GRAND CHALLENGE 2:

Curb Climate Change and Adapt to Its Impacts

It is now more certain than ever that humans are changing Earth's climate.[97] The burning of fossil fuels for electricity generation, transportation, heating, cooling, and other energy uses has raised the concentration of global atmospheric carbon dioxide (CO_2) to more than 400 parts per million (ppm)—a level that last occurred about 3 million years ago when both global average temperature and sea level were significantly higher than today.[98] At the same time, the production of fossil fuels and agricultural and industrial processes also have emitted large amounts of methane and nitrous oxide, both powerful greenhouse gases, into the atmosphere.

The heat trapped by the sharp rise in greenhouse gases has increased Earth's global average surface temperature by about 1.8°F (1.0°C) over the past 115 years, and at an increased rate since the mid-1970s (see Figure 2-1).[99] This warming has been accompanied by rising sea levels, shrinking Arctic sea ice, reduced snow pack, and other climatic changes. Many urban areas across the globe have witnessed a significant increase in the number of heat waves. More rain is falling during the heaviest rainfall events, causing flooding and further stressing low-lying coastal

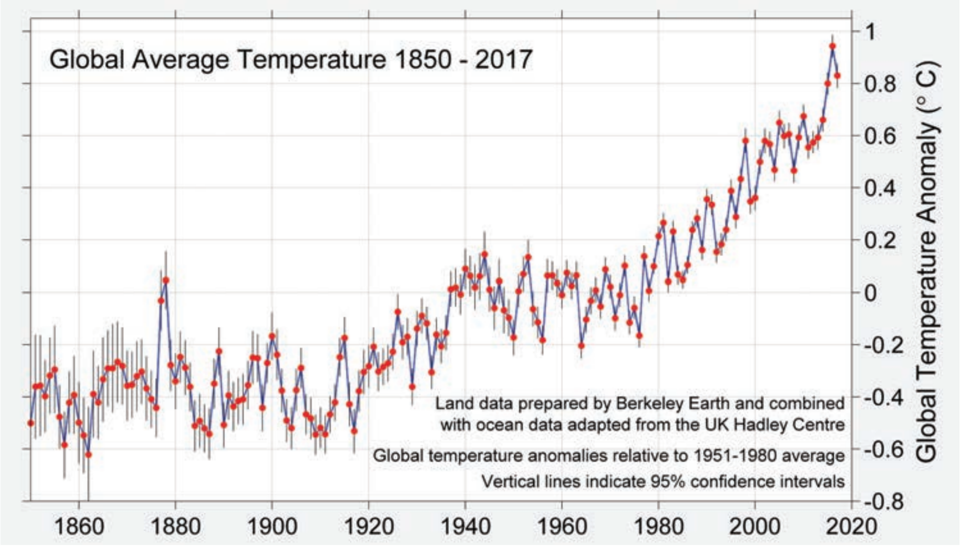

FIGURE 2-1. Earth's global average surface temperature has risen about 1.8°F (1.0°C) over the past 115 years, with much of that increase occurring since the mid-1970s. The temperature changes (anomalies) are relative to the global average surface temperature of 1951–1980.

zones already vulnerable to storm surges and other causes of temporary coastal flooding, along with sea-level rise.[100] In other areas, prolonged dry periods and droughts are increasing the risk of destructive wildfires and water shortages.

If greenhouse gas emissions continue to rise in the 21st century, Earth is expected to warm by an additional 4.7°F to 8.6°F (2.6°C to 4.8°C) by 2100 (relative to 1986-2005).[101] The greater the warming, the greater the impacts will be. In the United States, each degree of warming (Celsius) is projected to result in a 3 to 10 percent increase in the amount of rainfall during the heaviest rain events, a 5 to 15 percent reduction in the yields of crops as currently grown, and a 200 to 400 percent increase in the area burned by wildfire in western states.[102] Similar types of changes are expected in many other parts of the world, which could be most devastating to low-income countries that do not have the resources to respond or adapt.[103]

Warming of about 5.4°F (3°C) or more could push Earth past several "tipping points." For example, this amount of warming could melt the Greenland ice sheet, which would raise global average sea level an additional 20 feet (6 meters).[104] It could also accelerate the thawing of permafrost, which would accelerate the release of CO_2 and methane stored in frozen soil, exacerbating warming.[105] While projections such as these are useful in planning for the changes ahead, it is also important to recognize that a great deal remains unknown, particularly when it comes to the complex feedbacks among human activities, ecosystems, and the atmosphere.

For decades, scientists have led the efforts to understand and predict climate change effects, but engineers are now recognizing that their efforts are needed to help develop and implement solutions. Conceptually, climate solutions are divided into two areas of focus: mitigation and adaptation. Mitigation refers to efforts to reduce the magnitude or rate of climate change by reducing emissions of carbon dioxide and other greenhouse gases or removing them from the atmosphere. Adaptation refers to solutions that avoid or lessen the impacts of climate change on people, ecosystems, resources, and infrastructure. Environmental engineers have an opportunity to be leaders in developing technologies and systems that provide solutions on both of these fronts. Given that future climate changes likely hold surprises, it will be important to remain nimble, incorporate new knowledge, and work to address uncertainty as environmental engineers develop, test, and implement solutions.

Reducing the Rate and Magnitude of Climate Change

A sharp reduction in emissions of greenhouse gases to the atmosphere is needed to slow climate change and prevent some of the most severe impacts. For the past few decades, international climate talks have focused on establishing goals to minimize the planet's warming, with the most recent goals set at limiting future warming to 3.6°F (2°C) above preindustrial levels. The 2016 Paris Agreement set an aspirational target of limiting warming to 2.7°F (1.5°C). Since the planet already has warmed about 1.8°F (1°C), scientists have calculated that, in order to stay within the 3.6°F (2°C) limit, atmospheric CO_2 concentrations must not rise beyond 450 ppm, which in turn requires 40 to 70 percent reductions in global anthropogenic greenhouse gas emission by 2050 compared to 2010, and emissions levels near zero or below in 2100.[106]

A special report issued in 2018 by the Intergovernmental Panel on Climate Change urged world leaders to work toward limiting warming to 2.7°F (1.5°C) to avoid the severe impacts on weather extremes, ecosystems, human health, and infrastructure that are expected to occur at 3.6°F (2°C) warming.[107] Meeting that tougher goal will require global emissions to be reduced by about 45 percent from 2010 levels by 2030, reaching net zero emissions by 2050. Meeting those emissions targets will require dramatic reductions in global CO_2 emissions combined with the active removal of CO_2.[108]

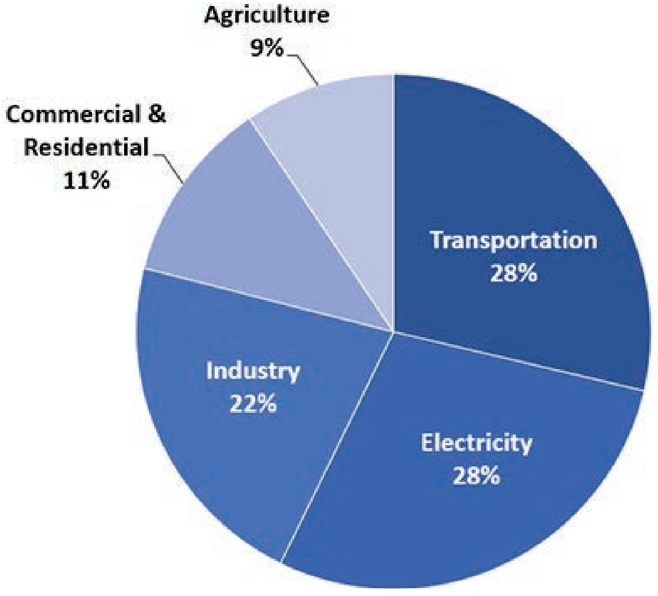

FIGURE 2-2. Total U.S. greenhouse gas emissions by sector in 2016, in CO_2 equivalents.

Greenhouse gas emissions are driven by the use of energy for electricity generation, transportation, industry uses, commercial and residential needs, and agriculture. Figure 2-2 shows the U.S. breakdown for greenhouse gas emissions sources. Emissions can be reduced by using energy more efficiently, switching to fuels that produce less (or no) greenhouse gases, and capturing the emissions before they enter the atmosphere.

In general, reducing emissions will require that existing and planned transportation, building, and industrial infrastructure be converted to electricity that is generated with substantially lower carbon intensity. Doing so will have the added co-benefit of reducing the environmental and human health impacts associated with coal, oil, and natural gas extraction and fossil-fuel-generated electricity (see Challenge 3).[109]

Using Energy More Efficiently

High-income countries have already substantially reduced their energy use per capita and per unit of economic output. These improvements have resulted from significant technological changes, such as the advent of LED lighting, energy-efficient appliances, and other efficiency intelligence in buildings; industrial restructuring to enhance productivity; and investment in fuel-efficient transportation technologies. Lower- and middle-income countries are beginning to make similar gains.

Efficiency gains made to date, however, will not be sufficient to avoid a 3.6°F (2°C) average rise in global temperatures. More than 80 percent of vehicle miles traveled in 2050 need to be powered by something other than an internal combustion engine.[110] Substantial efficiencies also are needed in industry and in the heating and cooling of buildings. In Germany, for example, a high-level commission calculated that German buildings would need to achieve a 54 percent improvement in efficiency by 2030 to meet stated emission reduction goals.[111] Effectively deploying new and emerging technologies can help advance these goals. It has been estimated that energy-efficient technologies for residential and commercial buildings, transportation, and industry that exist today or are expected to be developed soon could reduce U.S. energy use by 30 percent, slashing greenhouse gas emissions along with other air pollutants, while also saving money.[112]

Switching to Fuels That Produce Less (or No) CO_2

As discussed in Challenge 1, there are many sources of energy that produce little or no CO_2 emissions, including solar, wind, geothermal, and hydropower. Although low-emissions energy sources exist, there is still a long way to go toward their widespread adoption. As of 2017, U.S. electricity generation was composed of about 63 percent fossil fuels, 20 percent nuclear, and 17 percent hydropower and other renewables.[113] A study by the Department of Energy's National Renewable Energy Laboratory shows that it is feasible for the United States to generate most of its electricity from renewable energy by 2050, but a number of challenges remain.[114] Cost has been a significant barrier, although costs are dropping for both solar and wind power technologies.[115]

Reducing U.S. emissions enough to stay within the 2.7°F (1.5°C) limit would require the current balance of energy production to shift substantially, such that 70-85 percent of electricity is generated from noncarbon-emitting sources.[116] In China, maturation and economic restructuring of the industrial sector has already substantially reduced coal consumption per unit of output, a trend that is projected to continue and be further enhanced by their recently introduced carbon cap and trade system.[117] In addition, China is leading the charge in developing renewable energy, for example, building 45 percent of the world's solar installations in 2016.[118]

Advances are needed to improve the efficiency and reduce the costs of such energy sources to make them competitive with traditional fossil fuel–based sources. In addition, since many renewables produce energy intermittently, there is a need for energy storage systems with increased capacity, scalability, reliability, and affordability, as discussed in Challenge 1.

Nuclear power is one low-emission energy source that already comprises one-fifth of U.S. electricity generation. Increasing the use of nuclear power could help reduce carbon-emitting energy generation, but there are significant barriers, including cost, public concerns related to safety and waste disposal, the high business and regulatory risks involved in designing and building nuclear power plants, and the lack of progress in developing long-term waste repositories. Retiring existing nuclear plants will exacerbate the challenge of reducing CO_2 emissions from the power system, because large increases in renewable and other zero-emitting energy sources will be needed simply to replace zero-emitting nuclear energy. To support continued nuclear capacity, working in combination with renewables, research is needed on advanced nuclear technologies for next generation reactors designed to significantly improve performance and safety.[119]

Moving to electrically powered transportation with increased renewable energy generation would substantially reduce fossil fuel use, because more than 90 percent of the transportation fuels are petroleum based.[120] Electric vehicle technology has advanced substantially in the past 5 years, with roughly 2 million all-electric and plug-in hybrid vehicles on the road worldwide today,[121] and automobile companies are increasing investments in electric vehicle production. For example, Volvo announced a plan to transition all of the company's car models to electric or hybrids by 2030, Ford has announced an $11 billion investment in electric vehicles, and GM plans to release 20 new models of electric vehicles by 2023.[122] Several countries, including Britain, France, and Norway, cities such as Beijing, and several U.S. states have proposed banning gasoline- and diesel-powered cars as early as 2030.[123] Achieving the transition to electric-based transportation systems raises many engineering challenges beyond the need for low-carbon energy sources, including the need for charging infrastructure, better battery performance, and faster recharge times.

Making progress toward reducing emissions will depend in large part on private-sector investments and on the behavioral and consumer choices of individual households, which are explored in more detail in Challenge 5. Governments at federal, state, and local levels can influence those choices through policies and incentives. Such policies can include setting a price on emissions, such as a carbon tax or cap-and-trade system; providing information and education on voluntary emission reductions; and mandates or regulations designed to control emissions, for example, the Clean Air Act, automobile fuel economy standards, appliance efficiency standards, building codes, and requirements for renewable or low-carbon energy sources in electricity generation.

Advancing Climate Intervention Strategies

Even if human-caused carbon dioxide emissions were to cease today, it would take millennia for natural processes to return Earth's atmosphere to preindustrial carbon dioxide concentrations.[124] To avoid the worst impacts of warming, it is no longer enough to reduce emissions. Deploying negative-emission technologies that remove carbon dioxide from the atmosphere and reliably sequester it will also be needed.[125]

Some carbon dioxide removal strategies focus on accelerating natural processes that take up carbon dioxide. Changes in agricultural practices can enhance soil carbon storage, for example, by planting fields year-round in crops or other cover crops.[126] Land use and management practices can be employed that increase the amount of carbon stored in terrestrial environments, such as forests and grasslands and in near-shore ecosystems, such as mangroves, tidal marshes, and seagrass beds.[127] One recent study estimates that nature-based approaches can deliver more than one-third of the carbon reductions needed by 2030 to stay within the 3.6°F

(2°C) limit at competitive costs,[128] but there are many unknowns. Further research is needed to determine what conditions and practices can maximize carbon uptake in plants over the long term. There can also be unintended effects. For example, planting more trees in northern boreal forests can contribute to warming, because in winter months the trees can obscure snow that reflects sunlight.

Other technologies being explored seek to actively remove CO_2 from the atmosphere and from point sources and sequester it. One technology involves growing plants such as switchgrass to be converted to fuel, coupled with capturing and storing any CO_2 emissions from biofuel burning (called bioenergy with carbon capture and sequestration, or BECCS). Another approach proposes using chemical processes to capture CO_2 directly from the air and concentrate it for storage (called direct air capture and sequestration, or DACS). These technologies will be needed around the world because many countries will still be using significant amounts of fossil-fuel-generated electricity by 2050. They will also be needed to mitigate emissions where electrification is not possible and for industrial processes that produce carbon dioxide.

Engineering challenges in carbon removal strategies include the need to reduce costs, increase the scale of the technologies, and store or reuse the carbon in ways that keep it from being released back into the atmosphere. Available land is a key limiting factor for the potential of removing CO_2 through reforestation or growing fuel crops; removing 10 gigatons CO_2 per year (about one quarter of global yearly emissions) by 2050 would require the use of hundreds of millions of hectares of arable land.[129] Land use at that scale could threaten food security, given that food demands are expected to increase by 25 to 70 percent over the same time period.[130] Breakthroughs in agriculture discussed in Challenge 1, including advances in crop productivity, alternative methods of growing food, food waste reduction, and changes in diet, will be needed.

A different set of climate intervention strategies seeks to reduce warming by reflecting sunlight off of specially treated clouds and aerosols. In general, such technologies are not as developed as carbon dioxide removal strategies and carry greater risks of unintended consequences that are not well understood.[131]

Reducing Other Greenhouse Gases

Methane, nitrous oxide, and some industrial gases (e.g., hydrofluorocarbons) comprise about 18 percent of U.S. greenhouse gas emissions in terms of CO_2 equivalents.[132] Molecule for molecule, those gases are much stronger climate warming agents than CO_2, although they are less abundant, and some do not last as long in the atmosphere. Methane, for example, is about 28 times more potent as a greenhouse gas compared to CO_2, making it particularly important to prevent or capture methane leaks from oil and gas systems, coal mines, shale gas extraction, and landfills.[133] To that end, there is a need for better systems and methodologies to measure and track methane leakage throughout those systems.[134]

Agriculture is one of the largest sources of non-CO_2 greenhouse gases. Methane is produced when livestock digest their food and also is emitted in large quantities

from rice paddies. Nitrous oxide arises from the use of nitrogen fertilizers. Precision agriculture techniques can help farmers minimize fertilizer use and reduce nitrous oxide emissions (see also Challenge 1). Feeding livestock easier-to-digest foods and strategically managing livestock waste—through proper storage, reuse as fertilizer, and recovery of methane—also can help reduce emissions.[135] Efforts to curb agricultural methane emissions can benefit from new insights and biotechnology tools that offer new ways to study the complex microbial ecosystems involved in soils, manure management, and livestock digestion.

Some short-lived pollutants that are not greenhouse gases also contribute to warming. One example is black carbon, commonly called soot, which absorbs sunlight and traps heat in the atmosphere. Black carbon is produced by incomplete fuel combustion and burning of biomass (e.g., the dung used in cookstoves). Black carbon also can amplify regional warming by leaving a heat-absorbing black coating on otherwise reflective surfaces, such as snow in mountainous regions. Although North America and western Europe were the major sources of soot emissions until about the 1950s, low-income nations in the tropics and East Asia are the major source regions today. Identifying and targeting the largest sources of black carbon could be crucial to curbing warming in the short term.

What Can Environmental Engineers Do to Curb Climate Change?

Environmental engineers have an opportunity to be leaders in developing technologies that will help slow warming through alternative energy development, green infrastructure, carbon capture and sequestration, and monitoring and measurement, as summarized in Box 2-1. Although the challenge to curb climate change will stretch environmental engineering beyond its traditional boundaries, many of the skills typical of environmental engineers can be applicable for advancing these goals. For example, the design of technologies to capture and store carbon underground, in soils, and in coastal ecosystems can take advantage of environmental engineers' expertise in water chemistry, environmental microbiology, groundwater and surface water hydrology, and atmospheric chemistry. Environmental engineers can also bring large-scale perspectives to illuminate how proposed technologies will interact with multiple systems. Specific applications of those skills might include

- Using the tools of geochemistry to engineer accelerated mineralization processes that would transform carbon into a stable carbonate, while avoiding water quality impacts.
- Using the emerging tools of synthetic biology and microbial ecology to abate greenhouse gas emissions and generate chemicals, materials, and fuels.
- Using the tools of life-cycle assessment to explore efficiencies for producing low-carbon liquid fuels from biomass feedstocks without increasing overall water use.
- Using the tools of life-cycle assessment to assess and optimize the energy return on investment (the ratio of the amount of usable energy delivered from a particular energy resource to the amount of energy used to obtain that energy resource).

BOX 2-1. EXAMPLE ROLES FOR ENVIRONMENTAL ENGINEERS TO HELP CURB CLIMATE CHANGE

Environmental engineers can play an important role in collaboration with other disciplines to address four areas related to slowing climate change.

Increasing Energy Efficiency

- Using life-cycle analysis, identify opportunities for improved energy efficiency across sectors to focus energy efficiency improvements toward those with the greatest benefits.
- Identify opportunities for the use of the heat that is a by-product of the generation of electricity. Currently much of this heat is "wasted" during cooling processes.

Advancing Alternative Energy Sources

- Identify opportunities for addressing environmental issues associated with promising renewable energy sources, including hydropower, solar, and wind.
- Develop low-cost reliable anaerobic carbon conversion systems to turn organic wastes, including human waste as well as agricultural plant and forest residues, into energy.
- Develop strategies to manage nuclear waste.

Advancing Climate Intervention Strategies

- Develop biological and mechanical carbon capture methods that can be scaled at reasonable cost.
- Develop uses for captured carbon and methods for safe storage, including monitoring for leakage.
- Improve understanding of the factors that influence the permanence of carbon capture by vegetation and soils.

Reducing Other Greenhouse Gases

- Develop monitoring tools to detect emissions of methane in natural gas systems and methods to minimize or eliminate them.
- Develop technologies and approaches to reduce greenhouse gas emissions from agriculture.
- Identify the largest sources of black carbon and develop low-cost strategies to reduce these emissions.

Adapting to Climate Change Impacts

Many of the things people use or do every day—from roads to farms, buildings to subways, jobs to recreational activities—were optimized for the climate of the 19th and 20th centuries. They were built with the assumption of certain temperature ranges, precipitation patterns, frequency of extreme events, and other manifestations of climate, which are now shifting. Even if humankind were to succeed in limiting global climate change in accordance with current goals, adaptation will be needed to protect people, ecosystems, infrastructure, and cultural resources from the impacts of climate change, many of which are already evident.

Sea level is one area in which those impacts are already being felt. Since 1900, global mean sea level has risen about 8 inches, driven by expansion of the warming ocean, melting of mountain glaciers, and losses from the Greenland and Antarctic ice sheets.[136] This rise has caused coastal cities to see an uptick in flooding, both during storms and as "sunny-day" flooding from tides alone. These flooding events disrupt economies, make it difficult to deliver emergency services, and disproportionately affect older, infirm, and low socioeconomic status populations.

Global sea level is expected to rise by an additional 0.5 to 1.2 feet by 2050 and 1 to 4.3 feet by 2100, which will increase the frequency and severity of flooding (see Figure 2-3). Even at the low end of that estimate, up to 200 million people could be affected worldwide and 4 million people could be permanently displaced as frequent or permanent flooding makes low-lying developed areas uninhabitable.[137] Some communities already are being forced to relocate as a result of sea-level rise, including Native American communities in Alaska, communities south of New Orleans in the Louisiana Delta and island communities in the Pacific and Indian oceans. In addition to flooding, sea-level rise causes erosion and saltwater encroachment, which kills forests near the coasts, reshapes marshes and wetlands, and renders aquifers along the coast unusable for human consumption without desalination technology.

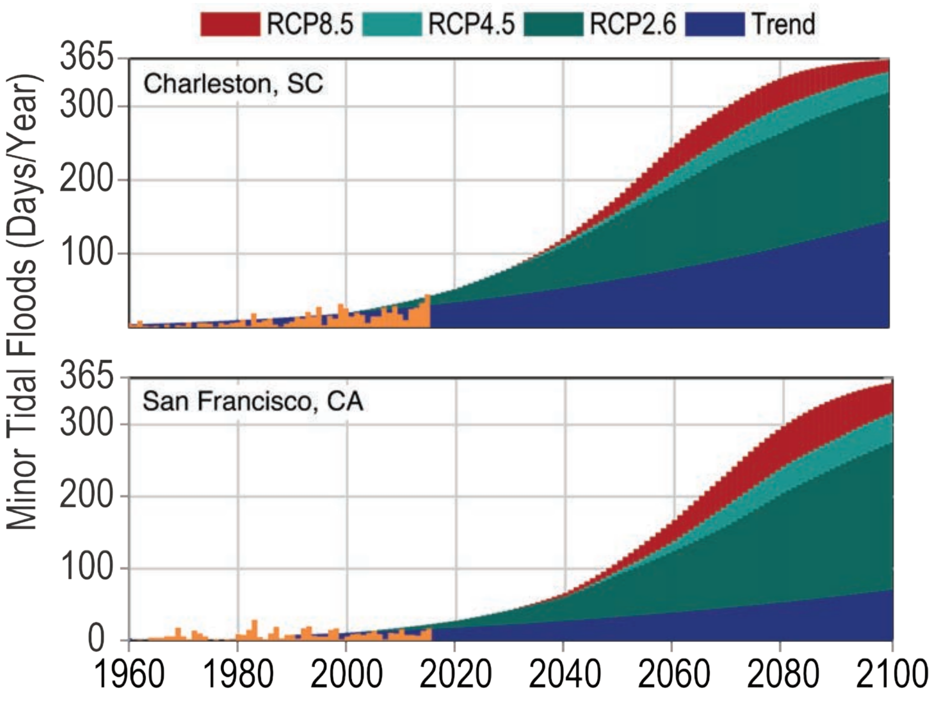

FIGURE 2-3. Annual occurrences of tidal flooding, also called sunny-day or nuisance flooding. Recent documented events are shown in orange and future flooding projections based on three greenhouse gas emission scenarios known as representative concentration pathways (RCP) ranging from low (RCP2.6) to high (RCP8.5).

Climate change is also expected to intensify regional contrasts in precipitation that already exist: Dry areas are expected to get drier and wet areas to become even wetter. Changes in precipitation patterns have resulted in heavier rainfalls, reduced snow cover, and glacial extent, and doubled the amount of land area classified as "very dry."[138] Warmer temperatures tend to increase evaporation from oceans, lakes, plants, and soil, exacerbating the impacts in areas of reduced precipitation.

Extreme precipitation events are becoming more frequent, leading to increased flooding as well as spikes in the release of some pollutants during heavy storms.[139] In August 2016, for example, more than 2 feet of rain fell in central Louisiana over 10 days, an event the National Weather Service called a "one in a thousand year" event. Scientists predict that climate change will cause an increase in the number of the most severe hurricanes, leading to stronger storm surges and more intense rainfall events.[140] In 2017, Hurricane Harvey dumped a staggering 50 inches of rain on Houston, which is as much rain as typically falls there over an entire year. Work is ongoing to assess the future probability of similar rainfall events.

As Earth's climate warms, changing temperatures are expected to reduce agricultural productivity for some major crops and may exacerbate the impacts of agricultural pests and pathogens.[141] Extreme heat waves will become more frequent, causing additional wildfires and further degrading air quality. Urban residents, especially those without access to air conditioning, are vulnerable to heat waves, as heat island effects make building and pavement surfaces 7°F to 22°F (4°C to 12°C) warmer than the surrounding natural environment.[142]

These changes are expected to pose a number of serious risks to human societies, affecting freshwater management, ecosystems, biodiversity, agriculture, urban infrastructure, and human health. To manage the risks and lessen the impacts, there is an urgent need to develop and deploy adaptation measures. Appropriate adaptation measures will vary from location to location, and some climate change impacts will be beyond the scope of adaptation. In some places, incremental steps will be sufficient to manage risk over the next several decades. In other places, transformative changes, such as relocation, are likely to be required. Because there is a great deal of uncertainty regarding future changes, advances in tools that support robust decision making under deep uncertainty[143] and adaptive management—a model that maximizes flexibility as new knowledge becomes available—will be crucial.

Adaptation strategies range from technological and engineered solutions to social, economic, and institutional approaches. Social and cultural factors will affect which strategies are acceptable to local communities. The following examples highlight current strategies being developed and future areas of focus for adaptation. Other examples related to water scarcity are discussed in the context of Challenge 1.

Building Disaster Resilience

Communities need to increase their resilience to disasters, such as floods and wildfires, which are expected to become more frequent and more intense in the decades ahead. Flood impacts can be lowered by, for example, developing building standards based on future flood risks and curtailing development in high-risk areas. Improved local projections of flood risk based on changes in climate and land use are needed to inform such planning and decision making; advanced GIS technologies are offering flexible tools that engineers and communities can use toward this goal. In a departure from past strategies, which emphasized centralized flood control management with levees and dams that have severe impacts on river and floodplain ecosystems, communities are increasingly turning to natural systems to manage flood risks while enhancing habitat, water quality, and other environmental services.

Resilience is the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events.[146]

Wildfires play a natural role in preserving the health of forests and other ecosystems that are adapted to wildfire. However, growth of communities into the wildland-urban interface and also climate change, which has made fire seasons longer and droughts worse, has increased the costs and impacts of wildfires.[144] California suffered its worst fire season ever in 2017, which was followed by rainstorms that triggered devastating mudslides. Globally, billions of dollars are spent to remediate impacts on human health, property damage, loss of tourism, and the restoration of crucial ecosystem goods and services.[145]

A major need related to wildfire is the creation of improved models and measurements to predict wildfire spread and the transport of wildfire smoke emissions. Other efforts to increase resilience to wildfire include improved landscape design principles and adaptive management to protect assets through tree cultivation, prescribed burning, grazing, and education programs to reduce accidental ignitions.

Reducing Impacts on Ecological Systems and Services

For many aquatic and terrestrial species, climate change has altered habitat conditions, leading to changes in biodiversity and species abundance and distribution. Increasing ocean temperatures and nutrient inputs from rivers are expanding the number and size of areas with low-oxygen conditions ("dead zones"), impacting commercial fisheries. Declining Arctic sea ice is reducing the habitat and hunting ground for polar bears, threatening survival of the species. Some changes are happening too quickly to allow for adaptation. However, efforts to reduce other environmental stressors, such as pollution (see Challenge 3), could reduce the severity of climate impacts and prevent species extinctions. Other adaptation strategies include habitat restoration, assisted migration, active management of invasive species, and updated management strategies for fisheries.[147]

Adapting Agricultural Practices

Technological advances during the 20th century's green revolution dramatically improved agricultural yields, economic stability, and food security in many parts of the world.[148] However, climate change threatens to undercut some of these advances. Agricultural adaptations such as adjusting planting dates, seed or crop selection (for example, to develop more flood- and drought-tolerant crops), or altering irrigation practices have the potential to buffer the impacts of climate change.[149] In the long run, it may be necessary to shift the location of agricultural operations or even to shift human diets (see Challenge 1). Additional economic and institutional strategies will be necessary to maintain food security amid increased weather variability and climate extremes.[150]

Adapting Infrastructure for Sea-Level Rise

Widespread adaptations in infrastructure are needed to adjust to climate change. Adaptation strategies include ensuring that critical infrastructure and systems such as water supply, wastewater, and solid waste management systems, electricity-generating facilities, hospitals, and transportation systems are resilient to expected heat, storm, and flooding stressors. With projections of 1 to 4 feet of sea-level rise by the end of the century,[151] engineers are developing ways to hold back the sea where possible or to buy time until more transformative adaptation strategies, including managed retreat, are developed.

In the near term, the city of Miami, Florida, is spending $400 million to raise streets, build sea walls, and construct pumps to reduce frequent flooding.[152] Natural areas, such as coastal wetlands and mangroves, are being protected or restored to maintain natural buffers against storm surge (see Box 2-2). In the Netherlands, engineers have designed long-term strategies to protect heavily developed areas and accommodate increased flooding in less-developed regions. Innovations include smart dikes with embedded sensors that relay real-time status reports to decision makers and ecologically enhanced dikes to provide habitat for marine organisms.[153]

BOX 2-2. REBUILDING WETLANDS IN LOUISIANA

The wetlands of southern Louisiana, the largest in the United States, are disappearing at an alarming rate. More than 1,900 square miles have been lost since 1930 from natural and human causes. Levees and canals have diverted the flow of sediments from the Mississippi River that once sustained the wetlands, while sea-level rise and natural subsidence continue to affect the coastline. Coastal wetlands, including salt marshes and mangroves, provide habitat for local fisheries and are the first line of protection against hurricanes and storm surge. Without action, the state could lose an additional 2,250 square miles of land over the next 50 years. The 2017 Louisiana Coastal Master Plan,[154] approved unanimously by Louisiana's legislature, focuses on restoring the natural flow of sediments to the wetlands, as well as such projects as marsh creation, barrier island restoration, and oyster reef restoration. Wetland loss is problematic in many places, and environmental engineers can contribute to the design of green infrastructure that helps restore lost ecosystems services and retain habitats at risk from sea level rise.

To inform decision making, cities need comprehensive analyses to understand the adaptation options, their potential impacts, and the benefits and costs of local, regional, national, and private-sector infrastructure investments to manage future risks. It will be particularly important to develop economic and institutional strategies to support low-income and vulnerable communities as these adaptation measures are implemented.

Anticipating and Responding to Health Threats

Climate change has a broad range of implications for human health.[155] Changes in temperature are expected to increase heat-related illnesses and deaths (see Figure 2-4), while increases in ozone and wildfires are expected to worsen air pollution, with major effects on human health. Temperature changes may directly affect the transmission of vectorborne and zoonotic diseases carried by rodents and insects, such as ticks and mosquitoes, by increasing the frequency and shifting the geographic areas at risk. Changes in temperature and precipitation patterns may also affect the prevalence or distribution of foodborne, waterborne, and water-related diseases.[156] Temperature changes can also affect wildlife migration patterns, potentially leading to more human-wildlife contact and increasing the risk of infectious diseases that originate in animal populations and spread to humans.

The risk of infectious disease outbreaks also can rise in mass displacement events, such as natural disasters. In the aftermath of Hurricane Maria in 2017, Puerto Rico grappled with many health issues including an outbreak of leptospirosis a bacterial disease.[157] Outbreaks in such settings pose enormous challenges for policy makers and medical, public health, and environmental health personnel, and such events can also contribute to food and water insecurity and malnutrition and cause stress to those who are displaced from their homes.

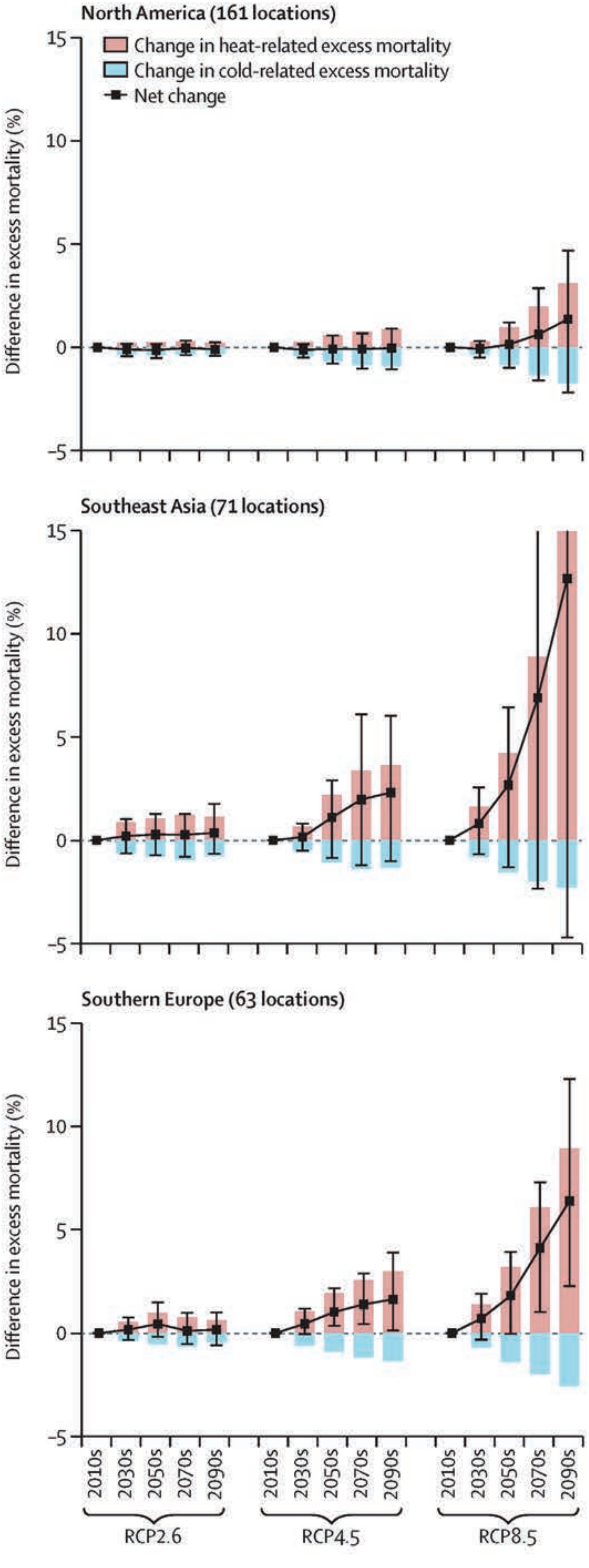

FIGURE 2-4. Projections of temperature-related excess mortality in cities in North America, Southeast Asia, and southern Europe under low-, medium-, and high-greenhouse gas emission scenarios, termed representative concentration pathways (RCP2.6, RCP4.5, and RCP8.5, respectively).

Adaptation strategies could include strengthening infectious disease surveillance systems, developing rapid point-of-care diagnostic tests, and improving rapid response capabilities for disasters and infectious disease outbreaks. Progress toward ensuring water and food security and reducing air and water pollution would also reduce the human health impacts from climate change. One strategy for adaptation in urban areas is to mitigate the urban heat island effect, with efforts needed to test and evaluate the potential for reflective surfaces, vegetation, and other features to reduce the temperature of cities.

What Environmental Engineers Can Do to Advance Climate Change Adaptation

Responding to climate change is about making choices amid substantial uncertainty. Decision strategies have been developed to support robust planning and decision making under deep uncertainty.[158] To support these decision processes, engineers and scientists can improve the understanding of potential long-term climate impacts and examine and communicate the effectiveness and consequences of adaptation strategies, considering a wide array of environmental, social, and economic factors (see also Challenge 5). Environmental engineers are trained with a broad, systems view, which enables them to become a vital bridge across disciplines and act as integrators of information. Using modeling and decision support tools, environmental engineers can work with diverse interdisciplinary teams to synthesize information, analyze adaptation alternatives, and weigh the costs, benefits, and risks. Environmental engineers have skills in uncertainty analysis and can support iterative risk management approaches to analyze climate adaptation strategies for effectiveness and lessons learned in the context of an evolving understanding of climate science. Examples of specific opportunities for environmental engineers to help address this challenge are highlighted in Box 2-3.

BOX 2-3. EXAMPLE AREAS IN WHICH ENVIRONMENTAL ENGINEERS CAN ADVANCE EFFORTS TO ADAPT TO CLIMATE CHANGE

Environmental engineers, working with civil engineers and experts in climate science and data, can play a number of roles in adapting to the expected impacts of climate change:

Building Disaster Resilience

- Develop a national wildfire smoke forecast system.
- Analyze changing coastal and inland flood risks under climate change and land-use change, including risks to priority infrastructure.

Adapting Urban and Coastal Infrastructure

- Analyze the benefits and costs of gray versus green infrastructure, including pollution control and ecosystem services.
- Identify cost-effective adaptation strategies for water and wastewater infrastructure at risk from sea-level rise.

Ecosystems

- Develop a better understanding of ecosystem services in mitigating the impact of climate change.
- Develop and evaluate approaches to reduce pollutant loading to ecosystems.
- Develop strategies to reduce and mitigate impacts of environmental degradation, deforestation, and ecosystem loss.

Agriculture

- Analyze large-scale costs and benefits of major changes to agriculture, including location and dietary changes.

Health

- Develop sensors capable of rapid pathogen detection in humans, animals, and the environment.
- Use green infrastructure, vegetation, and other methods to reduce urban heat island effects while improving water quality in vulnerable communities.
- Participate in formulation and implementation of innovative strategies to reduce the risk of transmission of vectorborne, zoonotic, foodborne, and waterborne diseases.