



West Nile Virus (WNV), carried by mosquitos, is also likely to see a change in new cases as temperatures increase. Existing research estimates an additional 59 cases per year of West Nile Neuroinvasive Disease (WNND), a severe outcome associated with WNV, among children at 2°C of global warming, rising to 133 cases at 4°C. The regions with the largest increases in cases include the Southern Great Plains and the Southeast. While small in magnitude, these results may indicate an increase in other mosquito-borne diseases as well.

HOW CLIMATE CHANGE ALTERS INFECTIOUS DISEASE AND IMPACTS CHILDREN

Temperature and precipitation levels affect the habitat, range, and density of pathogens, vectors, and hosts. Therefore, as the climate changes, the geographic extent and concentrations of the organisms that spread disease will change, including mosquitos and ticks.[399,400,401,402,403,404,405,406] Diseases may no longer be common or endemic in some areas due to increased temperatures or changes in precipitation levels, but the diseases may become endemic in new parts of the country or may be present for longer periods of the year in others. Finally, human behavior is an important element in the spread of vector-borne diseases. As the climate warms, and it becomes possible or necessary for some individuals to spend more time outside, the opportunity increases for exposures to ticks, mosquitos, and other vectors to occur.[407]

IMPACTS OF INFECTIOUS DISEASES ON CHILDREN

Mosquitos and ticks are key causes of childhood vector-borne diseases linked to climate change. Lyme disease is one of the best-known and most common vector-borne diseases in the U.S.[408] People develop Lyme disease after being bitten by the blacklegged tick (also known as the deer tick, *Ixodes scapularis* Say) or the western blacklegged tick (*I. pacificus* Cooley and Kohls) infected with the bacteria *Borrelia burgdorferi* sensu stricto.[409] In 2019, the U.S. Centers for Disease Control and Prevention (CDC) reported 35,000 confirmed and probable cases in the U.S. Of those, children between the ages of 0 and 19 experienced 6,560 confirmed and probable cases—approximately 32% of total cases.[410] Children aged 5-9 have the highest historical incidence rate of Lyme disease of any age group.[411] Symptoms include a range of short-term effects, including a classic rash (erythema migrans; commonly known as the "bullseye" or "target" rash). In some instances, children can also experience lifelong or life-threatening effects, including lethargy; neurological impacts, such as facial paralysis commonly known as Bell's Palsy; meningitis; juvenile arthritis; and carditis, also known as

Infectious diseases and children

- Climate change will influence the geographic extent and concentration of organisms that spread disease, including mosquitos and ticks.
- Lyme disease, transmitted via ticks, can result in a short-lived rash or lifelong neurological or heart conditions.
- West Nile Virus, transmitted via mosquitos, is generally mild in children, except for those who are immunocompromised. Other diseases associated with mosquitos include Zika, chikungunya, dengue, and malaria, and are currently rare in the U.S.
- Food- and water-borne diarrheal diseases could also become more prevalent in the U.S. under climate change.

inflammatory heart disease.[412,413,414,415] Juvenile arthritis generally is the most common, severe long-term effect.[416] Research suggests that longer periods between exposure and treatment are linked to more serious and persistent health outcomes in children.[417] Lyme disease can also result in a rare syndrome with non-specific, generally subjective symptoms that has become known as "chronic Lyme" or "post-treatment Lyme disease syndrome," in which symptoms persist for more than six months post-treatment.[418] At this time, few studies exist for pediatric cohorts that detail how children's health may be affected over the long term.[419,420]

Other tickborne diseases that are endemic in the U.S. include anaplasmosis, babesiosis, and Rocky Mountain spotted fever.[421,422,423,424] Each is transmitted by the bite of different tick species across the country, and some may occur as concurrent infections with Lyme disease.[425] Rocky Mountain spotted fever also is known as rickettsiosis, the general name for diseases caused by the bacteria *Rickettsia* spp.[426] Rickettsiosis mostly commonly is found in children and can cause extremely serious health effects and lead to death.[427,428]

WNV is the most common domestic mosquito-borne disease in the U.S.[429] In the U.S., it is spread primarily by the species *Culex pipiens, C. tarsalis*, and *C. quinquefasciatus.*[430] In children, the primary means of exposure are via mosquito bites,[431] although WNV can be transmitted from mother to child *in utero* and through breast milk.[432,433] Fortunately, WNV does not typically present symptomatically or seriously as frequently in children as in adults (1-5% of WNV cases present in children); however, it can cause severe health effects in young patients, especially those who are immunocompromised.[434] Symptoms and health outcomes span from mild (including rash, gastrointestinal upset, and flulike symptoms[435]) to severe (including encephalitis, symptoms similar to polio myelitis and meningitis, paralysis, and other effects, including death[436,437]). Further, WNV can cause less-specific damages to the central nervous system and associated chronic health effects.[438,439] The long-term ramifications of these more severe health outcomes are considerable, as they can lead to permanent damage or death, especially in immunocompromised children.[440,441]

Mosquitos are successful vectors for numerous other diseases that can have deleterious health impacts in children. Since 2015, the Zika virus has spread primarily via *Aedes* spp. mosquitos[442] in tropical and subtropical environments.[443] The virus can be transmitted during pregnancy to a fetus and can lead to extremely serious birth defects, including brain damage (such as microcephaly).[444] Children also can be exposed to and develop complications from the Zika virus, which generally has milder health effects[445] but still may impact cognition in severe cases.[446] These effects can have lifelong consequences for children and parents, which researchers project could cost millions to billions of dollars in healthcare costs.[447] Other global mosquito-borne diseases associated with considerable child health concerns include chikungunya, dengue, eastern equine encephalitis, and malaria.[448,449,450] Each can have severe health implications for children, including the potential to cause neurological damage and moderately high mortality rates.[451,452,453] Fortunately, current incidence rates in the U.S. are low for each of these types of diseases and commonly are associated with international travel. However, incidence rates have been increasing over the past few decades, and the diseases have the potential to become endemic in the U.S.[454,455,456,457,458]

Other types of infectious diseases, such as those that are food- or water-borne diarrheal diseases, could become more prevalent in the U.S. under climate change. For example, *Cryptosporidium,*[459] *Salmonella,*[460] *Escheria coli (E.coli),*[461] and *Shigella*[462]all have links to climate change and cause gastrointestinal illness. The pathogens are likely to become more prevalent with increases in extreme rainfall, changes in temperature that promote bacterial growth, insufficient or damaged infrastructure, considerable storm runoff, poor wastewater management, or some combination of these elements.[463,464,465] The subsequent illnesses can lead to childhood deaths if left untreated, owing to resultant malnutrition and dehydration.[466,467] This is especially true in younger and immunocompromised children.[468]

Infectious disease presents many potential issues related to disparities across demographic groups. Research suggests correlations between underdiagnosis or misdiagnosis of Lyme disease, in part because the rash may be difficult to detect on darker skin.[469,470,471] Additionally, Black children may be less likely to receive antibiotics either as a precautionary measure or as treatment.[472,473] Research shows that Black individuals experience greater rates of Lyme carditis, which is linked to delayed treatment.[474] Limited research also demonstrates that proportionately there is a greater cost of Lyme disease and other types of tick-borne illnesses and treatment that is borne by low-income individuals who either cannot afford treatment, or who seek or receive delayed healthcare, relative to those who are not low income or have health insurance.[475,476] Similarly, other types of infectious diseases in the U.S. have had disproportionately adverse effects on different populations of children. For instance, the Zika virus was found to have the greatest impacts on Hispanic or Latino children, including newborns, infants, and older individuals.[477] Areas of higher incidence of mosquito-borne illnesses, such as Zika or WNV, frequently are in low-income areas.[478,479]

LYME DISEASE

This section quantifies the potential increase of Lyme disease cases among children linked with future temperature and precipitation associated with climate change. It leverages the analysis by Yang et al. (in review),[480] which associates national historical precipitation and temperature patterns (e.g., changes in national temperatures, rather than global temperatures) with new cases of Lyme disease among children in the eastern U.S., where the disease currently is prevalent.[*] Based on the historical relationship, the authors project the future number of Lyme disease diagnoses associated with infections from the blacklegged tick and the bacteria that causes Lyme disease as linked with climate change.

Figure 26: Lyme Disease Analysis Steps

Step 1
Identify baseline number of new Lyme diagnoses each year

Step 2
Calculate changes in tick and bacteria presence related to future rainfall and temperature

Step 3
Estimate change in new Lyme disease cases among children

Figure 26 describes the analysis steps taken for this report, with more details about the methods, data sources, and assumptions provided in Appendix F. First, baseline Lyme disease diagnoses among children are derived from data maintained by the U.S. Centers for Disease Control and Prevention. Next, changes in tick and Lyme disease-causing bacteria presence related to future rainfall and temperature are modeled. Finally, presence is used to estimate Lyme disease cases among children.

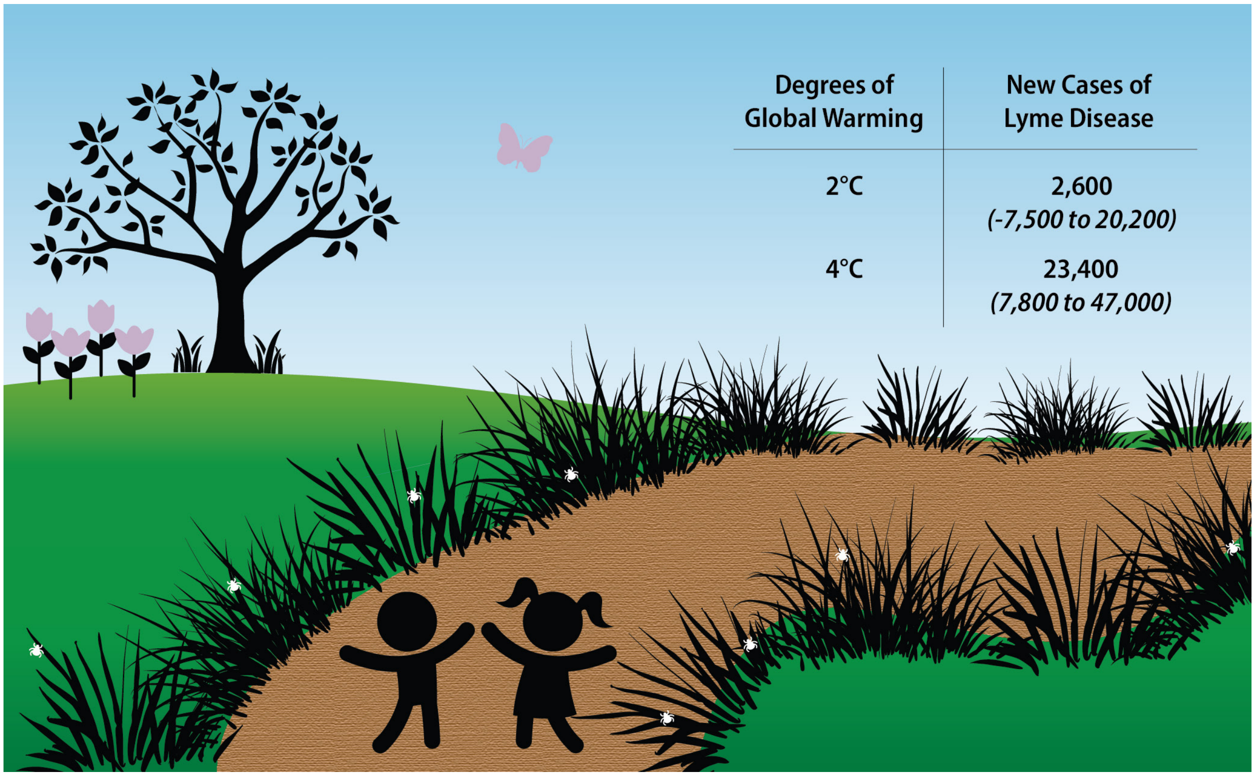
Yang et al.'s analysis confirms that ticks and the Lyme disease-causing bacteria are highly sensitive to temperature and precipitation conditions, and that their range and prevalence are expected to increase as climate continues to change. In general, this means that areas of the U.S. with suitable climatic conditions and habitat to support tick populations generally shift northward. However, differences in rainfall trajectories, and potential impacts on tick and host movements or behaviors, make for a more nuanced geographic picture of future tick habitat.

How are Lyme disease and climate change connected?

Lyme disease is closely connected with climatic conditions. Disease transmission occurs most often between nymphal ticks and humans, other mammals, rodents, and birds.[481] Longer periods of warmer temperatures and increased humidity earlier in the year allow ticks to emerge sooner and stay active for longer.[482,483] That said, the ticks and their hosts will not extend to or remain in areas that are too hot or cold,[484] have heavy rainfall, or are overly wet or dry.[485] As land use changes and host animals expand their ranges, so do ticks; and, as a consequence, Lyme disease is found in new locations.[486,487] Another important factor is that certain hosts such as lizards do not process or carry the bacteria; therefore, disease transmittal is not as common where these host species are the primary food sources for the ticks.[488] Additionally, with moderate warming, humans may spend more time outside (i.e., in typically cooler northern regions), which may increase opportunity for exposure to ticks and thus to Lyme.[489] All of these changes are reflected in how Lyme disease cases over the past 30 years have spread into new areas and increased.[490]

[*] The study scope includes 21 states (Connecticut, Delaware, Illinois, Indiana, Iowa, Maine, Maryland, Massachusetts, Michigan, Minnesota, New Hampshire, New Jersey, New York, North Carolina, Ohio, Pennsylvania, Rhode Island, Vermont, Virginia, West Virginia, and Wisconsin) as well as the District of Columbia.

Figure 27: Projected Additional Cases of Lyme Disease Among Children Per Year Attributable to Climate Change



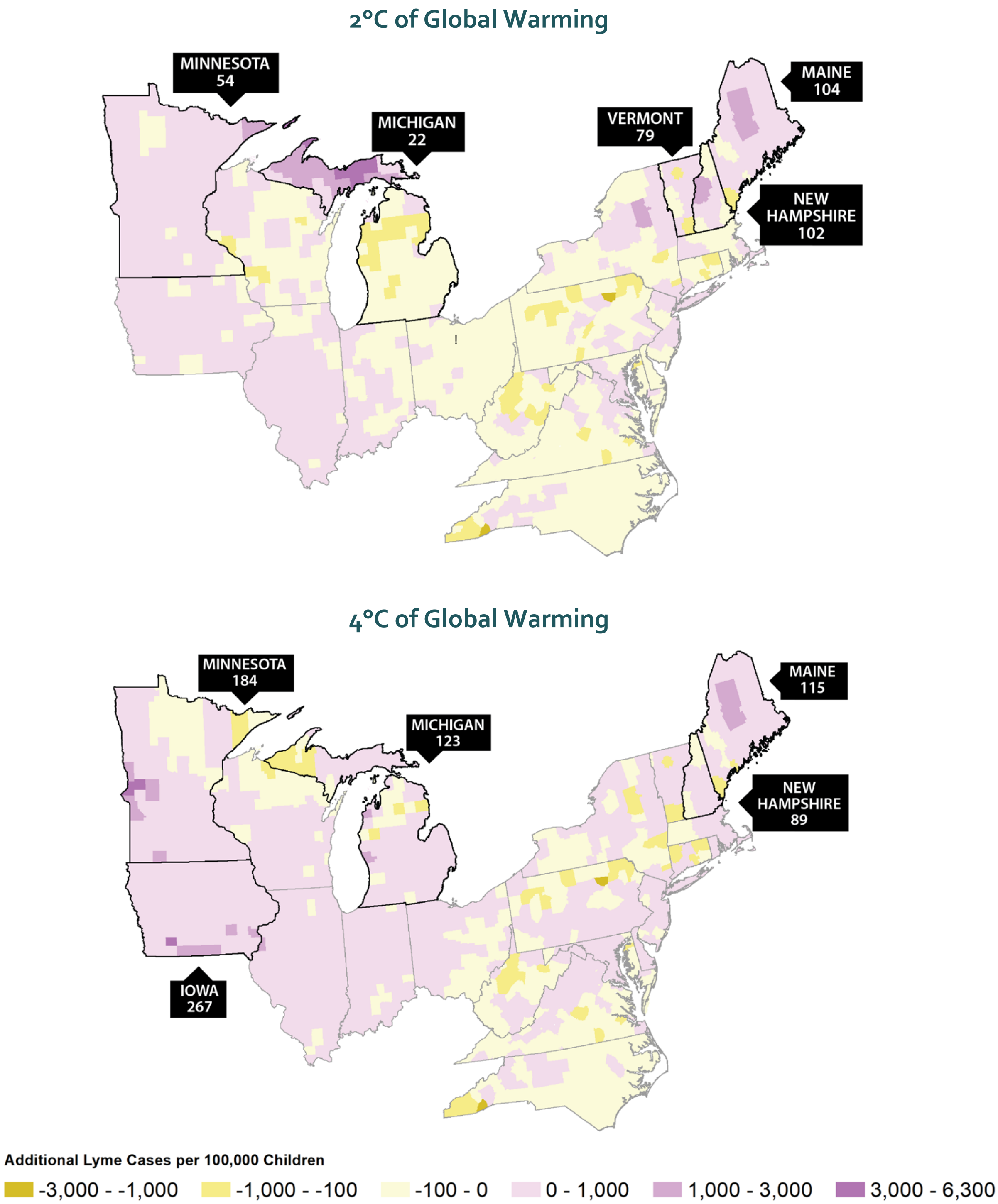
Degrees of Global Warming	New Cases of Lyme Disease
2°C	2,600 *(-7,500 to 20,200)*
4°C	23,400 *(7,800 to 47,000)*

Notes: This graphic presents the results of the Lyme disease analysis at 2°C (equivalent to 3.6°F) and 4°C (equivalent to 7.2°F) of global warming. The results describe additional impacts per year for children living in the study region (see Figure 28 for details) and conditions relative to baseline (1986-2005), and assume populations of children will increase over the 21st century (see Chapter 2, Appendix A). The table displays the average and range across climate models. Figure 29 provides baseline levels. Appendix F provides results for additional degrees of global warming.

Figure 27 summarizes the estimated number of additional cases of Lyme disease among children linked with these changing climatic conditions. Across the 21 states and the District of Columbia included in Yang et al.'s sample, the analysis estimates an additional 2,600 (ranging from 7,500 to 20,200 across climate models) cases per year among children at 2°C of warming, and 23,400 (7,800 to 47,000) additional cases per year at 4°C of warming. In order words, these projections suggest a dramatic increase in cases at more extreme warming levels. Even so, it is well-documented that Lyme disease is underreported,[491,492,493] with CDC estimates that as few as one in ten actual cases are captured in its data. Because the estimates in this analysis are calibrated based on historical reporting, the actual number of future cases similarly may be different.

Recent research is limited regarding the cost of Lyme disease in children. Yang et al. identify an average healthcare cost of approximately $4,200 per case of Lyme disease, adjusted from Adrion et al.,[494] which considers children in the sample, although the study also includes all adults under age 65 (2021 dollars). Beyond healthcare costs, there may be indirect costs associated with lost productivity, including lost workdays among parents caring for sick children, as well as quality of life losses among affected children and their caretakers.

Figure 28: Estimated Distribution of Additional Lyme Cases Per Year Among Children



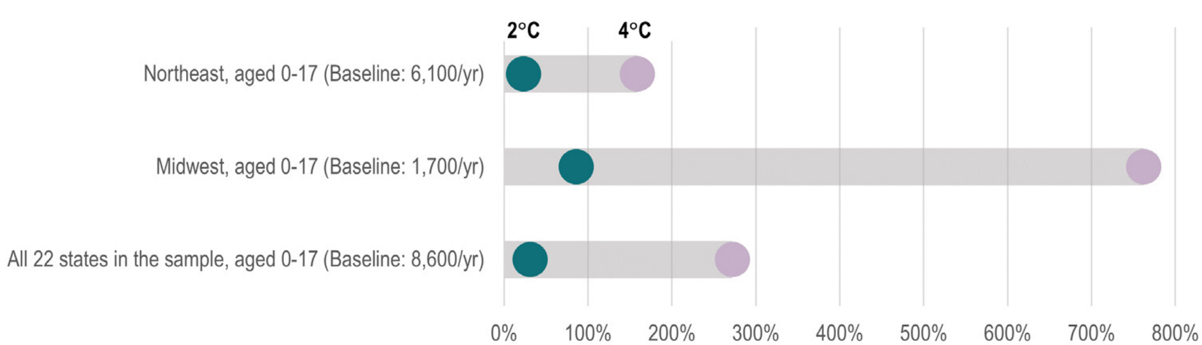
Notes: These maps present new Lyme cases attributable to climate change per year relative to baseline levels at 2°C and 4°C of global warming. Areas with darker purple shading have higher rates of affected children; areas with darker yellow shading see the largest reduction relative to baseline infections. The five states with the highest rates of affected children relative to the county populations are outlined in black. See Appendix F for more details.

Figure 28 conveys the spatial patterns of these new cases of Lyme disease per 100,000 children at 2°C and 4°C of warming relative to the baseline, where purple shading highlights increases in new cases and yellow shading emphasizes decreases in new cases. As shown, not all areas are expected to experience additional cases of Lyme disease among children at either temperature threshold. In fact, most of the 21 states and the District of Columbia show pockets of both increasing and decreasing case rates. Overall, the states with the most additional cases are in the northernmost parts of the Northeast and Midwest. Michigan is one state where the spatial extent of new cases dramatically changes between the two temperature levels; increasing case rates are experienced only in the Upper Peninsula at 2°C of global warming while other areas of the state demonstrate increasing rates starting at 4°C of global warming.

These regional patterns are further illustrated in Figure 29, which depicts changes in new cases relative to their baseline levels (1986-2005) as climate change progresses among the 21 states and the District of Columbia included in the analysis. Across this geography, the number of cases increases 31% and 272% at 2°C and 4°C of warming, respectively. At the regional level, increases relative to baseline are less in the Northeast than in the Midwest, although baseline rates are currently significantly higher in the Northeast.

Finally, following the analytical methods for assessing social vulnerability as described in Chapter 2 and Appendix A, this analysis does not determine that overburdened populations of children are more likely to live in areas with the greatest climate-driven increases in Lyme disease cases. The social vulnerability analysis finds that White, non-Hispanic children are 73% to 93% more likely to live in areas with the highest potential for Lyme disease at 2°C and 4°C of warming (see Appendix F). This does not mean that there are no inequities associated with Lyme disease (see earlier discussion in this chapter); rather, they may not be captured through this analysis. As evidenced by existing research and discussed elsewhere in this chapter, early-stage Lyme disease may be underreported and undertreated among some overburdened populations, which increases the probability of more severe outcomes in these communities.

Figure 29: Estimated Percent Change in New Cases of Lyme Disease Per Year Among Children Relative to Baseline by NCA Region and Overall



Note: This graphic shows the number of new annual Lyme disease cases associated with climate change relative to baseline conditions (1986-2005) by NCA region and overall under assumptions described in Appendix F. The teal circles present increases at 2°C while the purple circles convey increases at 4°C.

WEST NILE VIRUS

Climate change is projected to alter the geographic distribution of West Nile Virus (WNV) and its vectors, causing additional disease outbreaks stemming from infected mosquitos. Approximately 1% to 5% of all WNV cases present symptomatically in children, and these cases are usually milder than in adults.[495] However, the lack of severity may result in under-reporting or misclassification among younger individuals.[496] Cases of West Nile neuroinvasive disease (WNND) occur in less than 1% of people infected with WNV, and frequently result in hospitalization for severe symptoms that are harder to misclassify or ignore.[497]

Belova et al. estimated the future number of WNND cases associated with increasing temperatures in the U.S. among people of all ages.[498] The authors rely on data that show approximately half of all U.S. counties reported at least one WNND case between 2004 and 2012, meaning the suitable habitat for mosquitos carrying WNV is much broader geographically than the suitable habitat for ticks that cause Lyme disease. At the baseline, the Southern Great Plains region of the U.S. has the highest incidence rates for WNV infections.

The study findings translate to 1,490 and 3,330 additional cases of WNND at 2°C and 4°C of global warming, respectively, compared to a baseline of 971 annual cases. According to the U.S. CDC, children accounted for approximately 4% of all WNND cases reported from 1999 to 2007.[499] Applying that proportion to the Belova et al. results, the analysis estimates an additional 59 cases of WNND among children at 2°C of global warming, rising to 133 cases at 4°C. Children living in North Dakota, South Dakota, Nebraska, Colorado, and Arizona are more likely to be impacted at the highest rates per capita as climate changes. The regions with the highest projected total cases include the Southern Great Plains as well as the Southeast. The direct medical costs stemming from WNND across all ages are approximately $46,000 per case (2021 dollars).

These results demonstrate that the number of WNND cases resulting from climate change among children is not expected to be significant, particularly relative to the increases in Lyme disease cases at 1°C of global warming. However, WNND is just one outcome of an WNV infection, and WNV is just one of many mosquito-transmitted diseases that affect children. Therefore, the results from Belova et al. may indicate that other diseases that involve mosquitos as vector species could increase in the future as the climate continues to change.

Chapter 8: What You Can Do

Many health outcomes from climate change can be prevented or minimized through well-timed and appropriate action. Successful strategies to minimize adverse health outcomes depend on a combination of social factors, improved forecasting of weather and climate conditions, and further research to better understand the relationship between climate change and how children may be impacted.

This report showcases some of the ways in which children are vulnerable to a variety of health effects from climate change due to biological and developmental factors. It also demonstrates how climate change can have unequal effects on overburdened populations due to differences in exposure, sensitivity, and adaptive capacity, which are influenced by historic inequities deeply rooted in our laws, policies, and institutions.

There is an urgency to act to reduce emissions of greenhouse gases that cause climate change, while also taking actions to reduce health risks to children. Importantly, there are steps all of us can take to reduce these risks to current and future generations of children. This final chapter is designed to facilitate a call to action by proposing steps people can take to reduce the impacts of climate change on children's health. The chapter concludes with recommendations on how researchers can work to fill critical gaps in our understanding of these risks.

MINIMIZE HEALTH IMPACTS TO CHILDREN

This section summarizes some of the actions people can take to minimize the impacts of climate change on children. These suggestions draw from abundant resources EPA and other Agencies have assembled (external sources underlined).

Talk about the risks of living in a changing climate with children, their friends, schools, physicians, sports teams and coaches, and other parents. If you have questions about how climate risks may impact the health of a child, consult with medical professionals for their recommendations.

How is the EPA helping to minimize the health impacts of climate change on children?

EPA's mission is to protect and improve human health and the environment. Helping vulnerable populations such as children adapt to and protect themselves against climate impacts is fundamental to that ethos. EPA endeavors to protect children's health in a variety of ways, including by providing information on how to keep children safe during and after different types of natural disasters, as well as researching climate change effects on children. The agency also researches how climate change can exacerbate childhood exposures to chemical contaminants.

Educate children and community members (parents, schools, recreation programs, etc.) about how to recreate safely while limiting their exposures to environmental hazards, including vector-borne diseases and elevated temperatures. This includes encouraging children to wear insect repellant to avoid tick and mosquito bites, being aware of where ticks live, and preventing mosquito bites. Urge children to hydrate often, exercise earlier in the day when temperatures are cooler, find shade and indoor places to cool off, and wear safe sunscreen when outdoors. Empowering children and helping them understand their individual risks at all stages will contribute to their individual resilience against climate change impacts.

Keep track of local air quality using the Air Quality Index and pollen counts on your local weather reports. Also, pay attention to wildfire, smoke, and ash warnings. When the air quality is poor, consider limiting children's time outdoors, and have children avoid playing near high-traffic areas.

Keep kids safe during and after an extreme weather event. Work with clinicians to develop community guidelines and develop action thresholds for specific local conditions and areas. Make sure your family has an evacuation or safety plan if you live in an area prone to severe weather. After a flood, watch for signs of mold and be sure to clean and dry affected areas. Focus on providing children access to clean potable water and avoid having them wade in floodwaters or be exposed to debris from disasters. If children are exposed to storms or floods, watch for gastrointestinal illness.

Know your community and community members, and if you see neighbors who may need a hand, help out! Learn what climate stressors could impact you based on where you live. Use EPA's EJSCREEN tool to identify areas that may have higher environmental burdens and vulnerable populations. Become aware of adaptation resources and solutions available in your community and support the development of those that are needed, including evacuation strategies and disaster response strategies.

Discover ways you can work with your neighbors and your community to integrate smart growth and environmental justice to prepare for and lessen the impacts of climate change, address disparities, and build healthy neighborhoods. Work with communities to improve home efficiency and insulation, and to develop community heat and cold action plans to protect against illness.

Learn the locations of large, industrial U.S. greenhouse-gas emitting facilities and how much they emit using the Facility-Level Information on GHGs Tool (FLIGHT).

Learn about adaptation mechanisms that can be used to protect you and your family from climate hazards, including subsidies to help cover the costs of residential A/C and heat use and flood resilience measures. Develop heat action and response plans to help your community prepare for and prevent heat-related illness.

Plant trees and other vegetative cover to help offset heat while encouraging a sense of community. Overburdened communities are especially vulnerable to the impacts of urban heat islands, particularly in the summer. Encourage investments in green and cool roofs, permeable pavements, and smart growth development practices.

Help increase climate change data and understanding with students by participating in citizen science projects, which encourage public participation in scientific research.

Learn more about climate change science so that you can speak knowledgeably about the greenhouse effect and the causes of climate change, and even be able to answer some commonly asked questions about climate change.

Get involved in decision making. Local governments have voluntary advisory boards and neighborhood councils where you can help to shape policies and funding decisions. They need diverse participants, including people from the neighborhoods most affected by climate change and health and environmental hazards.

CONTRIBUTE TO SLOWING CLIMATE CHANGE

Individuals can take actions to reduce greenhouse gas emissions that cause climate change. Reducing greenhouse gas emissions has immediate and long-term benefits in reducing climate change and its impacts. The long-term benefits are particularly important in children's lifetimes.

Promote environmental stewardship by encouraging your community schools, homeowners, and local businesses to reduce their greenhouse gas emissions by managing their energy use and waste generation. Reducing emissions is at the essence of limiting climate change, thus preventing the most severe health effects reviewed in this report.

Heat and cool your home smartly by properly sealing and insulating your home; upgrading to ENERGY STAR certified windows, doors, and heating and cooling systems, including certified smart thermostats; and maintaining your heating and cooling equipment. For a whole-house systems approach, use the ENERGY STAR Home Advisor tool or Home Performance with ENERGY STAR. Also, consider other improvements such as rooftop gardens, cool roofs, sustainable landscaping, and switching to green power generated from renewable energy sources like rooftop solar. Take advantage of state and Federal tax credits for residential renewable energy installation projects, such as those for solar panels and for energy-efficient appliances and vehicles.

Take advantage of no-to-low-cost energy-saving tips, such as adjusting thermostats and turning off lights when space is unoccupied, unplugging electronics when not in use, using ENERGY STAR LED lightbulbs, adjusting window shades to reduce heating and cooling requirements, and installing programmable thermostats. Use EPA's Best Value Finder to find the lowest-priced ENERGY STAR certified products.

Use greener transportation as much as possible. Biking, walking, carpooling, and public transportation can significantly reduce greenhouse gas emissions. Choose an energy-efficient vehicle or switch to an electric vehicle.

FILL KEY RESEARCH GAPS

This report is intended to provide a snapshot of some of the ways in which children's health and well-being may be affected by different climate change-related stressors. However, it is not comprehensive, and it shows how much we still do not know about the relationship between climate change and how children may be impacted physically, psychologically, socially, and inequitably. This section highlights some of these concepts for consideration in efforts to improve research on climate and children's health. Note that references to "demographics" pertain to race, ethnicity, gender, sex, and socioeconomic status.

- Due to data limitations, the analyses in this report consider impacts in the contiguous U.S. specifically. This is due in part to the lack of research focused on climate change effects on children outside of this geographic area. Future efforts should include climate stressors and health outcomes in Alaska, Hawai'i, and the U.S. territories. For further information on data limitations, please see the Technical Appendices accompanying this report.
- Future analyses should incorporate a broader set of child demographics that could be used for 1) better understanding population-specific effects and 2) understanding how different socioeconomic factors could amplify or worsen effects, or result in different health outcomes than those measured in this report. For example, additional investigation is needed on the effects of heat on learning, specifically from an equity lens, factoring in how aggregated characteristics may modify outcomes.
- There are limited data on how climate change causes or exacerbates developmental and mental health effects in children. Therefore, research into how children are being affected, both conceptually and in ways that can be quantitatively measured, is needed. For example, extreme events affecting housing, such as floods and wildfires, can have short- and long-term impacts on children who may experience stress and anxiety from the fear of losing their home, or may experience post-traumatic stress disorder.
- It is difficult to conduct epidemiological and qualitative studies to understand the effects of climate change events on birth and health outcomes during the periods of pre-conception through early childhood. However, the more data of these types that are available, the better future assessments can be of how children are impacted by climate stressors.
- Future analyses should be expanded with the availability and application of data from electronic health records, including doctor's office and ED visits, hospital admissions, and prescription records. These data would provide a nuanced level of detail regarding specific health issues that could be connected to climate data. Additionally, epidemiological studies

focusing on compounded effects at a national scale and adjusting for different demographics could help to address limitations to data availability.

- Pursue analyses of climate change-induced effects at fine spatial resolutions, and with consideration for effects on individual and combined demographics. Research at finer spatial scales would capture a more precise picture of how effects are impacting specific areas and subpopulations of children and their short- and long-term health outcomes.
- As described in this report, well-timed adaptation has the potential to reduce substantially some of the adverse effects of climate change on children (e.g., protection of coastal properties, or installation of air conditioning to reduce learning losses from extreme heat). However, it is currently difficult to project where and to what extent these adaptation measures might be implemented, and the timing of their adoption nationwide. Research advancements are necessary to improve society's ability to forecast the likely implementation of adaptation measures, costs and benefits, and their long-term effectiveness.
- Further development of metrics/indicators is needed to help quantify how well society is doing to address children's health risks as they relate to climate change mitigation and adaptation responses.

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