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9.1 Key Findings

Vulnerability Varies Across Individuals, Time Scales, and Places

Key Finding 1: Across the United States, people and communities differ in their exposures, their inherent sensitivity, and their adaptive capacity that enables them to respond to and cope with climate change related health threats. Vulnerability to climate change varies across time and geographic areas, across communities, and among individuals within communities [Very High Confidence].

Climate Factors Interact with Non-Climate Factors to Increase Health Risk

Key Finding 2: Climate change related health risks interact with some of the same non-climate factors that increase the risk of poor health generally. Non-climate factors, such as those related to demographic changes, socioeconomic factors, and pre-existing or chronic illnesses, may amplify, moderate, or otherwise influence climate-related health effects, particularly when they occur simultaneously or close in time or space [High Confidence].

Increased Vulnerability to Climate-Related Health Impacts is Widespread Across Ages and Stages of Life

Key Finding 3: People experience different vulnerabilities at different ages and life stages. For example, the very young and the very old are particularly sensitive to climate-related health impacts [High Confidence].

Mapping Tools and Vulnerability Indices Help to Identify Where and for Whom Climate Health Risks are Greatest

Key Finding 4: The use of geographic data allows for more sophisticated mapping of risk factors and social vulnerabilities to identify and protect specific locations and groups of people [Medium Confidence].
9.2 Introduction
Climate change is already causing and will likely continue to cause a range of health impacts that vary across different population groups in the United States. The vulnerability of any given group is a function of its sensitivity to climate-related health impacts, its exposure to those risks, and its capacity for responding to or coping with climate variability and change. Vulnerable groups of people, described here as populations of concern, include: those with low income, some communities of color, limited English proficiency and immigrant groups, Indigenous peoples, children and pregnant women, older adults, vulnerable occupational groups, persons with functional disabilities, and persons with biologically determined vulnerability, such as pre-existing or chronic medical conditions. Planners and public health officials, politicians and physicians, scientists and social service providers are tasked with understanding and responding to the health impacts of climate change. Collectively, their characterization of vulnerability should consider how populations of concern experience disproportionate, multiple, and/or complex risks to their health and well-being in response to climate change.

9.3 A Framework for Understanding Vulnerability
9.3.1 Defining Vulnerability and Related Concepts
Some populations of concern demonstrate relatively greater vulnerability to the health impacts of climate change. The definitions of the following key concepts are important to understand how some people or communities are disproportionately affected by climate-related health risks (Figure 1).

Vulnerability is the propensity or predisposition to be adversely affected by climate-related health effects, and encompasses three elements: exposure; sensitivity or susceptibility to harm; and the capacity to adapt or to cope. Exposure is the presence of people in places that may be adversely affected by climate-related health risks. Sensitivity is the degree to which people or communities are affected, either adversely or beneficially, by climate variability and change. Adaptive capacity is the ability of communities, institutions, or people to adjust to potential hazards, to take advantage of opportunities, or to respond to consequences. A related term, resilience is the capacity of social systems to cope with hazardous events or trends, while maintaining the capacity for adaptation and learning. Having strong adaptive capacity confers resilience.

Risk is the potential for consequences to develop where something of value (such as human health) is at stake and where the outcome is uncertain. Risk is often represented as the probability of the occurrence of a hazardous event multiplied by the expected severity of the impacts of that event. Risk results from the interaction of vulnerability, exposure, and hazard. A related concept, hazard, is the potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health
impacts, as well as damage and loss to property, infrastructure, livelihoods, or services. Stressors are events or trends, whether climate- or non-climate-related, that increase vulnerability to climate-related health effects (definitions adapted from IPCC, 2014).

9.3.2 Factors that Contribute to Vulnerability

The Social Determinants of Health Framework

Figure 2 displays the World Health Organization’s (WHO) Social Determinants of Health and Health Inequities Framework, which conceptualizes vulnerability to the health risks associated with climate change across populations of concern. This framework describes climate-related health impacts, socioeconomic and political contexts for determining health, and the context shaped by individual characteristics (such as gender, education, occupation, income, and ethnicity). The framework also shows how multiple factors, such as psychosocial factors (including a person’s network of friends and family), biological factors (such as pre-disposition to certain diseases), sense of well-being, social cohesion, and human behavior collectively determine health (CSDH 2008; Friel et al. 2008).

Many of the health impacts of climate change interact with social and economic systems. By connecting these systems and the social and political forces that shape and drive them, the social determinants of health can help characterize impacts and consider interventions (such as mitigation or adaptation) that may be adopted to reduce or prevent exposures in populations of concern (Reid et al. 2012; Harlan et al. 2013; CSDH 2008).

Vulnerability Factors that Contribute to Exposure

Exposures to climate-related variability and change are determined by a range of factors that individually and collectively shape the nature and extent of exposures. These factors include:

- **Occupation**: Certain occupations can put workers at risk, particularly if they are working outdoors or are performing duties that expose them to extreme weather, such as emergency responders (Schulte and Chun 2009).

- **Time spent in risk-prone locations**: Where a person lives, goes to school or works, or spends leisure time can contribute to exposure. Locations that confer greater climate-related health threats include: urban areas (because of the “heat island” effect), areas where airborne allergens occur at levels that aggravate respiratory illnesses, communities experiencing depleted water supplies or vulnerable energy and transportation infrastructure, coastal and other flood-prone areas, and locations affected by drought and wildfire (Balbus and Malina 2009; Uejio et al. 2011; O'Neill et al. 2008).

- **Displacement by extreme weather events**: People may be forced to evacuate their homes and relocate in the wake of hurricanes, floods, sea level rise, or wildfires. Others may choose to
leave their homes due to increased frequency or severity of heat waves, extreme precipitation, drought, storms, or other weather extremes (Donner and Rodriguez 2008).

- **Socioeconomic status:** Persons living in poverty may not have adequate resources to effectively prepare for or respond to weather emergencies (Harlan et al. 2006; Woodruff et al. 2003).

- **Condition of infrastructure:** Older buildings may expose occupants to increased indoor air pollutants and mold, stagnant airflow, or high indoor temperatures. Persons fleeing from flooding, wildfires, or other weather-related emergencies may be hampered by damage and destruction to transportation, utilities, medical, or communication infrastructure (Pastor et al. 2006; Bullard and Wright 2009).

- **Compromised mobility, cognitive function, and other mental or behavioral factors:** These factors can lead to increased exposure to climate-related health impacts if people are not aware of health threats or are unable to take actions to avoid, limit, or respond to risks (CDC 2013).

**Characterizing Biological Sensitivity**

The sensitivity of human communities and individuals to climate change stressors is determined, in part, by biological traits. Among those traits are the overall health status, age, and life stage. From fetus, to infant, to toddler, to child, to adolescent, to adult, to the elderly, persons at every life stage have varying sensitivity to climate change impacts (Shannon et al. 2007; Sheffield and Landrigan 2011; Balbus and Malina 2009). For instance, the relatively immature immune systems of very young children make them more sensitive to aeroallergen exposure (such as airborne pollens). In addition to life stage, people experiencing long-term chronic medical and/or psychological conditions are more sensitive to climate stressors. Persons with asthma or chronic obstructive pulmonary disease (COPD) are more sensitive to exposures to wildfire smoke and other respiratory irritants. Social and economic factors also affect disparities in the prevalence of chronic medical conditions that aggravate biological sensitivity (Frumkin et al. 2008; Keppel 2007).

**Adaptive Capacity and Response to Climate Change**

Many of the same factors that contribute to exposure also influence a population’s or individual’s ability to adapt to climate variability and change. Socioeconomic status, the condition of infrastructure, the accessibility of health care, certain demographic characteristics, human capital (the skills, knowledge, and experience of a community), and other institutional resources all contribute to the timeliness or effectiveness of adaptation.
9.4 Populations of Concern

9.4.1 Communities of color, Low income, Immigrants, and Limited English Proficiency Groups

In the United States, populations of color, low-income groups, people with limited English proficiency (LEP), and certain immigrant groups (especially those who are undocumented) live with many of the factors (see Section 9.2.2) that contribute to vulnerability to the health impacts of climate change. These populations are at increased risk of exposure given their higher likelihood of living in risk-prone areas (such as urban heat islands or coastal and other flood-prone areas), areas with older or poorly maintained infrastructure, or areas with an increased burden of air pollution (Luber and McGeehin 2008; Frey 2011; CDC 2012b; Miranda et al. 2011). These groups of people also experience relatively greater incidence of chronic medical conditions, such as cardiovascular and kidney disease, diabetes, asthma, and COPD (CDC 2012a, 2013; Blackwell et al. 2014), which can be exacerbated by climate-related health impacts (McGeehin and Mirabelli 2001; Luber and McGeehin 2008; Basu and Ostro 2008; Lin et al. 2009; Semenza et al. 1999). Socioeconomic and educational factors, limited transportation, limited access to health education, and linguistic isolation collectively limit the ability to prepare for, respond to, and cope with existing or new health risks (Younger et al. 2008; Larson et al. 2009; Semenza et al. 1999; Satia 2009; CDC 2012b; DHHS 2013; Maldonado et al. 2013a; Luber and McGeehin 2008; Knowlton et al. 2009; McMichael 2013). These populations also may have limited access to medical care and may not be able to afford medications or other treatments (DHHS 2013; Blackwell et al. 2014). For LEP and undocumented persons, high poverty rates, language and cultural barriers, and citizenship status limit access to and use of health care and other social services and make them more hesitant to seek out help (Ortega et al. 2007; Fuentes-Afflick and Hessol 2009; Vargas-Bustamante et al. 2010; Maldonado et al. 2013a; Eneriz-Wiemer et al. 2014; Riera et al. 2014).

The size of certain populations of concern in the United States affected by heightened vulnerability to climate-related health risks will continue to grow. Currently, Hispanics, blacks or African Americans, American Indians and Alaska Natives, Asian Americans, and Native Hawaiians and Pacific Islanders represent 37% of the total U.S. population (Humes et al. 2011; Census Bureau 2014a). By 2042, they are projected to become the majority (Census Bureau 2008). People of color already constitute the majority in four states (California, Hawaii, New Mexico, and Texas) and in many cities (Census Bureau 2014a). Numbers of LEP and undocumented immigrant populations have also increased. In 2011, LEP groups comprised approximately 9% (25.3 million individuals) of the U.S. population aged five and older (Whatley and Batalova 2013). In 2010, approximately 11.2 million people in the United States were undocumented (Passel and Cohn 2011).
Vulnerability to Climate-Related Health Stressors

Key climate impacts for communities of color and low-income, LEP, and certain immigrant populations include heat waves, other extreme weather events, poor air quality, food safety, infectious diseases, and psychological stressors.

**Extreme heat events.** Some communities of color, low-income, homeless, and immigrant populations are more exposed to heat waves (Ramin and Svoboda 2009; Shonkoff et al. 2011) as these groups often reside in urban areas affected by heat island effects (Harlan et al. 2006; Luber and McGeehin 2008; Jesdale et al. 2013; Uejio et al. 2011). In addition, these populations are likely to have limited adaptive capacity due to lack of adequately insulated housing, inability to use or to afford air conditioning, inadequate access to public shelters such as cooling centers, and access to health care (Luber and McGeehin 2008; Younger et al. 2008; Semenza et al. 1999; CDC 2011, 2013; DHHS 2013). These social, economic and health risk factors give rise to the observed increase in deaths and disease from extreme heat in some minority and poor populations (Basu and Ostro 2008; Luber and McGeehin 2008; Lin et al. 2009) (see also Ch. 2: Temperature-related Death and Illness).

**Other weather extremes.** As observed during and after Hurricanes Katrina and Hurricane/Post-Tropical Cyclone Sandy, populations of color and low-income people experience increased illness or injury, death, and displacement due to poor-quality housing, lack of access to transportation, inadequate health care services, and limited or no property insurance (Donner and Rodriguez 2008; Eisenman et al. 2007; Zoraster 2010; Schreiber et al. 2014). Adaptation measures can reduce or eliminate these disparities, but may not be readily available or affordable (Weisskopf et al. 2002; Eisenman et al. 2007; Donner and Rodriguez 2008; Zoraster 2010; Thethi et al. 2010; McMichael 2013; Joseph et al. 2014; Schreiber et al. 2014) (see also Ch. 7: Extreme Weather).

**Degraded air quality.** Climate change impacts on outdoor air quality will increase exposure in urban areas where large proportions of minority, low income, homeless, and immigrant populations reside (see also Ch. 3: Air Quality). Fine particulate matter (PM) and ozone levels already exceed National Ambient Air Quality Standards in many urban areas (EPA 2010, NRC 2010a, CDC 2011, Miranda et al. 2011). Given their relatively higher rates of cardiovascular and respiratory diseases in low-income urban populations (CDC 2011, 2012a; Blackwell et al. 2014), these populations are more sensitive to declines in air quality, resulting in increases in illness, hospitalization, and premature death (Pope and Dockery 1999; Donaldson et al. 2000; Leikauf 2002; Peden 2002; Pope et al. 2002; Gwynn and Thurston 2001; Finkelstein et al. 2003; Reynolds 2003; Lin et al. 2008). In addition, climate change can contribute to increases in aeroallergens, which exacerbate asthma (see also Ch. 3: Air Quality), an illness that is relatively more common among some communities of color and low-income groups.

**Waterborne and vectorborne diseases.** Climate change may increase exposure to waterborne pathogens that cause a variety of illnesses—most commonly gastrointestinal illness and diarrhea.
(see also Ch. 5: Water-Related Illness). Illness risk increases in crowded shelter conditions following floods or hurricanes (Alderman et al. 2012), which suggests that some low-income groups living in crowded housing (particularly prevalent among foreign-born or Hispanic populations) (HUD 2007) may face increased exposure risk. Substandard or deteriorating water infrastructure (including sewerage, drainage, and storm water systems, and drinking water systems) in both urban and rural low-income areas also contribute to increased exposure risk (Abara et al. 2012; Hennesy et al. 2008). Because of poor housing conditions and other socioeconomic factors, some populations of color and low-income populations may be at increased risk for exposure to diseases carried by vectors such as fleas, ticks, and mosquitoes (Ramos et al. 2008) (see also Ch. 4: Vectorborne diseases).

**Food safety and security.** Climate change may affect food safety and is projected to reduce the nutritional content of some crops, like wheat and soy (see also Ch. 6: Food Safety). Populations of color and low-income populations are more likely to be affected because they spend a relatively larger portion of their household income on food than more affluent households. These groups often suffer from poor quality diets and limited access to full-service grocery stores that provide healthy and affordable dietary choices (Powell et al. 2007; Larson et al. 2009; Satia 2009; Coleman-Jensen et al. 2012).

**Psychological stress.** Some communities of color, low-income populations, immigrants, and LEP groups are more likely to experience long-term stress-related mental health impacts, particularly during and after extreme weather events (see Ch. 8: Mental Health). This is due to barriers in accessing and affording mental health care, including counseling in native languages and the availability and affordability of medications (DHHS 2001; Weisler et al. 2006).

### 9.4.2 Indigenous Peoples in the United States

A number of health risks are higher among Indigenous populations, such as alcohol abuse, suicide, infant/child mortality, poor mental health related to historical or personal trauma, environmental exposures from pollutants or toxic substances, and diabetes caused by inadequate or improper diets (Espey et al. 2014; Wong et al. 2014; Hoover et al. 2012; Evans-Campbell 2008; Sarche and Spicer 2008; Milburn 2004). Because of existing vulnerabilities, Indigenous persons, especially those who are dependent on the environment for sustenance or who live in geographically isolated or impoverished communities, are likely to experience higher exposure and lower resilience to climate-related health effects. Indigenous Arctic communities have already experienced difficulty adapting to climate change effects such as reductions in sea ice thickness, changes in permafrost distribution, increases in coastal erosion (Ford et al. 2014; Hinzman et al. 2005; Laidler et al. 2009; Wang and Overland 2012) and landslide frequency (Crozier 2010) and, alterations in the range of some fishes (Babaluk et al. 2000), increased weather unpredictability (Ford and Smit 2004), and northward advance of the tree line (Weller et al. 1999). These climate changes have disrupted traditional hunting and subsistence practices and may threaten infrastructure such as housing, transportation, and pipelines (Ford and Smit 2004), which may force relocation of villages (Ruckelshaus et al. 2013).
Food safety and security. Examples of how climate changes can affect Indigenous peoples’ health include: changes in the abundance and nutritional quality of certain foodstuffs, such as berries for Alaska Native communities (Kellogg et al. 2010); declining moose populations in Minnesota (Lenarz et al. 2009); rising temperatures and lack of available water for farming among Navajo people (Redsteer et al. 2011a); and declines in traditional rice harvests among the Ojibwe in the Upper Great Lakes region (Cheruvelil and Barton 2013). Traditional foods and livelihoods are embedded in Indigenous cultural beliefs and subsistence practices (Donatuto et al. 2014; Egeland and Harrison 2013; Lynn et al. 2013; Donatuto et al. 2011; Turner and Clifton 2009; Turner et al. 2008; Garibaldi and Turner 2004). Climate impacts on traditional foods may result in poor nutrition and increased obesity and diabetes (Kuhnlein et al. 2004).

Changes in aquatic habitats and species affect subsistence fishing (Moerlein and Carothers 2012). Rising temperatures affect water availability. Lower oxygen levels in freshwater and seawater degrades water quality and promotes the growth of disease-causing bacteria, viruses, and parasites (Melillo et al. 2014). Warming can exacerbate shellfish disease and make mercury more readily absorbed in fish tissue. Mercury exposure adversely affects people, particularly during the prenatal stage (Cozzetto et al. 2013; Booth and Zeller 2005). In addition, oceans are becoming more acidic as they absorb carbon dioxide from fossil fuel burning and other sources, which can lower shellfish survival (Melillo et al. 2014). This affects Indigenous peoples on the West and Gulf Coasts and Alaska Natives whose livelihoods depend on shellfish harvests (Lewitus et al. 2012). Rising sea levels will also destroy fresh and saltwater habitats that some Indigenous peoples located along the Gulf Coast rely upon for subsistence food (Carter et al. 2014).

Water security. Indigenous peoples may lack access to water resources and to adequate infrastructure for water treatment and supply. A significant number of Indigenous persons living on remote reservations lack indoor plumbing and rely on unregulated water supplies that are vulnerable to drought, changes in water quality, and contamination of water in local systems (EPA 2008; Redsteer et al. 2011a). Existing infrastructure may be poorly maintained or in need of significant and costly upgrades (TWWG 2012). Heavy rainfall events and warm temperatures have been linked to diarrheal outbreaks and bacterial contamination of water sources (see Ch. 5: Water-Related Illness). Acute diarrheal disease has been shown to disproportionately affect children on the Fort Apache reservation in Arizona (Sack et al. 1995), and result in higher overall hospitalization rates for American Indian/Alaska Native infants (Singleton et al. 2007). Increased extreme precipitation and potential increases in cyanobacterial blooms (see Ch 5: Water-Related Illness) are also expected to stress existing water infrastructure on tribal lands and increase exposure risk to waterborne pathogens (Doyle et al. 2013; Cozzetto et al. 2013).

Loss of cultural identity. Climate change threatens sacred ceremonial and cultural practices through changes in the availability of culturally relevant plant and animal species (Maldonado et. al 2013b; Doyle et al. 2013). Impacts of climate change may compound historical impacts associated with colonialism. Loss of tribal territory and disruption of cultural resources and
traditional ways of life (Hodge and Limb 2010; Hodge et. al 2009) lead to loss of cultural identity (Cunsolo Willox et al. 2012, 2013, 2015). The loss of medicinal plants due to climate change may leave ceremonial and traditional practitioners without the resources they need to practice traditional healing (Redsteer et al. 2015). As more young people leave the reservation for better school and employment opportunities, these relocations may reduce interactions across generations and undermine the sharing of traditional knowledge, tribal lore, and oral history (Alessa et al. 2008; ACIA 2004).

**Degraded infrastructure and other impacts.** Rising temperatures may damage transportation infrastructure on tribal lands. Changing ice or permafrost conditions, flooding, and drought-related dust storms may block roads and cut off communities from access to evacuation routes and emergency medical care or social services (Redsteer et al. 2011b). Poor air quality from blowing dust affects southwestern Indigenous communities, particularly in Arizona and New Mexico, and is likely to worsen with drought conditions (Draut et al. 2013). Exposure to impaired air quality also affects Indigenous communities, especially those downwind from urban areas or industrial centers.

### 9.4.3 Children and Pregnant Women

Children are uniquely vulnerable to adverse health effects associated with environmental exposures due to factors related to their immature physiology and metabolism. Children pass through a series of windows of vulnerability that begin in the womb and continue through their second decade of life. Children have a proportionately higher intake of air, food, and water for their body weight compared to adults (Shannon et al. 2007). They also share unique behaviors and interactions with their environment that may increase their exposure (Sheffield and Landrigan 2011). There is, however, large variation in vulnerability among children at different life stages due to differing physiology and behaviors (Figure 3). Research findings are pointing to a number of ways in which climate change may exacerbate existing health problems based on the exposure, other socioeconomic factors, and the developmental stage of the child (Balbus and Malina 2009; Bernstein and Myers 2011; Sheffield and Landrigan 2011; Xu et al. 2012a, 2012b).

[Figure 3. Children at Different Lifestages Experience Unique Vulnerabilities to Climate Change]

**Vulnerability to Climate-Related Health Stressors**

**Extreme heat events.** An increase in the frequency and intensity of extreme heat events (see Ch. 2: Temperature-related Death and Illness) will affect those children who spend significant time outdoors. Student athletes are susceptible to heat-related illnesses when they practice outside in hot and humid weather and may be poorly acclimated to physical exertion in the heat. Some 9,000 high school athletes in the United States are treated for exertional heat illness (such as heat stroke and muscle cramps) each year, with the greatest risk among high school football players (CDC 2010; Kerr et al. 2013). This appears to be a worsening trend. Between 1997 and 2006, emergency department visits for all heat-related illness increased 133% and youth made up
almost 50% of those cases (Nelson et al. 2011). In the last decade, the number of deaths due to heat stroke has doubled among U.S. high school and college football players (Gottschalk and Andrish 2011).

**Other weather extremes.** Climate change is likely to affect the mental health and well-being of children, primarily by increasing exposure to traumatic weather events that result in injury, death, or displacement. In the United States, more than 10% of children ages 2 to 17 are expected to experience a disaster (fire, tornado, flood, hurricane, or earthquake) during childhood (from infancy to 18 years of age) (Becker-Blease et al. 2010). Exposures to traumatic events can impact children’s capacity to regulate emotions, undermine cognitive development and academic performance, and contribute to Post-traumatic Stress Disorder (PTSD) and other psychiatric disorders (such as depression, anxiety, phobia, and panic) (Fairbank et al. 2014). Children’s ability to cope with disasters is affected by factors such as socioeconomic status, available support systems, and timeliness of treatment. Negative mental health effects in children, if untreated, can extend into adulthood (Fairbank et al. 2014).

**Degraded air quality.** Several factors make children more sensitive to the effects of respiratory hazards, including lung development that continues through adolescence, the size of the child’s airways, their level of physical activity, and body weight. Climate change has the potential to affect future ground-level ozone concentrations, particulate matter concentrations, and levels of some aeroallergens (see Ch. 3: Air Quality Impacts). Ground-level ozone and particulate matter are associated with increases in asthma episodes and other adverse respiratory effects in children (Strickland et al. 2010; Parker et al 2009; Ostro et al. 2009). Nearly seven million, or about 9%, of U.S. children suffer from asthma (Bloom et al. 2013). Asthma accounts for 10 million missed school days each year (Eder et al. 2006). Particulate matter such as dust and emissions from coal-fired electricity generation plants (see Air Quality Chapter) is also associated with decreases in lung maturation in children (Gauderman et al. 2004).

Changes in climate also contribute to longer, more severe pollen seasons that may be associated with increases in childhood asthma episodes and other allergic illnesses (see Ch. 3: Air Quality Impacts). Children may also be exposed to indoor air pollutants which include both particulate matter originating outdoors as well as indoor sources such as tobacco smoke and mold (McCormack et al. 2009). In addition, high outdoor temperatures may increase the amount of time children spend indoors.

**Waterborne illnesses.** Climate change induced increases in heavy rainfall, flooding, and coastal storm events are expected to increase children’s risk of gastrointestinal illness from ingestion of or contact with contaminated water (Lane et al. 2013; Xu et al. 2012b; Bernstein and Myers 2011; Kistin et al. 2010). An increased association between heavy rainfall and increased acute gastrointestinal illness has already been observed in children in the United States (Drayna et al. 2010, see also Ch. 5. Water-related Illness). Increases in reports of swimming-related diarrheal disease (CDC 2012c) and eye and ear infections from the waterborne bacteria *Vibrio*
algicolyticus (Dechet et al. 2008) suggest that children are especially vulnerable to recreational exposures to waterborne pathogens (see Ch. 5. Water-related Illness). In part this is due to the fact that on average, children swallow twice as much water as adults while swimming (McBride et al. 2013).

**Vectorborne diseases.** Tick-borne infections, such as Lyme disease and Rocky Mountain Spotted Fever, disproportionately affect children who spend a large amount of time outdoors (Bryant and Marshall 2000). Climate change is potentially driving the increasing prevalence and exposure to diseases spread by ticks and mosquitos, as the length of warm seasons and the habitat suitable for these vectors expands or shifts (see Ch. 4: Vectorborne Disease) (Ogden et al. 2014; Openshaw et al. 2010).

**Food safety and security.** Changes in food availability and quality related to climate change are likely to have significant impacts on children. Food insecurity already affects more than 20% of U.S. households with children (Coleman-Jensen et al. 2012). Children living in such households are more likely to have poor health status, to have been hospitalized at some time since birth, and to have increased developmental risk compared with food-secure families (Hager et al. 2010). Climate change may decrease crop yields, affecting supplies (Brown 2014) and decreasing calories for children and decreases in the nutritional quality of common foods such as wheat and rice (see Ch. 6: Food Safety) (Nelson et al. 2009; Ziska 2014).

**Vulnerability Related to Life Stage**

**Prenatal and pregnancy outcomes for mothers and babies.** Pregnancy, the developing fetus, and newborns are considered some of the most vulnerable life stages to environmental exposures, including climate-sensitive exposures such as changing patterns in food-, waterborne, and vectorborne diseases; poor air quality; increasing frequency and severity of extreme heat; and some extreme weather events. Climate-related exposures may lead to several adverse pregnancy and newborn health outcomes, including spontaneous abortion, low birth weight (less than 5.5 pounds), preterm birth (birth before 37 weeks of pregnancy), increased neonatal death, dehydration and associated renal failure, malnutrition, diarrhea, and respiratory disease (Rylander et al. 2013; Sheffield and Landrigan 2011). Other climate-related risk factors that may influence maternal and newborn health include water scarcity, worsened poverty, and population displacement (Rylander et al. 2013; Sheffield and Landrigan 2011). Relatively high preterm birth rates (that is 1 of every 9 infants born) occur in the United States (CDC 2015), where they contribute substantially to neonatal death and illness. Of the 1.2 million preterm births estimated to occur annually in high-income countries, more than 500 thousand (42% of the total) occur in the United States (March of Dimes et al. 2012). Extreme heat events have been associated with adverse birth outcomes such as low birth weight, preterm birth and infant mortality (Basu et al. 2010; Kent et al. 2014; Strand et al. 2011), as well as congenital cataracts (Van Zutphen et al. 2012). Epidemiological evidence examining seasonality of birth outcomes and the impact of prenatal exposure to ambient temperature indicates that temperature extremes may be a risk...
factor for preterm birth, stillbirth, and low birth weight (Strand et al. 2011; Rylander et al. 2013). Newborns are especially sensitive to ambient temperatures that are too high or too low because of limited temperature regulatory capacity (Polin et al. 2011).

In addition, exposure of mothers to inhaled particulate matter is associated with negative birth outcomes (Choi et al. 2008; Makri and Stilianakis 2008; Jayachandran 2009; Ritz et al. 2007; Dejmek et al. 1999; AAP 2004). Incidences of diarrheal diseases and dehydration may increase in extent and severity, which could be associated with adverse effects on pregnancy outcomes and the health of newborns (Rylander et al. 2013). Floods are associated with an increased risk of maternal exposure to environmental toxins and mold, reduced access to safe food and water, psychological stress, and disrupted health care. Other flood-related health outcomes for mothers and babies include maternal risk of anemia (a condition associated with low red blood cell counts sometimes caused by low iron intake) and eclampsia (a condition that can cause seizures in pregnant women), and spontaneous abortion (Callaghan et al. 2007; Tees et al. 2010; Hamilton et al. 2009; Harville et al. 2009).

**Infants and toddlers.** Infants and toddlers are particularly sensitive to air pollutants, extreme heat, and microbial water contamination, which are all affected by climate change. Ozone exposure in young children and exposure to air pollutants and toxins in wildfire smoke are associated with increased asthma risk and other respiratory illnesses (Lin et al. 2008; Bernstein and Myers 2011). Young children and infants are particularly vulnerable to heat-related illness and death, as their bodies are less able to adapt to heat than are adults (Basu and Ostro 2008; Basu 2009; Yip et al. 2008; Knowlton et al. 2009; Xu et al. 2012b). Children under four years record higher hospital admissions for respiratory illnesses during heat waves (Green et al. 2010). Rates of diarrheal illness have been shown to be higher in children under five in the United States (Imhoff et al 2004), and climate change is expected to increase children’s risk of gastrointestinal illness from ingestion or contact with contaminated water (Lane et al. 2013; Xu et al. 2012b; Bernstein and Myers 2011; Kistin et al. 2010, see also Ch. 5: Water-related Illness).

**9.4.4 Older Adults**

Older adults (generally defined as persons aged 65 and older) are vulnerable to the health impacts associated with climate change and weather extremes. A number of factors contribute to their vulnerability, including higher prevalence of certain preexisting medical conditions, functional and cognitive limitations, greater sensitivity to extreme heat, vulnerability incurred by location and conditions of local infrastructure, and the potential for social isolation and limited financial resources that make responding to emergent events and accessing health care more difficult or costly (Balbus and Malina 2009; Filiberto et al. 2010; NRC 2010b; Wang et al. 2010).

The number of older adults in the United States is projected to grow substantially in the coming decades. In 2010, older adults (65 and older) made up 13% of the U.S. population, but are projected to account for 20% in 2040 (Census Bureau 2014b). The group referred to by the
Census Bureau as the “oldest old,” (people 85 and older) currently comprises 1.5% of the U.S. population, a number projected to grow to 5% in 2040 (Census Bureau 2014b). This projected population growth is largely due to the aging of the Baby Boomer generation (an estimated 76 million people born in the United States between 1946 and 1964), along with increases in lifespan and survivorship (Gamble et al. 2013). Older adults in the United States are by no means uniform with regard to their climate-related vulnerabilities, but are a diverse group with distinct subpopulations that can be identified not only by age but also by race, educational attainment, socioeconomic status, social support networks, overall physical and mental health, and functional disability (Luber and Prudent 2009; NRC 2010b).

**Vulnerability to Climate-Related Health Stressors**

A range of potential health impacts for older adults, include: rising temperatures and heat waves; increased risk of more intense hurricanes (Categories IV and V), floods, droughts, and wildfires; degraded air quality; exposures to infectious diseases; and other climate-related hazards (Melillo et al. 2014).

**Extreme heat events.** Older adults exposed to extreme heat can experience multiple adverse effects (O’Neill and Ebi 2009). In the coming decades, extreme heat events are projected to become more frequent, more intense, and of longer duration, especially in higher latitudes and large metropolitan areas (Luber and McGeehin 2008; O’Neill et al. 2009). Between 1979 and 2004, 5,279 deaths were reported in the United States related to heat exposure, with those deaths reported most commonly among older adults aged 65 and older (Thacker et al. 2008). Disease incidence among older adults is expected to increase even in regions with relatively modest temperature changes (as demonstrated by case studies of a 2006 California heat wave) (Knowlton et al. 2009). In New York City, extreme high temperatures were associated with an increase in hospital admissions for cardiovascular and respiratory disorders, with the elderly among the most affected. Hospital admissions for respiratory illness were greatest for the elderly, with a 4.7% increase per degree Centigrade increase (Lin et al. 2009). Long-term increases in temperature may increase the risk of death in older people with chronic conditions, particularly those suffering from congestive heart failure and diabetes (Zanobetti et al. 2012). The percentage of older adults with diabetes, which puts individuals at higher risk for heat-related illness and death, has increased from 9.1% in 1980 to 19.9% in 2009 (CDC 2011).

**Other weather extremes.** Apart from the risks of direct physical injury or death, extreme weather events may cause secondary effects. These include: decreased availability and safety of food and water supplies; interruptions in communications, utilities, social services and health care services; and destruction or damage to homes and the built environment (Haq et al. 2008; Sanders et al. 2004). Hurricanes and other severe weather events lead to mental or emotional trauma before, during, and after the event (Cherry et al. 2010). The need to evacuate an area can pose increased health and safety risks for older adults, especially those residing in nursing or assisted living facilities. Moving patients to a sheltering facility is complicated, costly, and time consuming.
consuming and requires concurrent transfer of medical records, medications, and medical
equipment (CDC 2004; Laditka et al. 2008, see also Ch. 7. Extreme Events)

**Degraded air quality.** Climate change can affect air quality by increasing ground-level ozone,
fine particulate matter, aeroallergens, and dust (see Ch. 3. Air Quality) (Laumbach 2010; Reid
and Gamble 2009). Exposure to ground level ozone varies with age and can affect lung function
and increase emergency department visits and hospital admissions, even for healthy adults. Air
pollution can also exacerbate asthma and COPD and can increase the risk of heart attack in older
adults, especially those who are also diabetic or obese (Baja et al. 2010).

**Vector and waterborne diseases.** The abundance and distribution of some infectious disease
vectors (such as fleas, mosquitoes, and ticks) may be affected by climate change. Vectorborne
diseases pose a greater health risk among sensitive older adults with already compromised
immune systems. Flooding can also increase the incidence of water- and foodborne illnesses. An
early study from 1985 found that older adults (age 60 and older) made up approximately 25% of
hospital admissions for gastroenteritis (which can cause diarrhea and vomiting) following a
flooding event, but represented 85% of associated deaths (CCSP 2008).

**Vulnerability to Non-Climate Stressors**

**Vulnerable locations and condition of the built environment.** Older adults are particularly
vulnerable to climate change related health events based on their geographic location and
characteristics of their homes. More than half of the elderly U.S. adult population is concentrated
in 170 counties (5% of all U.S. counties) and approximately 20% of older Americans live in a
county in which a hurricane or tropical storm made landfall over the last decade (Zimmerman et
al. 2007). For example, Florida is a traditional retirement destination with an older adult
population of 16.8% in 2000, nearly 4% higher than the national average. The increasing severity
of tropical storms may pose particular risks for older adults in coastal zones (DHHS 2009). Other
geographic risk factors common to older adults, are the urban heat island effect, urban sprawl
(which affects mobility), characteristics of the built environment, and perceptions of
neighborhood safety (Stone et al. 2010; Browning et al. 2006).

Depending on construction and amenities, housing stocks can alter exposure and reduce or
exacerbate occupants’ risk of injury, illness and death. In deteriorating neighborhoods, where
safety and crime are a concern, older residents may fear venturing out of their homes and, as
such, live under a sort of self-imposed house arrest (Browning et al. 2006). Deteriorating
infrastructure, including the condition of housing and public transportation, is associated with
higher numbers of heat-related deaths in older adults. In multi-story residential buildings in
which residents rely on elevators, electricity loss makes it difficult, if not impossible, for elderly
residents and those with disabilities to leave the building to obtain food, medicines, and other
needed services (Haq et al. 2008). Also, older adults may not utilize air conditioning during heat
waves due to high operating costs (Balbus and Malina 2009; Hansen et al. 2011a, 2011b;
Sheridan et al. 2009).
**Vulnerability related to physiological factors.** Older adults are more sensitive to weather-related events due to age-related physiological factors. Elevated risks for cardiovascular deaths related to exposure to extreme heat have been observed in older adults (Ren et al. 2011; Basu and Ostro 2008). Generally poorer physical health conditions, such as long-term chronic illnesses, are exacerbated by climate change (Kovats and Hajat 2008; Conti et al. 2007; Hansen et al. 2011a, 2011b). Cognitive deficits that hinder effective and timely response to climate-related health risks increase vulnerability and reduce seniors’ capacity to respond to weather emergencies (Brault 2012; Agarwal et al. 2009). In addition, aging can impair the mechanisms that control body temperature, particularly for those taking psychotropic medications (drugs used to treat a variety of mental illnesses such as depression, anxiety, and psychosis) or other drugs that interfere with regulation of body temperature (Martin-Latry et al. 2007). Respiratory impairments already experienced by older adults will be exacerbated by increased exposure to outdoor air pollutants (especially ozone and fine particulate matter), aeroallergens, and wildfire smoke—all of which may be exacerbated by climate change (Wang et al 2010; Reid and Gamble 2009).

**Vulnerability related to functional disabilities.** Some functional limitations and mobility impairments increase older adults’ sensitivity to climate change. In 2007, 42% of older adults reported one or more functional limitations, while only about 19% of the general population reported such limitations. Dementia occurs at a rate of 5% of the population at age 71 to 79 years, with an increase to more than 37% at ages 90 and older (Agarwal et al. 2009). During weather emergencies, persons with mobility or cognitive impairments are likely to experience greater difficulty responding, evacuating, and recovering (Kovats and Hajat 2008).

### 9.4.5 Occupational Groups

Climate change may increase the prevalence and severity of known occupational hazards and exposures, as well as the emergence of new ones. Outdoor workers are often among the first to be exposed to the effects of climate change. Climate change is expected to affect the health of outdoor workers through increases in ambient temperature, degraded air quality, extreme weather, vectorborne diseases, industrial exposures, and changes in the built environment (Schulte and Chun 2009). Workers affected by climate change include farmers, ranchers, and other agricultural workers, commercial fishermen, construction workers, paramedics, firefighters and other first responders, and transportation workers (Lundgren 2013; Xiang et al. 2014; Spector and Sheffield 2014). Of special concern are workers who are vulnerable to the health effects of climate change based on other social and economic factors, such as migrant workers and day-laborers. For these groups, the health effects of climate change can be cumulative, with occupational exposures exacerbated by exposures that occur in the home associated with poorly insulated housing and lack of air conditioning. Workers may also be exposed to adverse occupational and climate related-conditions that the general public may altogether avoid, such as direct exposure to wildfires.
**Extreme heat events.** Higher temperatures or longer, more frequent periods of heat may result in more cases of heat-related illnesses (for example, heat stroke and heat exhaustion) and fatigue (Kjellstrom et al. 2009; Nilsson 2010; Gubernot et al. 2014; Xiang et al. 2014; Spector and Sheffield 2014), especially among more physically strenuous outdoor occupations. Heat stress and fatigue can also result in reduced vigilance, safety lapses, reduced work capacity, loss of economic productivity, and increased risk of injury. Elevated temperatures can increase levels of air pollution, including ground-level ozone, resulting in greater exposure of outdoor workers, linked to chronic health effects including respiratory illnesses (Lundgren 2013; Spector and Sheffield 2014; Schulte and Chun 2009, see also Ch. 2: Temperature-related Death and Illness).

**Other weather extremes.** Some extreme weather events and natural disasters, such as floods, storms, droughts, and wildfires, are becoming more frequent and intense (Melillo et al. 2014, see also Ch. 7: Extreme Weather). The need for more frequent, extensive, and complex emergency responses will expose rescue and cleanup workers to physical and psychological hazards (Noyes et al. 2009; Thacker et al. 2008). The safety of workers and their ability to recognize and avoid workplace hazards may be impaired by damage to infrastructure and communication disruption.

From 2000 to 2013, almost 300 U.S. wildfire firefighters were killed while on duty (USFA 2013). With the frequency and severity of wildfires projected to increase, more firefighters will be exposed. Common workplace hazards faced on the fire line include being overrun by fire (as happened during the Yarnell Hill Fire in Arizona in 2013 that killed 19 firefighters); heat-related illnesses and injuries; smoke inhalation; vehicle-related injuries (including aircraft); slips, trips, and falls; and exposure to particulate matter and other air pollutants. In addition, wildland fire fighters are at risk of rhabdomyolysis (a breakdown of muscle tissue) associated with prolonged and intense physical exertion (NIOSH 2012).

**Other workplace exposures to outdoor health hazards.** Other climate-related health threats for outdoor workers include increased waterborne and foodborne pathogens; increased duration of aeroallergen exposure with longer pollen seasons (Bartra et al. 2007; Ziska et al. 2007); and expanded habitat ranges of disease-carrying vectors which may influence the risk of human exposure to diseases such as West Nile virus or Lyme disease (Estrada-Peña 2002, see also Ch.4: Vectorborne Diseases).

**Box: Case Study: Occupational safety and health hazards for U.S. Armed Forces:**

**Vulnerability related to climate change**

Another emerging area of interest, but one where research is limited and key research questions remain, is the relationship between climate change and occupational safety and health hazards posed to members of the U.S. Armed Forces. The Department of Defense (DOD) recognizes that climate change will affect the operating environment, roles, and missions that the DOD undertakes both within the United States and abroad (DOD 2014, 2012, 2010). Given the varying environmental conditions in which the military operates, the DOD faces unique challenges in protecting and maintaining the health of its workforce. Climate change may increase the
frequency, scale, and complexity of future missions, including humanitarian assistance and
disaster response (DOD 2014), and may increase service members’ exposure to climate-related
health threats.

The most common non-combat related health problems during military deployment include
gastrointestinal illness and vectorborne, zoonotic, or parasitic infections (see Ch. 4: Vectorborne
Diseases) (Leggat 2010; Murray et al. 2007; Aronson et al. 2006). During operations in hot
climates, heat-related injuries among military personnel are common (Korzeniewski 2008). The
Armed Forces Health Surveillance Center (AFHSC) tracks diseases and other conditions to
protect the health of military personnel. AFHSC established guidelines for mandatory reporting
of 66 “reportable medical events,” which are conditions that may represent a significant threat to
public health and military operations (AFHSC 2012). Many of the Armed Forces reportable
events overlap with health threats discussed elsewhere in this report, including heat illness and
cold weather injuries; gastrointestinal illnesses such as giardiasis and cholera; and vectorborne,
zoonotic, and tropical diseases such as Lyme disease, brucellosis, and dengue fever, respectively.

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9.4.6 Persons with Functional Limitations/Disability and Limited Mobility or Cognitive
Capacity
Disability refers to functional impairments, activity limitations, or restrictions in a person’s
participation in normal life activities such as school, work, or recreation. The term “disability”
subsumes a wide variety and range of functional limitations related to expressive and receptive
communication, vision, cognition, and freedom of movement and behavior that, if not anticipated
and accommodated before, during, and after emergency weather events, can result in illness and
death (Kailes & Enders 2007). The extent of disability, or its severity, is reflected in the affected
person’s need for environmental accessibility and accommodations for their impairment(s)
(WHO 2001). Functional impairments affect movement, vision, hearing, speech, cognition, and
socially acceptable behaviors.

Disability can occur at any age and is not uniformly distributed across populations. Disability
varies by sex, race, ethnicity, and geographic location (NCHS 2014). In the United States in
2010, there were approximately 34.9 million non-institutionalized people of all ages with a
severe disability and an additional 19.5 million with a less severe disability (Brault 2012).
Working-age adults with disabilities are substantially less likely to participate in the labor force
(31.4%) than people without disabilities (76.2%) and experience twice the rate of unemployment
(14.7% and 7.2%, respectively) (BLS 2014).

People with disabilities experience disproportionately higher rates of social risk factors, such as
poverty and lower educational attainment that contribute to poorer health outcomes during
extreme weather or climate-related emergencies (CDC 2013). These factors compound the risks
posed by functional impairments and disrupt planning and emergency response. Of the climate-
related health risks experienced by people with disabilities, perhaps the most fundamental is their “invisibility” to decision makers and planners (Wolbring & Leopatra 2012). Limited research documents how people with disabilities fare during or after a disaster (for example, Lemyre et al. 2009).

An increase in extreme weather events can be expected to disproportionately affect populations with disabilities unless emergency planners make provisions to address their functional limitations in preparing emergency response plans. In 2005, Hurricane Katrina had a significant and disproportionate impact on people with disabilities. Of the 986 deaths directly attributable to the storm, 103 occurred among individuals in nursing homes, presumably with a disability (Brunkard et al. 2008). In the aftermath of Hurricane Sandy, the City of New York lost a lawsuit (Case 1.11-cv-06690-JMF, 2013) filed by the Brooklyn Center of the Disabled, with the finding that the city had not adequately prepared to accommodate the social and medical support needs of New York residents with disabilities.

Risk communication is not always designed or delivered in an accessible format or media for individuals who are deaf or have hearing loss, who are blind or have low vision, or those with diminished cognitive skills (Lazrus et al. 2012; Nick et al. 2009). Emergency communication and other important notifications (such as a warning to boil contaminated water) simply may not reach persons with disabilities. In addition, persons with disabilities often rely on medical equipment (such as portable oxygen) that requires a continuous source of electricity. Portable oxygen supplies must be evacuated with the patient (Jan and Lurie 2012).

9.4.7 Persons with Chronic Medical Conditions

Pre-existing medical conditions present risk factors for increased illness and death associated with climate-related stressors, especially exposure to extreme heat. In some cases, risks are mediated by the physiology of specific medical conditions that may impair responses to heat exposure. In other cases, the risks are related to unintended side effects of medical treatment that may impair body temperature, fluid, or electrolyte balance and thereby increase risks. Trends in the prevalence of chronic medical conditions are summarized in Table 1 in the Introduction chapter. In general, the prevalence of common chronic medical conditions, including cardiovascular disease, respiratory disease, diabetes, asthma, and obesity, is anticipated to increase over the coming decades (CDC 2014) (see Ch. 1: Introduction), resulting in larger populations at risk of medical complications from climate change related exposures.

Excess heat exposure has been shown to increase the risk of disease exacerbation or death for people with various medical conditions. Hospital admissions or emergency room visits are increased during heat waves for people with diabetes, cardiovascular diseases, respiratory diseases, and psychiatric illnesses (Schifano et al. 2009; Hansen et al. 2008; Ostro et al. 2010; Knowlton et al. 2009; Green et al. 2010; Basu 2009; Astrom et al. 2011; Kravchenko et al. 2013). Medical conditions like Alzheimer’s disease or mental illnesses can impair judgment and
behavioral responses in crisis situations, which can place people with those conditions at greater
risk (Hansen et al. 2011b).

Medications used to treat chronic medical conditions are associated with increased risk of
hospitalization, emergency room admission, and in some cases, death from extreme heat. These
medicines include drugs used to treat neurologic or psychiatric conditions, such as anti-psychotic
drugs, anti-cholinergic agents, anxiolytics (anti-anxiety medicines), and some antidepressants
(such as selective serotonin reuptake inhibitors or SSRIs) (Martin-Latry 2007; Stollberger et al.
2009; Nordon et al. 2009). (See also Ch. 8: Mental Health and Well-Being) In addition, drugs
used to treat cardiovascular diseases, such as diuretics and beta-blockers, may impair resilience
to heat stress (Hausfater et al. 2009; Stolleberger et al. 2009).

People with chronic medical conditions also can be more vulnerable to interruption in treatment.
For example, interrupting treatment for patients with addiction to drugs or alcohol may lead to
withdrawal syndromes (Miller and Arquilla 2008; Tofighi et al. 2014; Carlisle Maxwell et al.
2009). Treatment for chronic medical conditions represents a significant proportion of post-
disaster medical demands (Jhung et al. 2007). Communities that are both medically underserved
and have a high prevalence of chronic medical conditions can be especially at risk (Davis et al.
2010). While most studies have assessed adults, and especially the elderly, with chronic medical
conditions, children with medical conditions such as allergic and respiratory diseases are also at
greater risk of symptom exacerbation and hospital admission during heat waves (Xu et al.
2012a).

9.5 Measures of Vulnerability and Mapping
Vulnerability associated with exposures to climate related hazards is closely tied to place. While
an understanding of the individual-level factors associated with vulnerability is essential to
assessing population risks and considering possible protective measures, understanding how
vulnerable people are situated geographically with respect to potential exposures is critical for
designing and implementing appropriate adaptations. Analytic capabilities provided by mapping
tools allow public health and emergency response workers to consider multiple types of
vulnerability and how they interact with place. The development of indices that combine
different elements of vulnerability and allow visualization of areas and populations experiencing
the highest risks is related to improved GIS capabilities.

9.5.1 Approaches to Assessing Vulnerability
Methods to assess and measure vulnerability to climate change in populations of concern are
grounded in approaches that utilize both quantitative and qualitative methods. Quantitative
vulnerability assessments typically analyze vulnerability across large areas, such as state or
multi-state regions. Qualitative approaches are often more time- and resource-intensive and
typically focus on small areas such as households within a county or several counties within a
state. A qualitative vulnerability assessment may involve conducting surveys on the resilience of
health infrastructure to provide insight regarding underlying social processes (WHO 2013).
There are multiple approaches for developing vulnerability indices to identify populations of concern. The Social Vulnerability Index (SVI), developed by the Centers for Disease Control and Prevention (CDC) aggregates U.S. Census data to estimate the social vulnerability of census tracts (which are generally subsets of counties) (Figure 4). The SVI provides a measure of overall social vulnerability in addition to measures of elements that comprise social vulnerability (including socioeconomic status, household composition, race, ethnicity and language, and, housing/transportation). Each census tract receives a separate ranking for overall vulnerability and for each of the four elements, which are available at the census tract level for the entire United States. A similar methodology has been used to develop a vulnerability index for climate-sensitive health outcomes which, in addition to socioeconomic data, incorporate data on climate-related exposure and adaptive capacity (Manangan et al. 2014).

9.5.2 Application of Vulnerability Indices

Geographic Information Systems (GIS)—data management systems used to capture, store, manage, retrieve, analyze, and display geographic information—can be used to quantify and visualize factors that contribute to climate-related health risks. By linking together census data, data on the determinants of health (social, environmental, pre-existing health conditions), measures of adaptive capacity (such as health care access), and climate data, GIS mapping helps identify and position resources for at-risk populations (CSDH 2008; Friel et al. 2008; Gubler et al. 2001; Smit et al. 2001; Turner et al. 2003; Manangan et al. 2014). For instance, heat-related illnesses have been associated with social isolation in older adults, which can be mapped by combining data for persons living alone (determinants of health data), distribution of people aged 65 and older (census data), and frequency and severity of heat waves (climate data).

Vulnerability mapping can also enhance emergency and disaster risk management. (Blaikie et al. 1994; Hutton 2010). Vulnerability mapping conducted at finer spatial resolution (for example, census tracts or census blocks) allows public health departments to target vulnerable communities for emergency preparedness, response, recovery, and mitigation (Keim 2008). During the preparedness phase, vulnerability mapping can be used to identify vulnerable groups who are less likely to be prepared and most likely to need response support (Keim 2008). In the mitigation phase, vulnerability mapping can be used to determine optimal locations for emergency shelters and to develop planning and policies to address risks (Hutton 2010). During the response phase, vulnerability mapping can be used to determine resource allocation, to prioritize responses, and to tailor emergency communication. During the recovery phase, vulnerability mapping can identify populations that are least resilient to determine those who have experienced a debilitating impact. In each phase, the geographic characteristics of vulnerability can be used to determine where to position response resources (Blaikie et al. 1994; Keim 2008; Hutton 2010).
Emergency response agencies can apply lessons learned by mapping prior events. For example, vulnerability mapping has been used to assess how social disparities affected the geography of recovery in New Orleans following Hurricane Katrina (Finch et al. 2010). Maps displaying the intersection of social vulnerability (low, medium, high scores) and flood inundation (none, low, medium, high levels) showed that while the physical manifestation of the disaster had few race or class distinctions, the social vulnerability of communities influenced both pre-impact responses, such as evacuation, and post-event recovery (Finch et al. 2010). As climate change increases the probability of more frequent or more severe extreme weather events, vulnerability mapping is an important tool for preparing and responding to health threats.

**Box: Case Study: Mapping Heat Vulnerability in Georgia**

The CDC conducted a case study of heat-related vulnerability in Georgia using data from 2002 to 2008. This climate and health vulnerability assessment, which identifies people and places that are most susceptible to hazardous exposures from climate change, uses GIS to overlay six maps depicting population-level sensitivity (poverty levels, elderly people living alone, pre-existing health conditions, and people living in urban areas), adaptive capacity (a measure of access to healthcare), and exposure (a measure of heat events). The study found that vulnerability to heat-related illness in Georgia extends beyond urban zones. In fact, areas located in the southern portion of Georgia, which is more rural, experienced more hazardous heat events, had less access to health care, and had a higher percentage of people living alone. These types of studies allow researchers to use GIS to identify vulnerable communities, which can aid in the development of health interventions and other adaptations (Manangan et al. 2014). (Figure 5)

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### 9.6 Research Needs

Research is needed to understand how and to what extent vulnerable groups of people are faced with health risks associated with climate change. Research needs may include the following: the characterization of interactions between climate and non-climate health stressors; the use of mapping to assess human health impacts that utilize methods to improve geospatial modeling techniques designed to target services for affected populations; the utilization of alternative climate, land use, and demographic scenarios to project future health impacts; the characterization of tipping points or thresholds for which low-likelihood events may result in high-impact outcomes; and finally, the estimation of direct and indirect costs associated with alternative adaptation strategies.
9.7 Traceable Accounts

Process for Developing Key Findings

The Key Findings were developed by the Populations of Concern chapter author team, following detailed discussions and expert deliberation across a series of author conference calls (approximately ten meetings from May through November 2014) and during the discussions that took place at the all authors’ meeting and expert consultation in Washington DC during September 2014. The Populations of Concern chapter authors include two Lead Authors and 25 Contributing Authors. This version of the Key Findings was finalized during author calls on November 5 and 19, 2014. The Key Findings were derived after a comprehensive review of the peer-reviewed scientific literature and other inputs provided by the public in response to a call for comments announced in a Federal Register Notice. The Key Findings were benefitted by consultations with government, academic, and NGO subject matter experts.

Vulnerability Varies Across Individuals, Time Scales, and Places

Key Finding 1: Across the United States, people and communities differ in their exposures, their inherent sensitivity, and their adaptive capacity that enables them to respond to and cope with climate change related health threats. Vulnerability to climate change varies across time and geographic areas, across communities, and among individuals within communities. [Very High Confidence]

Description of evidence base. Current epidemiological evidence on climate-sensitive health outcomes in the U.S. indicates that health impacts will differ by location, pathways of exposure, underlying susceptibility, and adaptive capacity. These disparities in health impacts will largely result from differences in the distribution of individual attributes in a population that confers vulnerability (such as age, socioeconomic status, and race), attributes of place that reduce or amplify exposure (floodplain, coastal zone, and urban heat island), and the resilience of public health infrastructure.

Factors that contribute to exposure include: occupation (Schulte and Chun 2009), time spent in risk-prone locations (Balbus and Malina 2009; Uejio et al. 2001; O’Neill et al. 2008), displacement by weather extremes (Donner et al. 2008), economic status (Harlan et al. 2006; Woodruff et al. 2003), condition of infrastructure (Pastor et al. 2006; Bullard and Wright 2009), and compromised mobility, cognitive function, and other mental or behavioral factors (CDC 2013).

Biologic sensitivity and adaptive capacity are tied to many of the same factors determining exposures. All of these factors can change with time, life-stage (Shannon et al. 2007; Sheffield and Landrigan 2011; Balbus and Malina 2009). Social and economic factors also affect disparities in the prevalence of chronic medical conditions that aggravate biologic sensitivity (Frumkin et al. 2008; Keppel 2007).
Major uncertainties. Understanding how exposure, sensitivity, and adaptive capacity change over time and location for specific individuals, communities, and populations of concern is challenging, particularly when attempting to project impacts of climate change on health across long time frames (such as in the year 2100). Uncertainties remain with respect to underlying social determinants of health, public health interventions or outreach, rates of adaptation, and climate impacts at fine local scales.

Assessment of confidence based on evidence. Based on the evidence presented in the peer-reviewed literature, there is very high confidence that climate change impacts on health will vary with people, place, and time, as demonstrated by the complex factors driving vulnerability. Many qualitative and quantitative studies have been published with consistent findings and strong consensus that the impacts of climate change on human health will vary according to individual or community characteristics (including differential exposure, sensitivity, and adaptive capacity), which change over time and across geographical scales. These conclusions are well documented and supported by high quality evidence from multiple sources.

Climate Factors Interact with Non-Climate Factors to Increase Health Risk

Key Finding 2: Climate change related health risks interact with some of the same non-climate factors that may increase the risk of poor health generally. Non-climate factors, such as those related to demographic changes, socioeconomic factors, and pre-existing or chronic illnesses, may amplify, moderate, or otherwise influence climate-related health effects, particularly when they occur simultaneously or close in time or space. [High Confidence]

Description of evidence base. Exposures to climate change are likely to be influenced by a number of non-climate factors that contribute to the nature and extent of vulnerability. Some non-climate factors include:

- **Occupation**: where workers are at risk due to their place of employment or the nature of their duties (Schulte and Chun 2009).
- **Time spent in risk-prone locations**: Locations that experience greater risks include urban heat islands where exposed populations are likely to have limited adaptive capacity due to poor housing conditions, and inability to use or to afford air conditioning (Ramin and Svoboda 2009; Shonkoff et al. 2011; Jesdale et al. 2013; CDC 2011; Klineberg 2002; Harlan et al. 2006; Semenza et al. 1999; Luber and McGeehin 2008; Younger et al. 2008; CDC 2013; DHHS 2013).
- **Economic status**: People living in poverty are less likely to have adequate resources to prepare for or respond to weather emergencies or to access and afford necessary health or supportive services (Vargas-Bustamante et al. 2010; Fuentes-Afflick and Hessol 2008; Maldonado et al. 2013a; Ortega et al. 2007; Eneriz-Wiemer et al. 2013; Riera et al. 2013).
- **Condition of infrastructure**: Decaying infrastructure exposes people to increased health risks. Persons evacuating may be hampered by damage to transportation, utilities,
medical, or communication facilities and lack of safe food or drinking water supplies (Haq et al. 2008; Balbus and Malina 2009; Hansen et al. 2011; Sheridan et al. 2009; Redsteer 2011b).

- Biological traits contribute to the sensitivity of people to climate change. Among those traits are age or stage of life; chronic or pre-existing medical or psychological illnesses; and compromised mobility and cognitive function (Jhung et al. 2007; Davis et al. 2010; Xu et al. 2012).

Major uncertainties. A wide range of non-climate factors are expected to interact with climate change health risks to determine population vulnerability, all with some degree of uncertainty. The extent to which those factors affect vulnerability is, in many cases, not well understood and not readily amenable to measurement or quantification. Assessing the extent and nature of non-climate impacts as compared to impacts related to climate change is limited by data availability, particularly at the national level. Many studies of climate change vulnerability have limited geographic scope or focus on singular events in a particular location.

Assessment of confidence based on evidence. Based on the evidence presented in the peer-reviewed literature, there is high confidence that a wide range of health effects exacerbated by climate change will interact with non-climate factors to determine the vulnerability of some populations of concern. Many studies have been published about how non-climate factors may influence climate-related health effects across populations of concern, and the evidence presented is of good quality and consistency.

Increased Vulnerability to Climate-Related Health Impacts is Widespread Across Ages and Stages of Life

Key Finding 3: People experience different vulnerabilities at different ages and life stages. For example, the very young and the very old are particularly sensitive to climate-related health impacts. [High Confidence]

Description of evidence base. In the United States, older adults and young children are especially vulnerable to human health risks associated with climate change. Ground-level ozone and particulate matter are associated with increases in asthma episodes and other adverse respiratory effects in children (Strickland et al. 2010; Parker et al 2009; Ostro et al. 2009; Gauderman et al. 2004). Increased aeroallergens may also be linked to increases in childhood asthma episodes and other allergic illnesses (Ch. 3: Air Quality Impacts). Children are vulnerable to waterborne pathogens in drinking water and through exposures while swimming. There is an association between heavy rain and emergency department visits for children with gastrointestinal illness (Drayna, et al. 2010; McBride et al. 2013).

Children’s mental health is affected by exposures to traumatic weather events. More than 10% of children are expected to experience a disaster (fire, tornado, flood, hurricane, or earthquake) in...
their lifetime (Becker-Blease et al. 2010). These exposures can undermine cognitive
development and contribute to psychiatric disorders (Fairbank et al 2014).

Extreme ambient temperature is an important determinant of health in older adults (O’Neill and
Ebi 2009; Luber and McGeehin 2008) and has been associated with increased hospital
Older adults are particularly affected by extreme weather events that compromise the availability
and safety of food and water supplies; interrupt communications, utilities, and emergency
services; and destroy or damage homes and the built environment (Haq et al. 2008; Sanders et al.
2004; CDC 2004; Ladirka et al. 2008). Some functional and mobility impairments make older
adults less able to evacuate when necessary (Agarwal et al. 2009; Kovats and Hajat 2008).

**Major uncertainties.** Uncertainties remain regarding the extent to which climate-related
disruptions to health and well-being are affecting populations of concern, especially young
children and older adults. There is less information on the magnitude of these effects at a
national level given limitations in data availability. Many studies of age-related vulnerability
have limited geographic scope or focus on singular events in a particular location. Multiple
factors, all with some degree of uncertainty, converge to determine climate-related vulnerability
across age groups.

**Assessment of confidence based on evidence.** Based on the evidence presented in the peer-
reviewed literature, there is high confidence that a wide range of health effects exacerbated by
climate change will be experienced by vulnerable age groups, especially young children and
older adults. Many qualitative and quantitative studies have been published about the effects of
age or life stage on vulnerability to health impacts, and the evidence is consistent and of good
quality.

**Mapping Tools and Vulnerability Indices Help to Identify Where and for Whom Climate
Health Risks are Greatest**

**Key Finding 4:** The use of geographic data is allowing more sophisticated mapping of risk
factors and social vulnerabilities, to identify and protect specific locations and groups of people.

[Medium Confidence]

**Description of evidence base.** Geographic Information Systems (GIS) have the ability to link
together census data, data on the determinants of health (social, environmental, pre-existing
health conditions), measures of adaptive capacity (such as health care accessibility), and
environmental data for the identification of at-risk populations (Gubler et al. 2001; Smit et al.
2001; CSDH 2008; Friel et al. 2008; Turner et al. 2003; Manangan et al. 2014). Similarly,
demographic and environmental data can be integrated to create an index that allows for analysis
of the factors contributing to social vulnerability in a given geographic area (ATSDR 2015;
Manangan et al. 2014). Identifying vulnerability is an important step in developing prevention
strategies or determining where to focus health or emergency response resources (Blaikie et al. 1994; Keim 2008; Hutton 2010). A case study of heat-related vulnerability in Georgia provides one example of the utility of vulnerability mapping in a climate change context (Manangan et al. 2014).

**Major uncertainties.** Multiple factors, all with some degree of uncertainty, determine geographic vulnerability to the health impacts of climate change. Mapping tools and vulnerability indices are useful in characterizing geographically-based exposures. But, geocoded health data are not always available in all locations of interest. In fact, the extent of uncertainty increases at smaller spatial scales, which is typically the scale most relevant for targeting vulnerable communities.

**Assessment of confidence based on evidence.** Based on the evidence presented in the peer-reviewed literature, there is medium confidence that geographic data used in mapping tools and vulnerability indices can help to identify where and for whom climate health risks are greatest. A number of published studies provide consistent and good quality evidence to support a finding regarding the utility of mapping tools and vulnerability indices in a public health context, but methods are still emerging to support the application of these tools in the context of climate change. Overall, evidence is suggestive but not conclusive that mapping tools and vulnerability indices can help to identify where and for whom climate health risks are greatest.
9.8 References


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9.9 Figures

Figure 1. Determinants of Vulnerability

**Figure 1**: Defining determinants of vulnerability to health impacts, including exposure, sensitivity, and adaptive capacity.

**Caption**: Defining determinants of vulnerability to health impacts, including exposure, sensitivity, and adaptive capacity. (Figure source: adapted from Turner et al. 2003)

Figure 2. Social Determinants of Health

Caption: This figure conceptualizes vulnerability to the health risks associated with climate change across populations of concern. (Figure source: adapted from Solar and Irwin 2010)
Figure 3: Children at Different Lifestages Experience Unique Vulnerabilities to Climate Change

Children at Different Lifestages Experience Unique Vulnerabilities to Climate Change

Children are more sensitive to climate change due in large part to their developing bodies and immune systems.

Mothers and babies

Adverse pregnancy outcomes such as low birth weight and preterm birth have been linked to extreme heat events, airborne particulate matter, and floods, which are all affected by climate change.

School age and older children

Climate change is expected to increase health risks to older children from asthma and allergies, heat-related illness and death, vectorborne and waterborne disease, and extreme weather events.

Infants and toddlers

Young children are particularly sensitive to asthma, diarrheal illness, and heat-related illness and death, which are all expected to increase due to climate change.
Figure 4: Mapping Social Vulnerability

Caption: CDC Social Vulnerability Index (SVI): Interactive Web Map showing the overall social vulnerability of the U.S. Southwest, 2010 (Figure source: ATSDR 2015)
Figure 5: to accompany Text Box

(Figure source: adapted from Manangan et al. 2014)