U.S. Global Change Research Program

Compendium of Recent Federal Research on Climate Change and Human Health

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CREDITS

About this product

This is a product of the Crosscutting Group on Climate Change and Human Health (CCHHG), U.S. Global Change Research Program. It is a compendium of federally funded research activities focused on the human health impacts of climate change in the United States. Its primary intentions are to 1) inform Federal agency coordination of CCHHG efforts and 2) ensure that Federal research regarding climate and health is readily accessible to inform the Fifth National Climate Assessment (NCA5).

Crosscutting Group on Climate Change and Human Health

CCHHG Co-Chairs:

John Balbus – National Institutes of Environmental Health Sciences

Juli Trtanj – National Oceanic and Atmospheric Administration

Paul Schramm – U.S. Centers for Disease Control and Prevention

This product was developed by the following individuals:

Caitlin A. Gould – U.S. Environmental Protection Agency

Laura Judd – National Aeronautics and Space Agency

Research Workstream members and contributors to this product (alphabetical by last name):

John Balbus – National Institutes of Environmental Health Sciences

Rona Birnbaum (Co-Chair) – U.S. Environmental Protection Agency

Caitlin A. Gould (Co-Chair) – U.S. Environmental Protection Agency

Laura Judd (Co-Chair) – National Aeronautics and Space Agency

Shubhayu S. Saha – U.S. Centers for Disease Control and Prevention

Paul Schramm – U.S. Centers for Disease Control and Prevention

Kimberly Thigpen Tart - National Institutes of Environmental Health Sciences

Juli Trtanj – National Oceanic and Atmospheric Administration

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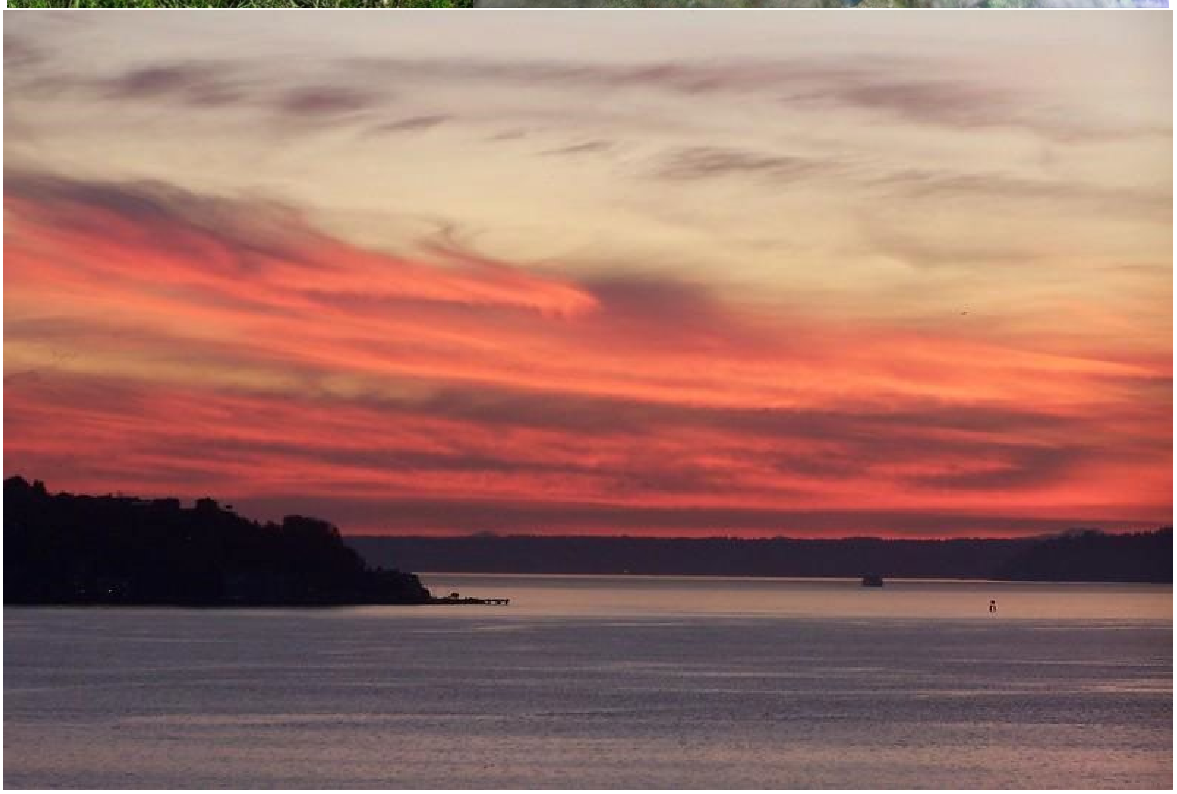

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INTRODUCTION AND OVERVIEW: MAPPING FEDERAL RESEARCH ON CLIMATE CHANGE AND HUMAN HEALTH

The following is a compendium of federally funded research activities focused on the human health impacts of climate change in the United States. This document was developed by the United States Global Change Research Program's (USGCRP) Crosscutting Group on Climate Change and Human Health (CCHHG),[1] with the primary intentions being to 1) inform Federal agency coordination of CCHHG efforts and 2) ensure that Federal research regarding climate and health is readily accessible to inform the Fifth National Climate Assessment (NCA5).

This document is based on responses received during a 2020 data call to agency representatives to the CCHHG. The topics discussed herein include temperature; extreme events; air quality; water-related illness; vector-borne disease; and others, such as rainfall and drought, chemical exposures following natural disasters, sea level rise and nuisance flooding, economic valuations, and water quality (beyond waterborne pathogens or toxins). Many of the topics have been covered in past scientific assessments including *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment* (CHA, 2016) and volumes I and II of the Fourth National Climate Assessment (NCA4, 2017, 2018).

Credit: USEPA

METHODOLOGY

This compendium only includes federally funded scientific literature and reports published since 2016. The CCHHG solicited input from member agencies that conduct or fund health and climate change research. The authors included items that focus on climate and human health, excluding articles and reports that lacked explicit connections to the direct effects on humans. As a compendium, papers are identified and highlighted but not assessed. In addition, papers that examined the health impacts of specific climate mitigation or adaptation policies were also

[1] Department of Agriculture (National Institute of Food and Agriculture), Department of Commerce (National Institute of Standards and Technology, National Oceanic and Atmospheric Administration), Department of Defense, Department of Health and Human Services (Indian Health Service, National Institutes of Environmental Health Sciences, National Institutes of Health, Substance Abuse and Mental Health Services Administration), Department of Labor (Occupational Safety and Health Administration), Department of State, Environmental Protection Agency, National Aeronautics and Space Administration, U.S. Agency for International Development.

excluded. Chapters include additional comments when relevant regarding why certain topics and papers were included or excluded in that chapter. Note that the funding agencies listed in the compendium are not necessarily the exclusive funders of climate change and health research in the Federal Government. Additionally, gaps in literature coverage may exist due to variation in responses from agencies to the 2020 data call for included information.

Entries were sorted or mapped by four of the major areas as identified in the CHA: air quality, water-related illness, temperature, and extreme events. Other literature relevant to climate change and human health but outside these four major categories is gathered in a fifth section. Entries were further delineated based on the following stages of methodology: 1) fundamental research, 2) observational studies, 3), predictive modeling, 4) vulnerability/adaptation/risk, and 5) economic valuation. These are defined accordingly:

Stages of Methodology - Definitions

Stage	Definition
Foundational/basic science	Foundational, or basic research is that which underpins scientific understanding of a concept. Examples include determining the toxicological properties of a substance, establishing the relationship between two natural phenomena, etc.
Observational studies	Research that involves conducting and collecting observations, such as case-control or cross-sectional studies.
Predictive modeling	The development of research models that are used to produce forecasts or predictions.
Vulnerability/adaptation/risk	Research that specifically addresses identifying areas of vulnerability, examines adaptation needs, and/or conducts a risk assessment.
Economic valuation	Research that monetizes the projected impacts of climate change.

AIR QUALITY

OVERVIEW

Out of the submitted entries to this data call, twenty journal articles were found to have links between climate, human health, and air quality supported by four Federal agencies (EPA, NASA, NIH/NIEHS, NSF). The research spanned from foundational science studies on developed research frameworks, as well as how changes in climate variables impact air quality and associated health impacts, through observational and modeling studies. A few of these manuscripts went further to estimate the economic valuation of the health impacts of climate change on air quality.

Studies linking air quality to health impacts are numerous and important in Federal research, although they are not included here unless there was a known association with climate change. For instance, a paper investigating the impact of climate change on smoke exposure-related mortality would be included in the air quality chapter; conversely, a study focusing on climate change and the resultant change in particulate matter concentrations in a region would not be included as it does not extend those results to a health outcome.

The table below includes information about the work, including keywords, title, lead author and year of publication, funding agency, and stages of methodology. The text below briefly summarizes the general findings in each stage of methodology.

Foundational/Basic Science

Five manuscripts identified included fundamental science connecting air quality, health, and climate. Anenberg et al. (2020) was a commentary designed to communicate lessons learned in using satellites for climate and air quality indicators. They identified the need for stakeholder engagement and participatory research when determining how individuals experience health outcomes, and also when developing and operationalizing datasets. O'Lenick et al. (2019) describes a conceptual framework for fully assessing indoor/outdoor air quality (and heat) exposure risk to include social vulnerability data.

Two other studies focused on dust storms and the impact of climate change on their frequency and on health using teleconnection and other calculated index associations. Tong et al. (2017) found that the frequency of dust storms in the western United States is linked to variations in sea surface temperature, particularly the Pacific Decadal Oscillation. Achakulwisut et al. (2018) and Achakulwisut et al. (2019) noted the relationship between dust storms and the "2-month Standardized Precipitation-Evapotranspiration Index" in the southwestern United States.

Observational Studies: Exposures and Health Impacts

The dust studies in the aforementioned foundational research section also included observational components. In addition to what was mentioned above, Tong et al. (2017) created a climatology (1988-2011) for dust storms in the western United States based on continuous long-term monitoring. They found that the frequency increased 240% from the 1990s to 2000s. This was correlated with increased incidence rates of Valley fever (increasing 800% between 2000 and 2011). Crooks et al. (2016) also found an increase in non-accidental mortality due to dust storms using lag conditional logistic regression models under a time-stratified case-crossover design at a county level from 1993-2005 in the United States.

Anenberg et al. (2019) documented the estimated mortality related to particulate matter (PM) in the most populated cities worldwide and also explored the association with carbon dioxide (CO_2) emissions. They found a weak positive correlation between CO_2 emissions and PM mortality rates, which suggests potential co-benefits of mitigating PM and climate change through low-carbon strategies.

Two studies were identified that linked climate change and pollen allergies. Anenberg et al. (2017) calculated emergency department (ED) visits due to asthma associated with oak pollen; in 2010, this number was 21,200, resulting in an economic cost of approximately $10 million. Neumann et al. (2018) followed on to the Anenberg study with an investigation into birch and grass pollens. They found that tens of thousands of ED visits each year are linked to exposure to these allergens. These studies' connections to climate change were more strongly correlated to the predictive model components discussed in the following section.

Wildfire PM impacts on health and vulnerability have been documented in at least four studies. While not all studies directly connect back to climate change, they provide characterization for health impacts due to fire emissions, which are projected to increase due to climate change. Liu et al. (2017) found a positive association between smoke wave days with particles with diameters smaller than 2.5 μm ($PM_{2.5}$) > 37 $\mu g/m^3$ and respiratory admissions of elderly (Medicare enrollees > 64 years old) in the western United States between 2004-2009. They then expanded upon this work in Liu et al. (2018), to identify who in the elderly population is most at risk of poor health outcomes associated with smoke wave days. The researchers found that the risk of hospital admission due to respiratory impacts is higher in women than men, in Blacks than Whites, and in individuals who have less education than those with more education.

Predictive Models

Predictive models play an important role in demonstrating the relationships between how climate change may affect health outcomes and externalities in the future. Predictions from these models may be used to help communities to prepare for extreme events and adverse health impacts.

Neumann et al. (2018) is one example of this. Using a methodology similar to that used for oak pollen results in Anenberg et al. (2017), Neumann et al. used their 2015 baseline year of 25,000-50,000 annual emergency department (ED visits) due to tree pollen and 10,000 summertime ED visits related to grass pollen. They then projected growth of these outcomes of 8% under RCP4.5 (the lower scenario modeled), and by 14% under RCP8.5 (the higher scenario modeled) by 2090, reflecting longer pollen seasons.

Wilson et al. (2017) projected how ozone mortality will be affected under climate change in the near future (2025-2035 versus 1995-2005), assuming anthropogenic emissions do not change. The results reflect how temperature increases may alter biogenic emissions impacting ozone production in 94 U.S. cities. On average, they predicted that ozone will increase 1.6 parts per billion by volume (ppbV) due to a warming of 1.94°F. They also predicted that this would result in greater rates of ozone-related mortalities weighted toward more exposure to moderate levels rather than extreme values. Nassikas et al. (2020) found that thousands of hospitalizations from 2045-2055 related to ozone exposure could be avoided under an RCP4.5 versus an RCP8.5 scenario. This likely would result in over $1 million saved annually.

Three articles focused on predictive modeling of health impacts of $PM_{2.5}$ under climate change scenarios. Fann et al. (2021) approached this with the research question, “What is the association of reducing air pollutant emissions with the human health burden associated with climate change?” Using two climate change scenarios, they found projected correlations between declines in emissions and mortality rates associated with $PM_{2.5}$ and ozone (O_3). In addition to the fundamental findings noted before from Achakulwisut et al. (2018), they projected that under RCP2.6, premature mortality would increase 24% for those > 30 years old, and cardiovascular and respiratory illnesses would increase 59% from 2076-2095, relative to 1996-2015 levels, due to climate change impacts on dust in the southwest United States. These statistics increase to 130% and 300%, respectively, under RCP 8.5. Similarly, Achakulwisut et al. (2019) further determined that under the higher climate change scenario representing unmitigated change, RCP8.5, the region could expect to see increases in PM-related mortalities by 230%, hospitalizations by 360%, increases to asthma-related emergency visits by 88%, and cardiovascular-related deaths by 210%, by 2080-2099 relative to 1986–2005.

Three articles pertained to predictive modeling of wildfire impacts on human health under various climate change scenarios. Liu et al. (2016) identified locations in the western United States that will be impacted by smoke waves, defined as two consecutive days of elevated $PM_{2.5}$ from fires, under the scenario of moderately increasing greenhouse gas (GHG) levels, contrasting 2004-2009 to 2046-2051. The study estimated increases of 57% in fire frequency and 31% in fire intensity experienced by 82 million people in the western United States by 2051. The study also determined that individuals living in parts of the Pacific Northwest and the Great Plains states are the most likely to experience the greatest future risks of wildfire smoke exposure. Ford et al. (2018) predicted that although mortality due to anthropogenic $PM_{2.5}$ emissions will decrease in the RCP4.5 and 8.5 scenarios, the increase in wildfire-related $PM_{2.5}$ is projected to occur, resulting in more fire-related $PM_{2.5}$ mortality. With a focus on Alaska, Woo et al. (2020) observed smoke exposures from 1997-2010 at monthly time scales at a census tract-level, followed by modeling present-day exposures as well as those projected in the future (2047-2051). They found that exposures to $PM_{2.5}$ from fires will increase over 100% for all of Alaska by mid-century, with impacts varying by sub-population.

Economic Valuation

The studies included in this section estimated the economic impacts of climate change related to negative health outcomes from air quality. One of these projects, Nassikas et al. (2020), found that comparing RCP4.5 versus RCP8.5 impacts scenarios using the EPA’s Benefits Mapping and Analysis Program-Community Edition (BenMAP) tool, 3,100 ozone-related asthma ED visits could be avoided in the 2045-2050 timeframe under the lower emissions scenario. This translates to over $1.7 million saved annually.

Achakulwisut et al. (2019) created a multi-level economic estimate of health-related impacts caused by dust in the southwestern United States. between 1986 and 2090. They determined first that from 1986-2005, related damages on average cost approximately $13 billion annually, in 2015 dollars. When considering climate change effects on dust in the U.S. southwest under an RCP8.5 scenario, they estimated an additional $47 billion per year in damages, on top of the $13 billion baseline (totaling approximately $60 billion in damages), by 2090.

Anenberg et al. (2017) also quantified economic impacts of allergen-induced asthma ED visits. Baseline (current) damages were estimated to be $10.4 million. Further, they estimated that, following predicted changes in the oak pollen season, ED visits could increase from the baseline by 5% by 2050, and 10% by 2090. They estimate that in 2090, the economic costs of these effects will be $12.7 million, undiscounted, leading to an aggregated damage amount of $346 million (2015 dollars). The lower RCP4.5 scenario resulted in a 50% change in avoided visits.

Zhang et al. (2017) studied the impacts to human health by 2050 under a global RCP4.5 scenario. They found that this strategy avoided 16,000 -$PM_{2.5}$-related and 8,000 ozone-related deaths annually in 2050 in the United States, demonstrating the impact of global strategies on domestic health. Economically, this could result in a value from avoided deaths of $45-137 per ton of CO_2 depending on valuation.

Research encompassing climate change, human health, and air quality								
				Stages of methodology				
Keyword	Title	Lead author/PI	Federal funder(s)	Foundational science	Observational studies	Predictive modeling	Vulnerability /risk/ adaptation	Economic valuation
PM	Particulate Air Pollution from Wildfires in the Western US Under Climate Change	Liu (2016)	NIH/ NIEHS					
PM	Effects of Increasing Aridity on Ambient Dust and Public Health in the U.S. Southwest Under Climate Change	Achakulwisut (2019)	EPA					
PM	Associations Between Simulated Future Changes in Climate, Air Quality, and Human Health	Fann (2021)	EPA					
Ozone	Ozone-Related Asthma Emergency Department Visits in the US in a Warming Climate	Nassikas (2020)	EPA					
Pollen	Impacts of Oak Pollen on Allergic Asthma in the United States and Potential Influence of Future Climate Change	Anenberg (2017a)	EPA					
Pollen	Estimates of Present and Future Asthma Emergency Department Visits Associated With Exposure to Oak, Birch, and Grass Pollen in the United States	Neumann (2018)	EPA					
PM	Intensified Dust Storm Activity and Valley Fever Infection in the Southwestern United States	Tong (2017)	NASA					

				Stages of methodology				
Keyword	Title	Lead author/PI	Federal funder(s)	Foundational science	Observational studies	Predictive modeling	Vulnerability /risk/ adaptation	Economic valuation
PM	Future Fire Impacts on Smoke Concentrations, Visibility, and Health in the Contiguous United States	Ford (2018)	NASA					
Pollutants	Using satellites to track indicators of global air pollution and climate change impacts: Lessons learned from a NASA supported science stakeholder collaborative	Anenberg (2020)	NASA					
PM, CO2, Co-benefits	Particulate matter-attributable mortality and relationships with carbon dioxide in 250 urban areas worldwide	Anenberg (2019)	NASA					
GHG, PM, Ozone	Co-benefits of global, domestic, and sectoral greenhouse gas mitigation for US air quality and human health in 2050	Zhang (2017)	EPA, NIEHS, NASA					
Dust	The Association between Dust Storms and Daily Non-Accidental Mortality in the United States, 1993-2005	Crooks (2016)	EPA					
PM, Wildfire	Who Among the Elderly Is Most Vulnerable to Exposure to and Health Risks of Fine Particulate Matter from Wildfire Smoke?	Liu (2017)	EPA, NIH					

				Stages of methodology				
Keyword	Title	Lead author/PI	Federal funder(s)	Foundational science	Observational studies	Predictive modeling	Vulnerability /risk/ adaptation	Economic valuation
PM, Wildfire	Wildfire-specific Fine Particulate Matter and Risk of Hospital Admissions in Urban and Rural Counties.	Liu (2018)	EPA, NIH		■			
PM, Wildfire	Air pollution from wildfires and human health vulnerability in Alaskan communities under climate change	Woo (2020)	EPA, NIH		■	■	■	
Exposure framework	Urban heat and air pollution: A framework for integrating population vulnerability and indoor exposure in health risk analyses	O'Lenick (2019)	EPA, NSF	■				
Ozone	Climate change impacts on projections of excess mortality at 2030 using spatially varying ozone-temperature risk surfaces	Wilson (2017)	EPA			■		
Dust	Drought-sensitivity of fine dust in the U.S. Southwest: Implications for air quality and public health under future climate change	Achakulwisut (2018)	EPA	■	■	■		
Ozone	Climate-attributable changes in air quality-related emergency department visits for asthma	Nassikas (2020)	EPA			■		■

WATER-RELATED ILLNESS

OVERVIEW

Five journal articles directly link climate change to health and water-related illnesses. The research either was conducted or funded by EPA or NOAA. This section included those papers that had clear connections between climate effects on water quality, or waterborne pathogens, toxins, or the like; and those where there were equally clear, linear relationships made in the papers to human health. For instance, we would include a paper investigating the impact of climate change on the propagation of *Vibrio* bacteria in food sources or recreational areas; however, we would not include a paper looking at the climate effects on the genotype of the same type of bacteria. Additionally, please note that some articles on extreme events, such as particularly bad harmful algal blooms (HABs) (e.g., the West Coast *Pseudo-nitzschia* bloom of 2015-2016), are included in the Extreme Events chapter, given the nature of the research performed and the focus of the article. A key difference between this chapter and other chapters, with the inclusion of HABs and other water-related organisms that can cause negative human health outcomes, is that in many cases there are limited drivers (climate change, nutrient inputs) that lead to the development of HABs, poor water quality, etc. Whereas, with other chapters, many of the health outcomes of interest are directly attributable to climate change effects (e.g., increased heat), the environmental hazards in this section are secondary. We did not include any entries that did not have clear connections to climate change and either human health directly, or the production of toxins and other means of harming human health.

The research spans from foundational science studies showing that climatic changes can lead to increased incidences and range of HABs, as well as stresses on infrastructure and the associated health impacts, through observational and modeling studies. Two of the journal articles provide economic valuations on these topics. The table below includes information about the funded work including key words, title, links to the articles, funding agency, and stages of methodology.

Foundational/Basic Science

At the crux of foundational science and waterborne diseases is understanding the roles of ambient and water temperatures; salinity (in the case of estuarine and marine environments); turbidity and upwelling; and nutrient availability in promoting the development of HABs, pathogenesis, and/or toxicity. Gobler et al. (2016) developed a model that, through hindcasts, demonstrated past linkages between increases in ocean temperatures and increasingly intense HABs in terms of their toxin production, duration, and extent. They focused specifically on algal species that produce saxitoxin, a human and animal neurotoxin, and okadaic acid, which causes gastrointestinal distress when consumed. Through this research, the PIs concluded that rising ocean temperatures likely contributed to the development and exacerbation of the HAB species covered within this study, and across the Atlantic coast of the United States, in particular. Dai et al. (2019) also examined the roles of two climate variables. These researchers examined how temperature and salinity promoted *Azadinium poporum* in Puget Sound, specifically focusing on how these variables affect algal growth and toxin production at the time of study and likely in the future. The researchers predicted that while increasing ocean temperatures due to climate change likely will lead to greater concentrations of *A. poporum* in Puget Sound, this may not lead to greater toxin levels.

Carmichael and Boyer (2016) approached the relationship between climate change, HABs, and public health from the perspective of defining the health effects of these waterborne hazards. The researchers concentrated on cyanobacterial HABs in Lake Erie. They explained that there are limited historical data describing the incidence of HABs and HAB-related disease in Lake Erie and the Laurentian Great Lakes as a whole. However, they stated that, as the climate changes and HABs become more prevalent in Lake Erie, an increase in HAB-related disease in future years is expected.

Observational Studies: Exposures and Health Impacts

The work by Du et al. (2016) showed connections between climate variables, including sea surface temperature and salinity, and a severe *Pseudo-nitzschia* bloom that occurred along the U.S. West Coast in 2015-2016 and led to widespread shellfish bed closures. The paper stated that there were two primary drivers of this bloom: a prevalence of phytoplankton and availability of nutrients throughout the water column due to severe upwelling, coupled with the anomalous persistent, warm temperatures of the “West Coast Blob” in the Pacific Ocean. The upwelling likely was compounded by the Blob, which in and of itself was linked to a strong La Niña weather pattern that was driven by climate change. The researchers assessed that the increase of nutrients throughout the water column exacerbated the severity of the HAB.

Economic Valuation

“Climate Change Impacts on Harmful Algal Blooms in U.S. Freshwaters: A Screening-Level Assessment” (Chapra et al., 2017) mentioned that the northeastern United States is predicted to see the greatest increase in occurrences of cyanobacterial HABs; however, the greatest economic impacts are likely to be found in the southeastern United States, as that region will see larger effects on recreational sectors. On average, this paper predicts that under different climate models, a waterbody will likely experience HABs an average of “about 7 days per year per waterbody under current conditions, to 16-23 days in 2050 and 18-39 days in 2090.”

Research encompassing climate change, human health, and water-related illness								
				Stages of Methodology				
Keywords	Title	Lead author/PI	Federal funder(s)	Foundational science	Observational studies	Predictive modeling	Vulnerability /risk/ adaptation	Economic valuation
HABs	Climate Change Impacts on Harmful Algal Blooms in U.S. Freshwaters: A Screening-Level Assessment	Chapra (2017)	EPA					
HABs	Ocean warming since 1982 has expanded the niche of toxic algal blooms in the North Atlantic and North Pacific oceans	Gobler (2017)	NOAA					
HABs	Initiation and Development of a Toxic and Persistent *Pseudo-nitzschia* Bloom off the Oregon Coast in Spring/Summer 2015	Du (2016)	NOAA					
HABs	The effect of temperature and salinity on growth rate and azaspiracid cell quotas in two strains of *Azadinium poporum* (*Dinophyceae*) from Puget Sound, Washington State	Dai (2019)	NOAA					
HABs	Health impacts from cyanobacteria harmful algae blooms: Implications for the North American Great Lakes	Carmichael (2016)	NOAA					

TEMPERATURE

OVERVIEW

From this data call, there were 34 papers (funded by NIH/NIEHS, CDC, EPA, NASA, and NSF) that directly connected temperature and its impact on human health. Many of these entries focused on the direct impact of temperature on human health without extending into the prediction of how this will vary due to climate change. Despite the lack of extension to climate change, these entries were included due to the significance of temperature as a climate change variable. Overall, climate change studies are heavily weighted toward the predictive modeling stages of methodology, whereas temperature as a parameter independent of climate change is more based on observational studies.

Foundational/Basic Science

The foundational work being done in temperature, climate, and health studies in recent years primarily spans the development of modeling frameworks and methodology. With respect to model development, Anderson et al. (2018a) identified and publicly shared (through GitHub) three models capable of predicting high mortality heat waves (20% or higher increased mortality risk). This established a foundation for future studies to model mitigation strategies for heat waves as a result of climate change. Similarly, Morefield et al. (2018) described a new modeling framework using the EPA's BenMAP software to estimate heat-related mortality based on changes in climate.

Though not directly connected to climate change research, some work has been done on developing basic methodology for heat exposure assessments in terms of measurement placement and spatial resolution requirements. Wang et al. (2019) investigated methodology for occupational heat exposure in Birmingham, Alabama, by comparing exposures based on personal temperature monitors clipped on person versus areal meteorology data. The researchers found that the personal monitors can be an added method to traditional strategies for quantifying heat exposure and work-rest schedules for outdoor workers. Wu et al. (2019) explored the impact of spatial resolution for temperature/health outcome (preterm births and non-accidental deaths) association studies to better understand the potential for misclassification in associations due to spatial resolution. This study explored results at the zip code, 12 km, and 1 km resolutions, and found that all resolutions resulted in similar estimates. That said, heat-island[2] impacts were only apparent at the 1 km resolution. Heaton et al. (2019) proposed that distributed lag models for assessing the cumulative impacts of heat over multiple days should be differentiated by age. They used a negative binomial regression model in this work to demonstrate that different age groups are impacted differently by heat over cumulative days.

More broadly and related to this work, in 2018, the EPA released *Mapping the Vulnerability of Human Health to Extreme Heat in the United States*, which documents methodologies and data requirements for assessing the vulnerability of populations to extreme heat based on one-on-one interviews done

[2] The tendency for higher air temperatures to persist in urban areas as a result of heat absorbed and emitted by buildings and asphalt, tending to make cities warmer than the surrounding countryside. Source: Maxwell, K., S. Julius, A. Grambsch, A. Kosmal, L. Larson, and N. Sonti, 2018: Built Environment, Urban Systems, and Cities. In Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 438–478. doi: 10.7930/NCA4.2018.CH11.

with governmental experts. Son et al. (2019) performed a review of over 200 research studies to identify the vulnerability of specific populations to temperature-related mortality, which can help identify targets for further research as well as drive adaptation/mitigation policies.

Observational Studies: Exposures and Health Impacts
Most studies that fall under this category do not connect back to climate change itself but focus instead on the effects of temperature on human health in a quantitative fashion. Many of the relationships that were found could be expanded upon in climate prediction modeling studies in the future. Additionally, a few further applied their models to projected changes due to climate change, which will be addressed in the next section. Studies highlighted here either used case-crossover designs or applied various regression methods to investigate impacts of temperature on health outcomes discussed below.

Case-crossover-designed studies include associations with temperature and opioid overdoses (Goedel et al., 2019), ED visits for children under the age of four (Sheffield et al., 2018), air quality and non-accidental death (Jian et al., 2017), and fatal traffic crashes (Wu et al., 2018). Goedel et al. (2019) found that lower-than-average temperatures resulted in increased risk of death from opioid overdoses in Connecticut and Rhode Island. Sheffield et al. (2018) documented that risk of heat exposure on children varies based on age, suggesting that public health strategies should be tailored to different age groups. Jian et al. (2017) found that heat-associated deaths vary by environmental quality (mostly air quality) and determined that there could be merit in integrating air quality into heat wave warnings to protect community health. Wu et al. (2018) discovered that fatal car crashes increase 3.4% on heat wave days versus non-heat wave days, with the risk increasing with driver age and location in rural areas.

A variety of regression methods were used to link above average temperature with health outcomes such as increased risk of low birth weight (Sun et al., 2019), kidney health (Honda et al., 2019), risk of heat stroke (Wang et al., 2016), and other cause-specific hospital admissions (Hopp et al., 2018) across the nation. Additionally, the triad of air quality, heat, and health outcomes were documented by Kioumourtzoglou et al. (2016), which found higher mortality rates and $PM_{2.5}$ long-term exposure in warmer U.S. cities. Positive associations for joint exposures of air quality and temperature and temperature variability though on non-fatal negative outcomes (hospital admissions) were found in New England by Yitshak-Sade et al. (2018). Rice et al. (2018) investigated the outdoor temperatures and their impact on lung function in the Northeast U.S. using fully adjusted linear models and average temperature over a set of time periods and found seasonal as well as air quality variations that may be driven by human behavior impacting outdoor exposure. Specifically, they found that each 5°C increase in temperature was correlated with lower lung function. They also found relationships between decreased lung function and unseasonably warm days, as well as seasonality (winter and spring).

Less connected to health outcomes, Jung and Uejio (2017) investigated how heat waves impact social media interactions in five major U.S. cities in 2014 by performing an autoregressive integrated moving average time series model of heat exposures versus social media posts about the heat or air conditioning to survey the ability for public health surveillance through social media platforms.

Predictive Models

Predictive modeling is central to connecting observational study findings of associated temperature exposure and health outcomes with expected changes in temperature due to climate change to estimate the impact to human health.

Weinberger et al. (2017) projected temperature-related mortality for ten U.S. cities using 40 downscaled climate models and exposure-response functions under two different RCP scenarios (4.5 and 8.5) through the rest of this century and found that the increase in excess mortality from heat outweighed the decrease in cold related mortality. The increase in heat-related mortality could be lessened with decreased emissions. Weinberger et al. (2018) more specifically focused on the southern New England region, finding that temperature-related ED visits would increase in future decades without adaptation strategies, but that temperature-related deaths would not change for that region.

Anderson et al. (2018b) used the health-based models identified in their previous paper (Anderson et al., 2018a, in the foundational science category above) to project changes in heat-wave mortality for 82 communities under two emission scenarios (RCP4.5 and 8.5), two population change scenarios (SSP3 and SSP5), and three adaptation scenarios (none, lagged, on-pace). They found that more high mortality heat waves will happen in all scenarios except for when the adaptation scenario is on-pace.

Grouland et al. (2019) demonstrated a novel approach using EPA's BenMap Software to estimate historical (1971-2000) and future (2041-2070) heat-related mortality and morbidity at a county level in Michigan and found that the burden on human health would significantly rise for all Michigan counties. Similarly, Limaye et al. (2018) also used EPA's BenMAP to project health risks associated with climate change in the eastern United States based on the baseline year 2007 at 36 km and 12 km resolutions, which each demonstrated increases in deaths and cardiovascular stress in populations over 65. In addition to the foundational description (above) of the new BenMAP modeling framework, Morefield et al. (2018) estimated an increase in heat-related deaths on a national scale due to climate change when considering two RCP scenarios (4.5 and 8.5) and population projections from the EPA's Integrated Climate and Land Use Scenarios project.

Globally, two studies (Guo et al., 2018; Vicedo-Cabrera et al. 2018) developed exposure-mortality models using observations around the globe to then project the impact of climate change on heat wave mortality. Vicedo-Cabrera et al. (2018) followed the perspective of the Paris Agreement to explore the possible benefits of achieving warming limits of under 1.5°C, 2.0°C, 3.0°C, and 4.0°C. They found that the impacts of climate change on heat wave-related mortality would be more limited if the 2.0°C warming limit were achieved and found the results of 1.5°C versus 2.0°C warming to be complex; the researchers did not account for population change or adaptation scenarios. Guo et al. projected heat-wave mortality out to 2099 using four different greenhouse gas, two adaptation, and three population scenarios to fully characterize multiple scenarios to help inform climate adaptation/mitigation policies. They found that the increase in heat wave mortality due to climate change likely will be larger in tropical and subtropical countries and less intense in the United States and Europe. They also determined that excess mortality would occur even with adaptation strategies, though at a much lower level. Wang et al. (2017) conducted a similar study estimating heat wave mortality in hundreds of U.S. cities due to climate change with a focus on adaptation. They found that not accounting for possible adaptation in these types of studies can lead to overestimates of excess deaths. The research findings also suggested that future adaptation strategies be tailored at regional levels, as impacts vary by region.

More specific to human development during pregnancy, Zhang et al. (2019) quantified the impact of heat exposure changes due to climate change in early pregnancy, and the development of congenital heart defects in the baby. This research used a national case-control study and looked at the impacts regionally in the United States.

Vulnerability, Risk, and Adaptation

Recent Federal research included assessing the success of heat alerts for negative health outcome prevention. For example, Weinberger et al. (2018b) quantified changes in mortality with respect to heat alerts in 20 U.S. cities between 2001 and 2006. Heat alerts from the National Weather Service (NWS) were not found to lower mortality rates in this study. The only city with a statistically significant lower mortality rate was Philadelphia. This study highlighted the need for more effective communication and other mitigation strategies to prevent excess death due to heat. Vidyanathan et al. (2019) conducted a county-level national study using heat indices and hospitalization records in the United States from 2003-2012. They found that heat burdens occurred in some regions below the NWS alert levels at the time of the study. Similarly, Adeyeye et al. (2019) characterized this risk for New York State and identified the need to change the heat advisory threshold and messaging in that region.

Zeigler et al. (2019) noted that communities themselves are often not involved in the research pertaining to them. They documented a case study in Detroit where community-based participatory research was used to study the impacts of heat on a specific community. They indicated that these approaches could strengthen climate research and methods for addressing climate change effects on health and equity.

Economic Valuation

Most studies that extended into estimates of economic valuation were based on work that also qualified for other stages of methodology. For example, in addition to their predictive model analysis, Grouland et al. (2019) also estimated a projected increase in the cost burden of healthcare in Michigan due to heat mortality ($280 million) and morbidity reflected by ED visits ($14 million). Liu et al. (2019) focused on health costs of temperature exposures in Minneapolis/St Paul, Minnesota, and found that the relationships varied by age group (greater mortality burden in the elderly, and greater morbidity in children). They also found that suboptimal low temperatures are more expensive than suboptimal high temperatures.

Lay et al. (2018) used an observational study to identify the relationship between maximum daily temperature and ED visits for hyperthermia (positive relationship) and cardiac emergencies (no relationship found) in people under 64 years of age, using an insurance database from May to September, 2005-2012, in 136 areas. These relationships were then extended to calculate the rates of hyperthermia based on two climate scenarios for 1995, 2050, and 2090 considering no adaptation measures. The results estimated healthcare cost increases due to climate change-related hyperthermia.

<table>
<tr><th colspan="9" style="background:#fde49c">Research encompassing climate change, human health, and temperature</th></tr>
<tr><th colspan="4"></th><th colspan="5">Stages of methodology</th></tr>
<tr><th>Keywords</th><th>Title</th><th>Lead author/PI</th><th>Federal funder(s)</th><th>Foundational science</th><th>Observational studies</th><th>Predictive modeling</th><th>Vulnerability /risk/ adaptation</th><th>Economic valuation</th></tr>
<tr><td>Morbidity, Mortality</td><td>Projected Changes in Temperature-related Morbidity and Mortality in Southern New England.</td><td>Weinberger (2018)</td><td>NIH/ NIEHS, CDC</td><td></td><td></td><td style="background:#fde49c"></td><td></td><td></td></tr>
<tr><td>Mortality</td><td>Projected temperature-related deaths in ten large U.S. metropolitan areas under different climate change scenarios.</td><td>Weinberger (2017)</td><td>NIH/ NIEHS</td><td></td><td></td><td style="background:#fde49c"></td><td></td><td></td></tr>
<tr><td>Equity, Heat waves</td><td>Shifting from "Community-Placed" to "Community-Based" Research to Advance Health Equity: A Case Study of the Heatwaves, Housing, and Health: Increasing Climate Resiliency in Detroit (HHH) Partnership.</td><td>Ziegler (2019)</td><td>NIH/ NIEHS</td><td></td><td></td><td></td><td style="background:#fde49c"></td><td></td></tr>
<tr><td>Heat, Morbidity, Mortality, Costs</td><td>Assessing the magnitude and uncertainties of the burden of selected diseases attributable to extreme heat and extreme precipitation under a climate change scenario in Michigan for the period 2041-2070.</td><td>Gronlund (2019)</td><td>NIH/ NIEHS, CDC</td><td></td><td></td><td style="background:#fde49c"></td><td></td><td style="background:#fde49c"></td></tr>
<tr><td>Heat waves, Mortality</td><td>Classifying heatwaves: Developing health-based models to predict high-mortality versus moderate United States heatwaves.</td><td>Anderson (2018a)</td><td>NIH/ NIEHS, NASA, NSF</td><td style="background:#fde49c"></td><td></td><td style="background:#fde49c"></td><td></td><td></td></tr>
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				Stages of methodology				
Keywords	Title	Lead author/ PI	Federal funder(s)	Foundational science	Observational studies	Predictive modeling	Vulnerability /risk/ adaptation	Economic valuation
Heat waves, Trends	Projected trends in high-mortality heatwaves under different scenarios of climate, population, and adaptation in 82 US communities.	Anderson (2018b)	NIH/ NIEHS, NASA, NSF					
Heat waves	Emergency Department Visits and Ambient Temperature: Evaluating the Connection and Projecting Future Outcomes	Lay (2018)	EPA, CDC					
Heat, Mortality	Climate change and heat-related excess mortality in the eastern USA	Limaye (2018)	EPA, NIEHS, NSF, NASA					
Heat	Heat-related health impacts under scenarios of climate and population change	Morefield (2018)	EPA					
Heat, Heart defects	Projected changes in maternal heat exposure during early pregnancy and the associated congenital heart defects burden in the United States	Zhang (2019)	EPA, NIH, CDC					
Children, Heat	Not so little differences: variation in hot weather risk to young children in New York City.	Sheffield (2018)	NIH/ NIEHS					
Heat waves, Traffic	Heat waves and fatal traffic crashes in the continental United States.	Wu (2018)	NIH/ NIEHS					

				Stages of methodology				
Keywords	Title	Lead author/PI	Federal funder(s)	Foundational science	Observational studies	Predictive modeling	Vulnerability /risk/ adaptation	Economic valuation
Heat waves	Medical diagnoses of heat wave-related hospital admissions in older adults.	Hopp (2018)	NIH/ NIEHS					
Heat waves	Heat stroke admissions during heat waves in 1,916 US counties for the period from 1999 to 2010 and their effect modifiers.	Wang (2016)	NIH/ NIEHS					
Heat	Mapping the Vulnerability of Human Health to Extreme Heat in the United States	EPA (2018)	EPA					
Heat, Mitigation	Assessment of extreme heat and hospitalizations to inform early warning systems	Vaidyanathan (2019)	CDC					
Economic costs	Degrees and dollars – Health costs associated with suboptimal ambient temperature exposure	Liu (2019)	CDC					
Occupational health	Estimating Occupational Heat Exposure From Personal Sampling of Public Works Employees in Birmingham, Alabama.	Wang (2019)	NIH/ NIEHS					
Opioid mortality	Increased Risk of Opioid Overdose Death Following Cold Weather: A Case-Crossover Study.	Goedel (2019)	NIH/ NIEHS					
Fetal growth	Ambient Temperature and Markers of Fetal Growth: A Retrospective Observational Study of 29 Million U.S. Singleton Births.	Sun (2019)	NIH/ NIEHS					

				Stages of methodology				
Keywords	Title	Lead author/PI	Federal funder(s)	Foundational science	Observational studies	Predictive modeling	Vulnerability /risk/ adaptation	Economic valuation
Air quality, Heat waves, Mortality	Effect Modification by Environmental Quality on the Association between Heatwaves and Mortality in Alabama, United States.	Jian (2017)	NIH/ NIEHS					
Kidney health	Daily ambient temperature is associated with biomarkers of kidney injury in older Americans.	Honda (2019)	NIH/ NIEHS					
Air quality, Temperature	The association between short and long-term exposure to $PM_{2.5}$ and temperature and hospital admissions in New England and the synergistic effect of the short-term exposures.	Yitshak-Sade (2018)	NIH/ NIEHS, EPA					
Air quality, Mortality	$PM_{2.5}$ and Mortality in 207 US Cities: Modification by Temperature and City Characteristics.	Kioumourtzoglou (2016)	NIH/ NIEHS, EPA					
Morbidity, Heat	Estimating policy-relevant health effects of ambient heat exposures using spatially contiguous reanalysis data	Adeyeye (2019)	NASA, CDC					
Mitigation, Mortality	Effectiveness of National Weather Service heat alerts in preventing mortality in 20 US cities.	Weinberger (2018b)	NIH/ NIEHS					
Heat waves, Emergency response	Social media responses to heat waves	Jung (2017)	EPA					

				Stages of methodology				
Keywords	Title	Lead author/PI	Federal funder(s)	Foundational science	Observational studies	Predictive modeling	Vulnerability /risk/ adaptation	Economic valuation
Heat waves	Quantifying excess deaths related to heatwaves under climate change scenarios: A multicountry time series modelling study	Guo (2018)	EPA					
Heat waves	Accounting for adaptation and intensity in projecting heat wave-related mortality	Wang (2017)	NIH					
Lung function	Association of outdoor temperature with lung function in a temperate climate	Rice (2018)	NIH/EPA					
Effect modification	Temperature-related mortality: a systematic review and investigation of effect modifiers	Son (2019)	EPA/NIH					
Heat waves	Influence of the spatial resolution of the exposure estimate in determining the association between heat waves and adverse health outcomes.	Wu (2019)	NIH					
Paris Agreement	Temperature-related mortality impacts under and beyond Paris Agreement climate change scenarios	Vicedo-Cabrera (2018)	EPA					
Heat, mortality, Age	Age-specific distributed lag models for heat-related mortality	Heaton (2019)	EPA					

EXTREME EVENTS

OVERVIEW

Of the entries in the compendium, nine journal articles provided by NASA, EPA, NOAA, and NIEHS directly link climate change to health and extreme events. The research spans from foundational science studies on how changes in climate impact the intensity and frequency of these events, and the associated health impacts through observational and modeling studies. A few of these manuscripts go further to estimate the economic valuation of associated events and health impacts.

In the context of this document, the term extreme events refers to severe events that are typically one-offs, rather than continuous or annual circumstances. For example, this document herein precludes events such as HABs that are worsening annually from being considered extreme, although it includes articles focusing on the causes and/or effects of specific events that are known to have been especially deleterious in nature (e.g., an exceptionally bad HAB in a localized area, dust storms, etc.). That said, it also includes information on extreme heat and storms, which may be perceived as chronic rather than acute, particularly under predictive scenarios.

Foundational/Basic Science

Articles encompassing foundational or basic science within this section include subjects such as precipitation and HABs, and associated effects. Smith et al. (2017) identified a correlation between extreme precipitation events and emergency department (ED) visits due to influenza, particularly when stratifying by race. Black Americans were demonstrated to have the highest odds of visiting the ED due to precipitation-linked influenza, compared to other races.

Trainer et al. (2020), S.K. Moore et al. (2020), and K.M. Moore (2020) investigated the relationship between climate extremes – e.g., the Pacific "Blob" of high air and water temperatures from 2013-2015 – and the development of extreme HAB events, as well as related, subsequent human health impacts. Trainer et al. demonstrated a relationship between severe HAB events, strong El Niño years, upwards trajectories of the Pacific Decadal Oscillation, and unusual marine heat waves. Individually or compounded, these climatic events may lead to or exacerbate HAB events and toxin production. The research team based their data off of the *Pseudo-nitzschia* HAB of 2015 that occurred off of the U.S. West Coast, from California to Alaska, and caused billions of dollars in losses. S.K. Moore et al. and K.M. Moore et al. investigated the foundational social science relationships regarding this bloom, outlining how these climatic events affected human health through this event and potentially via those in the future.

Kim et al. (2019) looked to compare land-use planning methods in Amsterdam, the Netherlands, and Houston, Texas, with regard to the efficacy of preparing for future flood risks, especially relative to urban growth. The researchers determined that Amsterdam's protective measures (i.e., infrastructure) currently have left the city better prepared to handle and mitigate future urban flood risk than Houston, even when accounting for Amsterdam's smaller urban footprint and fewer flood-prone areas. This data could be used by the city of Houston, and other, similar municipalities, to adopt measures similar to those in Amsterdam.

Observational Studies: Exposures and Health Impacts

Bobb et al. (2017) investigated the relationship between severe snowstorms and hospitalizations by focusing on records from four hospitals in Boston and admissions linked to “cardiovascular and cold-related diseases, falls, and injuries,” relative to days that had varying amounts of snowfall. Admissions on high-snowfall days increased for cold-related diseases, and decreased for cardiovascular-related diseases; however, the admissions linked to the latter increased on high-snowfall days. There was an increase in fall-related admissions on days with moderate snowfall. That said, as this is a singular study, more research is needed to show stronger correlations.

Gan et al. (2017) looked at how cardiopulmonary-related hospital admissions in Washington State in 2012 were affected by wildfires. The researchers considered how smoke, and subsequently $PM_{2.5}$, was linked to these types of hospitalizations. They found a significantly increased risk of hospitalization linked to asthma (8%), and mixed data regarding chronic obstructive pulmonary disease-related hospitalizations. The differences for the latter health outcome varied depending upon the type of smoke exposure estimation method used. Stowell et al. (2019) focused on health impacts of wildfire smoke on a wider variety of ages in Colorado from 2011-2014. Using their own exposure model to separate smoke $PM_{2.5}$ versus ambient $PM_{2.5}$, they found a 1 $\mu g/m^3$ increase in smoke $PM_{2.5}$ was associated with asthma and respiratory disease-associated hospital admissions, including in children and adults.

Predictive Models

Using the EPA’s Environmental BenMAP tool, Zhang et al. (2020) estimated the predicted effects of climate change on ozone and $PM_{2.5}$, and subsequently on human health in the United States over the periods of 2001-2010 and 2046-2005, using two RCP scenarios. They determined that the air pollutants would have the most significant effects on the morbidity and mortality of different types of weather extremes; heat and compound weather extremes were predicted to be the most literally and figuratively expensive and costly in terms of health, lives, and dollars.

Vulnerability, Risk, and Adaptation

K.M. Moore et al. (2020) used social science methods to assess how particular characteristics and demographics, and adaptive capacity methods, made populations in the U.S. Pacific Northwest more or less vulnerable to severe impacts caused by an extreme HAB in 2015. They expanded this to make recommendations for improving the adaptability of fishing communities in the United States when faced with potentially experiencing similar HAB events or other major coastal stressors.

Research encompassing climate change, human health, and extreme events								
				Stages of methodology				
Keywords	Title	Lead author/ PI	Federal funder(s)	Foundational science	Observational studies	Predictive modeling	Vulnerability /risk/ adaptation	Economic valuation
Precipitation, Populations of concern, Influenza	Extreme precipitation and emergency room visits for influenza in Massachusetts: a case-crossover analysis	Smith (2017)	EPA	■				
Extreme weather, Air pollution	Health and economic impacts of air pollution induced by weather extremes over the continental U.S.	Zhang (2020)	EPA			■		■
Snowstorms	Time-Course of Cause-Specific Hospital Admissions During Snowstorms: An Analysis of Electronic Medical Records From Major Hospitals in Boston, Massachusetts.	Bobb (2017)	NIEHS		■			
Flooding	Climate Change Preparedness: Comparing Future Urban Growth and Flood Risk in Amsterdam and Houston.	Kim (2019)	NIEHS	■			■	
Flooding	Citizen Science-Informed Community Master Planning: Land Use and Built Environment Changes to Increase Flood Resilience and Decrease Contaminant Exposure	Newman (2020)	NIEHS				■	
Wildfire	Comparison of wildfire smoke estimation methods and associations with cardiopulmonary-related hospital admissions	Gan (2017)	NASA		■			
HABs, Temperature	Climate extreme seeds a new domoic acid hotspot on the US west coast	Trainer (2020)	NOAA	■				

				Stages of methodology				
Keywords	Title	Lead author/ PI	Federal funder(s)	Foundational science	Observational studies	Predictive modeling	Vulnerability / risk / adaptation	Economic valuation
HABs, Populations of concern, Temperature	Harmful algal blooms and coastal communities: Socioeconomic impacts and actions taken to cope with the 2015 U.S. West Coast domoic acid event	S.K. Moore (2020)	NOAA	■				
HABs, Populations of concern, Temperature	Harmful algal blooms: identifying effective adaptive actions used in fishery-dependent communities in response to a protracted event	K.M. Moore (2020)	NOAA	■			■	
PM, Wildfire	Associations of wildfire smoke PM2.5 exposure with cardiorespiratory events in Colorado 2011–2014	Stowell (2019)	EPA, NASA		■			

OTHER AREAS OF RESEARCH

OVERVIEW

Ten research products published by Federal agencies (EPA, NASA, NIEHS, NIH, NOAA, NSF), included in this document, addressed relevant concepts that fell outside of the major themes that were identified. The research included in this section relates to the application of epidemiological methodologies, vector-borne disease, hospitalizations linked to ongoing drought, sea level rise and nuisance flooding, and environmental monitoring. The table below includes information about the work including topic, title, link to the publication site or DOI, funding agency, and stages of methodology. The text below briefly summarizes the general findings in each stage of methodology.

Foundational/Basic Science

Spangler et al. (2019) considered the applicability of gridded climate datasets to environmental epidemiologic data. The researchers found that altogether, these datasets may be used, although the types of models used should depend on the type of meteorological variables being considered. For example, the researchers determined differences in how well certain spatial data led to accurate exposure estimates, leading to variations at the county level.

Foundational science includes work that is relevant for establishing a baseline for human exposure estimates related to climate change. Madrigano et al. (2018) is a key example for extrapolating climate data using the types of methods described in Spangler et al. The Madrigano et al. research team looked at how certain industrial coastal communities were particularly at risk of exposure to harmful chemical contaminants (fugitive chemicals) following hurricane-driven flooding. Understanding these types of risks is important, as the authors indicated, as it helps communities to prepare for disasters, rather than having to react to consequences after an event.

Finally, epidemiology plays a crucial role in understanding the implications of climate change on human health. Anderson et al. (2019) discussed what they perceived to be the three most important areas of climate science that are in need of advanced epidemiological research: "1) climate attribution studies, 2) subseasonal to seasonal forecasts, and 3) decadal predictions."

Observational Studies: Exposures and Health Impacts

Spangler et al. (2019) and Berman et al. (2017) each included observational elements in their analyses. Spangler et al. is discussed in the prior section of this chapter. The Berman et al. study investigated how droughts in the western United States influenced cardiovascular and respiratory morbidity (measured as hospitalizations) and mortality in older Americans. By using Medicare and U.S. Drought Monitor data, the researchers determined that mortalities linked to the aforementioned health outcomes were significantly worse at the height of drought conditions; additionally, hospitalizations and mortality increased in areas that did not commonly experience drought. Respiratory-related hospitalizations decreased over the span of when a location was considered as being in a drought; however, this reduction in admissions did not occur when drought conditions were worsening.

Predictive Models

Lorie et al. (2020) utilized the National Coastal Property Model to estimate costs and benefits associated with behavior changes related to flood risk reduction. They determined that individual behaviors are often motivated by individual perceptions of costs and benefits to adaptive response, and that individuals and communities often underinvest in adaptive measures relative to standard cost-benefit assumptions due to financial, psychological, sociopolitical, and technological factors. For instance, individuals rarely abandon their properties, despite increases in risk. According to the authors, sub-optimal adaptive responses in Virginia Beach, Virginia, and Tampa, Florida – the two cities tested in the study – could lead to more than $1 billion in additional costs, including those incurred by storm surge. As the authors mentioned, the lessons learned from this study could be extrapolated to other coastal-flood-prone counties and cities.

Predictive models play an important role in anticipating and mitigating vector-borne diseases that are driven by climate factors. There were two articles included that showed relationships between climate change and disease spread by mosquitoes, in particular. Davis et al. (2017) looked at the relationship between temperature, precipitation, and West Nile virus in 2015 and 2016 in South Dakota, as a means of developing and evaluating a predictive model. The researchers discussed that the model accuracy improved during the height of the summer season, with greater amounts of mosquito data. Similar to this, Muñoz et al. (2020) developed the *Aedes*-borne diseases' environmental suitability (AeDES) system for monitoring and forecasting transmission of diseases such as dengue, Zika, and chikungunya that are borne by *Aedes*-genus mosquitos in the continental United States and border regions in Central America. The tool was fed by epidemiological, epidemiological, and climate models to develop forecasts at multiple timescales that in turn could be used to inform early-warning systems.

Fant et al. (2017) used the Hydrologic and Water Quality System (HAWQS) model and U.S. Basins, five climate models, and two climate scenarios to develop predictive models and assess future water quality in the continental United States through the end of this century. In particular, the study examined levels of water temperature, dissolved oxygen, total nitrogen, and total phosphorus. Ultimately, the agency and partners used these models to ascertain that the eastern portion of the United States is likely to experience poorer water quality outcomes than the western portion. The researchers also estimated a range of economic impacts, dependent upon different climate models and emissions scenarios. This led to the conclusion that under the higher scenario, climate change-related water quality issues could lead to economic effects of $1.2-2.3 billion/year in 2005 dollars in 2050, and $2.7-4.8 billion/year in 2005 dollars in 2090.

Vulnerability, Risk, and Adaptation

As Ekstrom et al. (2017) indicated, creating appropriate adaptation measures in an area is contingent upon understanding user and constituent needs. The authors of this paper surveyed staff at drinking water utilities in California regarding perceptions of climate change effects and risks. They found that smaller utilities seemed to be less prepared to handle climate change impacts on drinking water systems. Additionally, most utility staff looked for guidance from the government and colleagues at other drinking water facilities for guidance and input.

Economic Valuation

Neumann et al. (2020) developed climate damage functions for 15 climate impact sectors based on model estimates produced under the EPA's Climate Impacts and Risk Assessment (CIRA) framework and published in the *Multi-model framework for quantitative sectoral impacts analysis: A technical report for the Fourth National Climate Assessment*. The functions estimated the "economic impacts of climate change on human health, infrastructure, and ecosystems for seven U.S. regions through 2100." The researchers showed how existing model outputs can be applied towards creating damage functions, which in turn may be used for estimating out-year economic effects. The functions developed under this body of research are applicable to the contiguous United States, and may be updated based on future climate metrics, observations, and policy applications.

Research encompassing climate change, human health, and other areas of research								
				Stages of methodology				
Keyword(s)	Title	Lead author/PI	Federal funder(s)	Foundational science	Observational studies	Predictive modeling	Vulnerability /risk/ adaptation	Economic valuation
Methods	Suitability of gridded climate datasets for use in environmental epidemiology	Spangler (2019)	NIH/ NIEHS	■	■			
Nuisance flooding, Sea level rise	Modeling Coastal Flood Risk and Adaptation Response under Future Climate Conditions	Lorie (2020)	EPA			■	■	
Economic valuation	Climate damage functions for estimating the economic impacts of climate change in the United States	Neumann (2020)	EPA					■
Drought	Drought and the risk of hospital admissions and mortality in older adults in western USA from 2000 to 2013: a retrospective study.	Berman (2017)	NIH/ NIEHS		■			
Chemical exposures in disasters, Extreme events	Fugitive Chemicals and Environmental Justice: A Model for Environmental Monitoring Following Climate-Related Disasters.	Madrigano (2019)	NIH/ NIEHS	■				
Vector-borne disease	AeDES: a next-generation monitoring and forecasting system for environmental suitability of Aedes-borne disease transmission	Muñoz (2020)	NOAA, NSF, NIH			■		

				Stages of methodology				
Keyword(s)	Title	Lead author/ PI	Federal funder(s)	Foundational science	Observational studies	Predictive modeling	Vulnerability /risk/ adaptation	Economic valuation
Vector-borne disease	Integrating Environmental Monitoring and Mosquito Surveillance to Predict Vector-borne Disease: Prospective Forecasts of a West Nile Virus Outbreak	Davis (2017)	NASA					
Environmental epidemiology	The Future of Climate Epidemiology: Opportunities for Advancing Health Research in the Context of Climate Change	G.B. Anderson (2019)	NIH, NOAA, EPA					
Water quality, Modeling	Climate Change Impacts on US Water Quality Using Two Models: HAWQS and US Basins	Fant (2017)	EPA					
Water quality	Gauging climate preparedness to inform adaptation needs: local level adaptation in drinking water quality in CA, USA	Ekstrom (2017)	EPA					

U.S. Global Change
Research Program