Fifth National Climate Assessment: Appendix 4

Indicators

Appendix 4. Indicators

Authors and Contributors

Federal Coordinating Lead Author

Michael Kolian, US Department of Energy

Chapter Lead Author

Laura E. Stevens, North Carolina State University

Authors

Derek Arndt, NOAA National Centers for Environmental Information

Jessica Blunden, NOAA National Centers for Environmental Information

Erik W. Johnson, USDA Forest Service, Office of Sustainability and Climate

Ann Y. Liu, National Institute of Environmental Health Sciences / Kelly Government Solutions

Sheri Spiegal, USDA Agricultural Research Service, Jornada Experimental Range

Technical Contributors

Rebecca L. Achey, University of Colorado

Seth Bogle, USDA Forest Service, Geospatial Technology and Applications Center

Boyin Huang, NOAA National Centers for Environmental Information

Willem Klajbor, University of Miami, Cooperative Institute for Marine and Atmospheric Studies

Jennifer Lecker, USDA Forest Service

AnnaClaire Marley, Eastern Research Group Inc.

Miranda H. Mockrin, USDA Forest Service, Northern Research Station

Matthew C. Reeves, USDA Forest Service

Jared Rennie, NOAA National Centers for Environmental Information

William L. Royer, USDA Forest Service

Hua Shi, US Geological Survey, Earth Resources Observation and Science Center / ASRC Federal Data Solutions

William Sweet, NOAA National Ocean Service

Russell S. Vose, NOAA National Centers for Environmental Information

Steven E. Yochum, USDA Forest Service, National Stream and Aquatic Ecology Center

Review Editor

Azar M. Abadi, University of Alabama at Birmingham

Cover Art

Meredith Nemirov

Recommended Citation

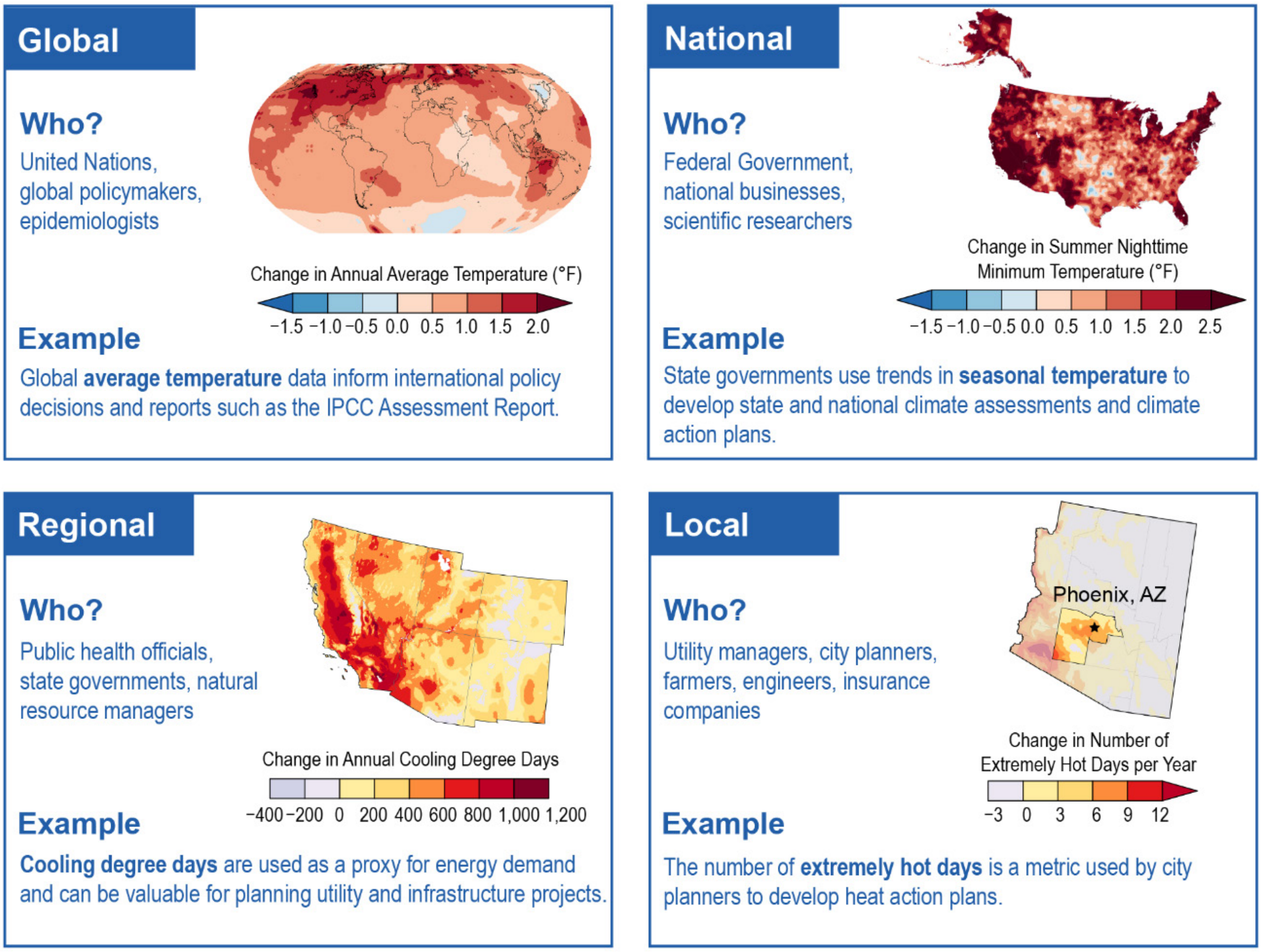
Stevens, L.E., M. Kolian, D. Arndt, J. Blunden, E.W. Johnson, A.Y. Liu, and S. Spiegal, 2023: Appendix 4. Indicators. In: *Fifth National Climate Assessment*. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.A4

Table of Contents

A4.1. The Importance of Indicators

To evaluate the impacts of climate change, it is essential to first understand the many ways in which our climate is changing. Indicators characterize how environmental conditions are changing over time to help communicate climate impacts, risks, and vulnerabilities. Indicators provide foundational science in support of the US Global Change Research Program's (USGCRP) sustained assessment process, including the National Climate Assessment (NCA). In the NCA, indicators are defined as data (presented as charts or maps) based on historical observations and measurements that are used to track conditions, trends, and impacts related to our changing climate. Indicators show changes in physical, ecological, or societal systems and can represent data at varying scales, from global to local (Figure A4.1). Indicators are of most value when maintained and updated on a regular basis so that users and stakeholders can make informed decisions based on the most up-to-date information. Taken individually, each indicator depicts a specific change over time, while a broad set of indicators helps to show interconnections among the many components of global change and a warming world (Box A4.1).[1] While each indicator has an important relationship to climate,[2] it is beyond the scope of this appendix to explore these connections in detail. Attribution and causation related to a changing climate are discussed in other chapters throughout NCA5 (e.g., Chs., 2, 3, 15).

Changes in Temperature at Multiple Scales



Presenting indicators at different scales allows stakeholders to obtain information relevant to their needs.

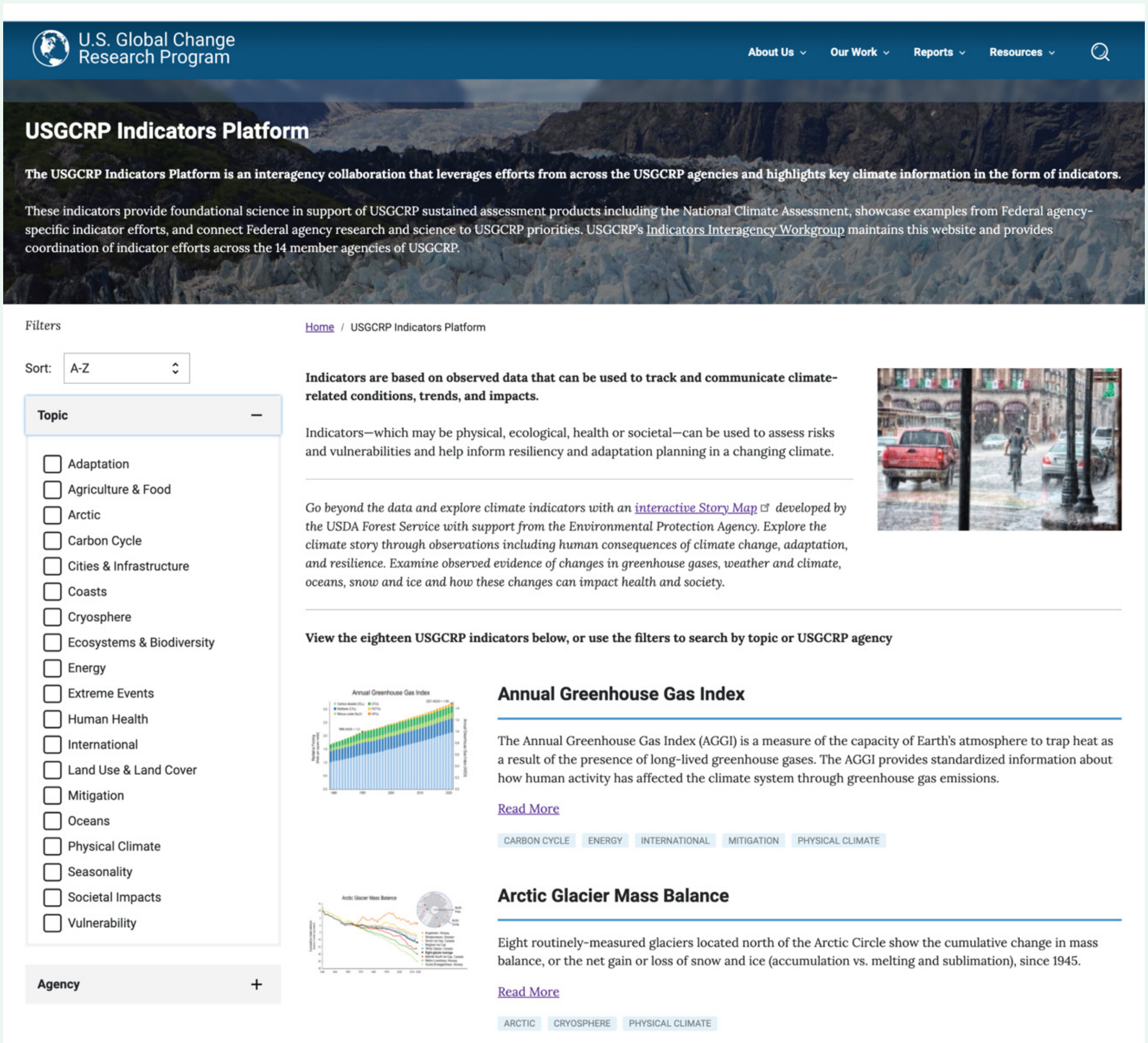
Figure A4.1. Many people use climate-related indicators for resource and management decisions, from small-scale farmers to global policymakers. Different indicators are relevant at different geographic scales, depending on who uses the information and for what purpose. In this figure, temperature indicators are shown at four scales, with each map depicting spatial patterns in the amount of observed change: (**top left**) global annual average temperature for the period 1993–2022, relative to 1901–1960; (**top right**) national (contiguous US and Alaska) summer nighttime minimum temperature for 1993–2022, relative to 1901–1960 (relative to 1926–1960 for Alaska; data are not available for the US Caribbean, Hawaiʻi, or the US-Affiliated Pacific Islands); (**bottom left**) regional (Southwest region) cooling degree days for 1993–2022, relative to 1951–1980; and (**bottom right**) local (Maricopa County, Arizona) number of days with maximum temperatures of 110°F or higher for 1993–2022, relative to 1951–1980. Data used for the regional and local indicators are available only from 1951 onwards. In general, increases in each metric have occurred since the start of their respective records, with important variations that are relevant to decision-makers at each scale (see Section A4.2 for additional explanation). Figure credit: North Carolina State University and NOAA NCEI.

Indicators are needed to support decision-making and describe and monitor impacts on people. Combined with other data, such as demographic and socioeconomic information (e.g., Figures A4.4, A4.14, 11.13), their utility is ever-growing, with many advancements being made in recent years (e.g., Di Napoli et al. 2022;[3] Kenney et al. 2020;[4] Walsh et al. 2020[5]). Indicators are being developed by USGCRP agencies (Box A4.1), their partners, academic institutions, and state, local, and Indigenous communities. The form, complexity, breadth, and design of indicators vary based on their intended uses, but effective indicators clearly convey information to advance understanding related to changes in key aspects of climate and the impacts on people and ecosystems. Measuring the health and societal effects of climate change is challenging because of the complex, often indirect relationships among climate drivers, environmental and social factors, and health outcomes.[6,7] Increasingly, physical, ecological, and socioeconomic data are being linked together to better track impacts on human systems, allowing communities to assess risks and make informed response and adaptation decisions. In the context of human health, identifying sets of indicators along exposure pathways can help track the related nature of exposures and the prevalence of health outcomes.[7,8] This holistic approach can provide insights into the extent to which changes in climate affect people and help identify opportunities for public health actions to reduce or prevent exposures and adverse health effects.

Box A4.1. Federal Indicator Resources

The US Global Change Research Program (USGCRP) coordinates efforts to highlight climate-relevant indicators from across federal agencies. The USGCRP Indicators Interagency Working Group guides this effort through advancing the research, development, and integration of indicators into USGCRP activities and products and highlights a subset of these on the USGCRP Indicators Platform (Figure A4.2).[9] Indicators hosted on the platform consist of peer-reviewed observational data and methods from federal entities and are routinely updated. They meet the standards set forth by the Information Quality Act regarding data quality, transparency, and traceability (App. 2).

USGCRP Indicators Platform



The USGCRP Indicators Platform leverages agency-supported science and data to understand how environmental, health, and societal conditions are changing.

Figure A4.2. Screenshot from the USGCRP Indicators Platform: https://www.globalchange.gov/indicators/. Figure credit: USGCRP 2023.[9]

Other federal climate-related indicators efforts include:

- CDC's National Environmental Public Health Tracking Climate Change Indicators[10]
- EPA's Climate Change Indicators in the United States[2]
- EPA's Climate Indicator Map Viewer[11]
- NASA's Vital Signs of the Planet[12]
- NOAA's National Marine Ecosystems Indicators[13]
- NOAA's State Climate Summaries[14]
- USDA's Climate Indicators for Agriculture[5]

Indicators appear in every NCA, with each report offering new ways to evaluate observed changes. This appendix marks the first time a section of the NCA has been established to present and discuss nationally relevant indicators. It highlights the important role of indicators and supports the NCA with scientific evidence, using a representative set of indicators relevant to multiple chapters. Observed changes relevant to each regional chapter can be represented with indicators, as shown in Table A4.1. Indicators in this appendix are grouped into six categories (Atmosphere; Ice, Snow and Water; Ocean and Coastal; Land and Ecosystems; Health; Adaptation and Mitigation), building on NCA4's Indicators of Change figure (Figure 1.2 in Jay et al. 2018[1]). Examples for each category were selected to cover a diverse range of regions, highlight both existing and newly developed indicators, and focus on topics relevant to urban and rural populations as well as the natural environment. These and many other indicators in NCA5 demonstrate that climate change is happening now (Table A4.1; KM 2.1; Figures 28.1, 30.5).

Table A4.1. Observed Regional Changes

This table shows observed changes pertinent to each NCA region, along with supporting evidence from associated NCA5 Key Messages and example indicators. The observed changes are only selected examples and do not necessarily convey which climate-related risks are most significant in each area. See the regional chapters for more detail on these observed changes and related climate impacts.

Region	Observed Change	Key Message	Example Indicator(s)
Northeast	Increasing frequency and intensity of precipitation	KM 21.2	Figure 2.8, Figure 21.1
	Increasing ocean temperatures	KM 21.2	Figure A4.11, Figure 21.4
	Rising sea levels	KM 21.2	Figure A4.10, Figure 2.5
Southeast	Increasing frequency, intensity, and duration of heatwaves	KM 22.2	
	Increasing wildfire risk	KM 22.2	Figure A4.14
	Rising sea levels	KM 21.4	Figure 2.5
US Caribbean	Increasing air temperatures	Ch. 23, Intro	Figure 1.5
	Increasing ocean temperatures	Ch. 23, Intro	Figure A4.11
	Increasing air pollution	KM 23.1	
Midwest	Increasingly variable precipitation	KM 24.1	Figure 2.4, Figure 2.8
	Lengthening growing season	KM 24.1	Figure 24.3
	Changing Great Lakes water quantity, quality, and temperature	KM 24.5	Figure 24.13
Northern Great Plains	Increasing winter temperatures	KM 25.1	Figure 2.4
	Increasing wildfire risk	KM 25.1	Figure A4.14
	Increasing frequency of spring flood events	KM 25.1	

Region	Observed Change	Key Message	Example Indicator(s)
Southern Great Plains	Increasing frequency and intensity of precipitation	Ch. 26, Intro	Figure 2.8, Figure 26.1
	Increasing ocean temperatures	KM 26.3	Figure A4.11
	Rising sea levels	KM 26.5	Figure 2.5
Northwest	Declining snowpack	Ch. 27, Intro	Figure A4.7
	Melting glaciers	Ch. 27, Intro	
	Rising sea levels	Ch. 27, Intro	Figure 2.5
Southwest	Declining flows in major rivers	KM 28.1	Figure 4.18, Figure 7.9
	Increasing wildfire risk	KM 28.5	Figure A4.14
	Increasing number of marine heatwaves	KM 28.2	Figure A4.11, Figure 28.4
Alaska	Thawing permafrost	Ch. 29, Intro	
	Increasing ocean temperatures	Ch. 29, Intro	Figure A4.11
	Declining sea ice	Ch. 29, Intro	Figure A4.6, Figure 2.3
Hawai‘i and the US-Affiliated Pacific Islands	Increasing drought frequency, severity, and duration	Ch. 30, Intro	
	Increasing tropical cyclone activity	KM 30.2	
	Rising sea levels	KM 30.3	Figure 2.5

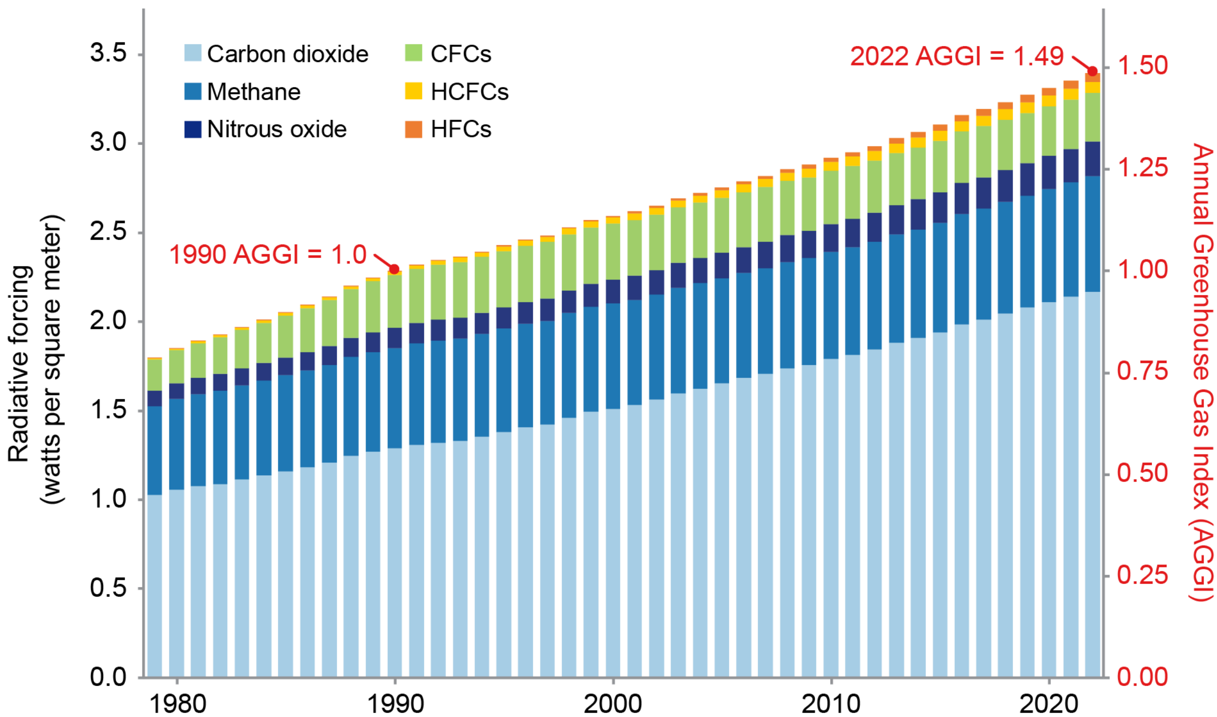
A4.2. Atmospheric Indicators

Both globally and across the US, temperatures are rising as a result of increasing greenhouse gases (GHGs) in our atmosphere (Figures 1.5, 2.4), primarily caused by human activities (Figures 2.1, 3.1; KMs 2.1, 3.1). Extreme events such as heatwaves, heavy downpours, and severe flooding are also increasing in frequency and intensity (KM 2.2; Figures 2.8, 21.1, A4.8). Atmospheric indicators are used to inform decision-making across a wide variety of scales (Figure A4.1) and often form the basis for assessing trends, impacts, and key risks[15] among all sectors.

Greenhouse Gases

Greenhouse gas emissions are the primary driver of climate change (KMs 2.1, 3.1), so tracking emissions is fundamental to understanding and responding to climate change. Figure 2.1 depicts the continual increase in carbon dioxide (CO_2) emissions by the greatest contributing countries and regions. The Annual Greenhouse Gas Index indicator (Figure A4.3) accounts for global emissions of CO_2 and the other major long-lived greenhouse gases from 1979 to 2022 and shows how the cumulative warming effects of these GHGs have been increasing over time.

Annual Greenhouse Gas Index



The warming effects of greenhouse gases are increasing over time.

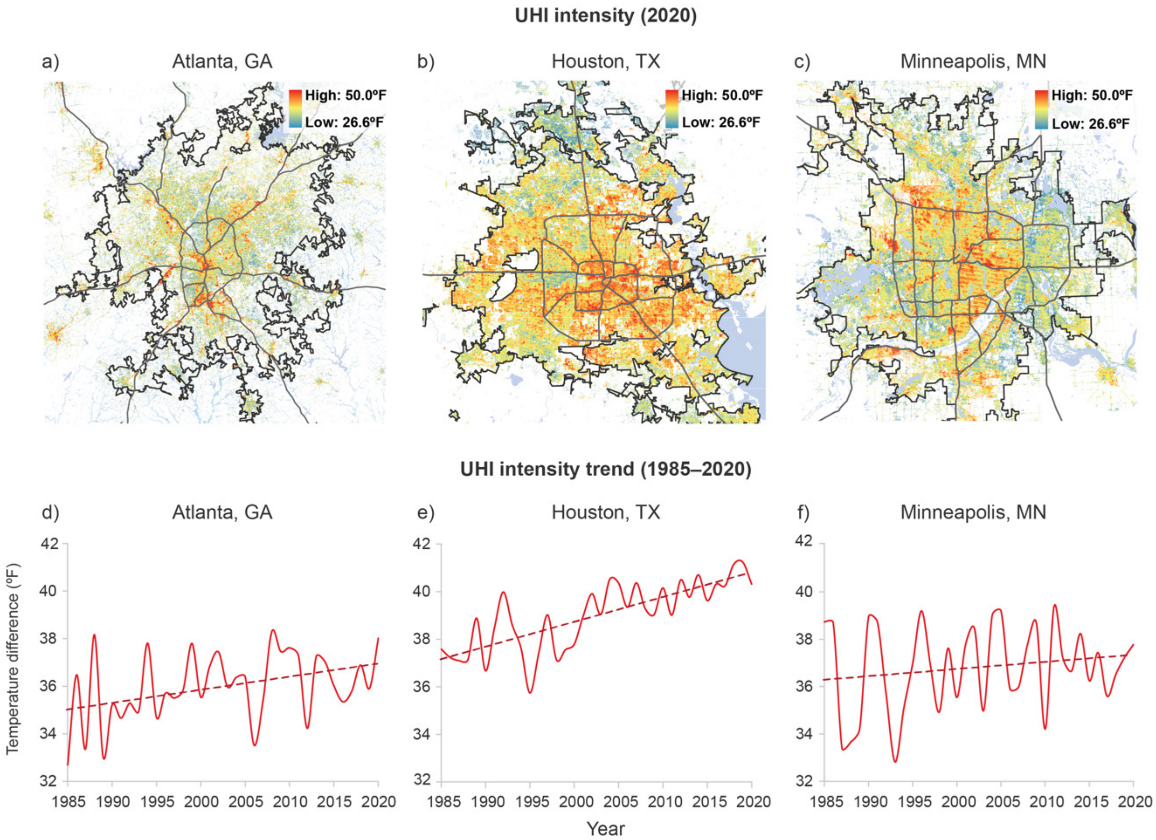
Figure A4.3. Radiative forcing (left vertical axis) is the change, either positive or negative, in the amount of energy from the sun that is trapped by Earth's atmosphere. Increases in the amount of radiative forcing will lead to warming. The Annual Greenhouse Gas Index (AGGI; right vertical axis) compares the total radiative forcing for each year from 1979 to 2022 to the year 1990 (represented by a red dot). The year 1990 was selected as the year for comparison because that is the year the Montreal Protocol[16] was signed, so its AGGI value is designated here as 1.0. The 2022 AGGI (also represented by a red dot) was 1.49, indicating that the average warming influence of long-lived greenhouse gases in the atmosphere has increased by a total of 49% since 1990. The increased radiative forcing leads to increasing temperatures, both in the oceans and over land. Indicators of these changes and impacts are found in this appendix and throughout the report. CFCs = chlorofluorocarbons, HFCs = hydrofluorocarbons, HCFCs = hydrochlorofluorocarbons. Adapted from USGCRP 2023.[17]

Temperature and Extreme Heat

Long-term observations show that warming due to climate change is unambiguous but is not occurring equally or in all areas (Figures A4.1, 2.4, 2.7). Figure A4.1 shows four different temperature indicators valuable to decision-makers at multiple scales. Globally, annual average temperatures have increased almost everywhere, with the greatest increases seen across North America and the Arctic (Figure A4.1, top left). On the national scale, nights have been warming faster than days (KM 2.2), with the greatest increases in summer nighttime minimum temperatures seen across large areas of Alaska, Florida, and the western and northeastern United States (Figure A4.1, top right). On the regional scale, cooling degree days (a proxy for energy demand used to cool buildings) have increased throughout the Southwest, with California experiencing the greatest changes (Figure A4.1, bottom left). And on a local level, the number of days per year with temperatures reaching 110°F or more have increased throughout Maricopa County, Arizona, with the Phoenix area experiencing notable increases in these extremely hot days (Figure A4.1, bottom right). Additionally, in the United States, the rate at which temperatures increase differs seasonally (Figure 2.4).[18] Changes in seasonal temperatures have led to shifts in the seasonality of certain events (Figure A4.13). In some areas, the combination of high humidity and high temperatures is contributing to the emergence of heat index values too severe for human tolerance (KM 2.3).[19,20] As temperatures increase, people's exposure to extreme heat becomes greater (KMs 3.12, 15.1).

These increasing temperatures directly and indirectly impact human health and societal outcomes (KM 2.2; Ch. 15). Populations directly exposed to more heatwaves experience increased heat-related illness and death.[21,22] Since the 1960s, the frequency of heatwaves and the duration of heatwave seasons have steadily increased in certain areas (KM 2.2).[23] Urban areas experience higher temperatures than surrounding landscapes because many structures such as roads and buildings absorb and radiate heat, exacerbating the effects of increasing temperatures (Figure A4.4; KM 12.1). Additionally, changes in land use in and around urban areas have contributed to temperature hotspots (Figure 6.3).

Urban Heat Island (UHI) Intensity



Urban heat island intensity is increasing in many US cities due to the combination of urbanization and rising temperatures.

Figure A4.4. Urban heat island (UHI) intensity is defined as the annual difference in average temperature between areas that are urban versus nonurban (within a 5 km, or approximately 3.1-mile, buffer zone of the city boundary). Indicators and maps of UHI intensity can help inform heat-mitigation strategies such as implementing urban vegetation cover.[24] Top row: Maps for the year 2020 are presented for (**a**) Atlanta, (**b**) Houston, and (**c**) Minneapolis, showing temperature differences used to determine UHI intensity for that year. Both hotspots and areas of lower temperatures are evident. Bottom row: Trends in average UHI intensity from 1985 to 2020 are presented for (**d**) Atlanta, (**e**) Houston, and (**f**) Minneapolis. Solid lines show observed data, while dashed lines represent the estimated trend for the period of record. Companion figures depicting the relationship between temperature and socioeconomic factors for these same cities can be seen in Figure 12.6. Figure credits: (a, c, d, f) adapted from Xian et al. 2022;[24] (b, e) USGS and NIEHS / Kelly Government Solutions.

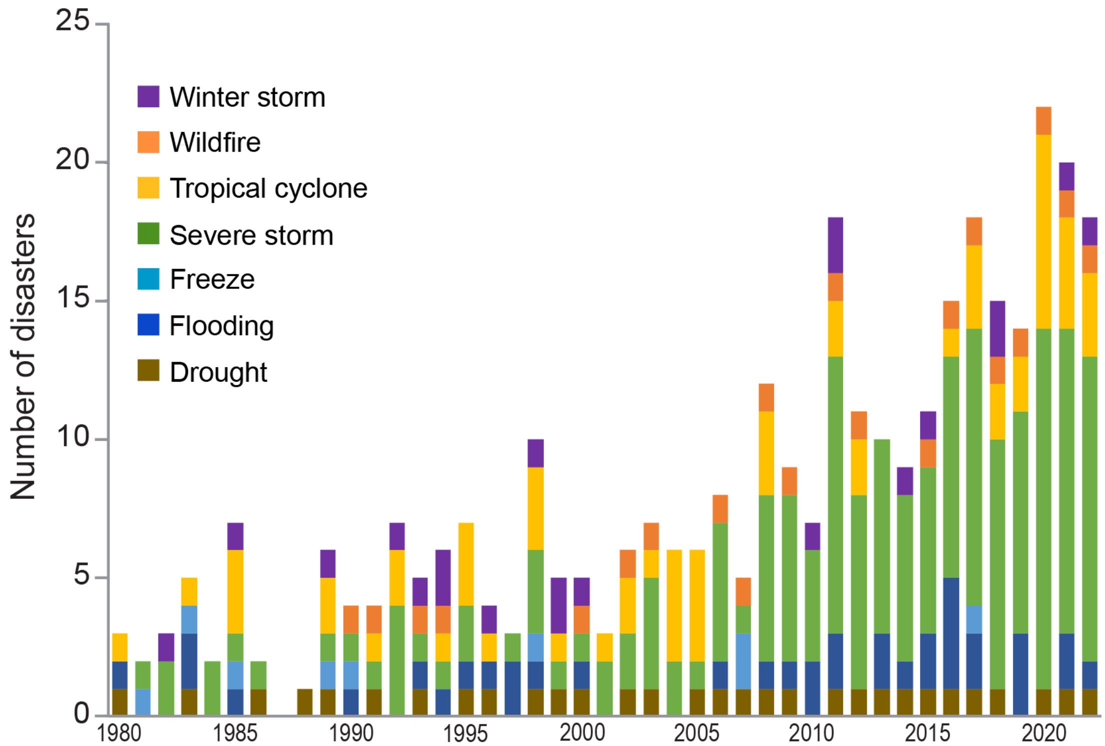
Precipitation

As temperatures rise, US precipitation patterns are changing, with long-term trends in average precipitation differing considerably by region and by season (Figure 2.4).[14] Indicators can show how changes in these patterns may affect different sectors. For example, too much or too little precipitation can impact both crop (KM 4.1) and hydropower (KM 5.1) production. Seasonal activities of sensitive plant and animal species may shift as precipitation amounts and timing change (Figure 8.11). Indicators can also be used to observe how heavy precipitation events are evolving in intensity (e.g., Figure 2.8), frequency (e.g., Kunkel et al. 2022[14]), and duration (e.g., Kunkel et al. 2020[25]). For example, evidence suggests that in recent years, extreme single-day precipitation events are increasing in the United States.[26] Heavy precipitation will become increasingly important to local engineering and community planning as the risk of flooding increases in a warmer world;[25] as a result, regional- and local-scale indicators are most valuable for informing adaptive actions to protect public health and safety.

Extreme Events

Climate change is increasing the frequency and severity of many extreme weather and climate events (Figure 1.7; KM 2.2), including heatwaves,[23] heavy precipitation (Figure 2.8; KMs 4.1, 21.1; KM 22.1), drought (Section A4.3), flooding (Section A4.3; KM 4.1), wildfire (Section A4.5; KM 7.1; Focus on Western Wildfires), and tropical cyclones (KM 2.2).[27] Other events, such as cold snaps, are becoming less frequent (KM 2.2). Extreme-event indicators allow communities to evaluate changes in risk, as major weather and climate disasters can threaten lives, damage property, and affect daily activities. One example is the number of disasters in the US each year that cause at least $1 billion in damages (Figures A4.5, 1.7, 2.6, 22.3). More frequent and compound extreme events (Focus on Compound Events) disproportionately impact already-overburdened groups (KM 18.2; Box 18.2), leaving communities with less time and fewer resources to respond to each disaster.

Billion-Dollar Disasters



The number of weather- and climate-related disasters exceeding $1 billion has substantially increased since 1980.

Figure A4.5. This indicator provides insight into the frequency of events exceeding $1 billion in damages (adjusted for inflation) from 1980 to 2022 across seven disaster types, each represented by its own color. The severe storm category includes events such as tornadoes, hail, and damaging winds but not tropical cyclones or winter storms. The only year with no billion-dollar events was 1987. Since then, the number of events each year has generally increased, with 2020 and 2021 having the two highest number of events on record. The number and cost of these disasters are due to several complex factors. Climate change is leading to increases in the frequency and intensity of extreme events, and, at the same time, there have been continual increases in the numbers of buildings, infrastructure, and people in climate-sensitive areas where these events may occur.[28] Economic factors can also play a role. For example, there is potential for property values to increase at rates higher than the Consumer Price Index, which can lead to higher damage assessments compared to previous years. An interactive version of this indicator, including the total annual cost and a breakdown by state and region, can be found at https://www.ncei.noaa.gov/access/billions/time-series/.[29] Adapted from USGCRP 2023.[30]

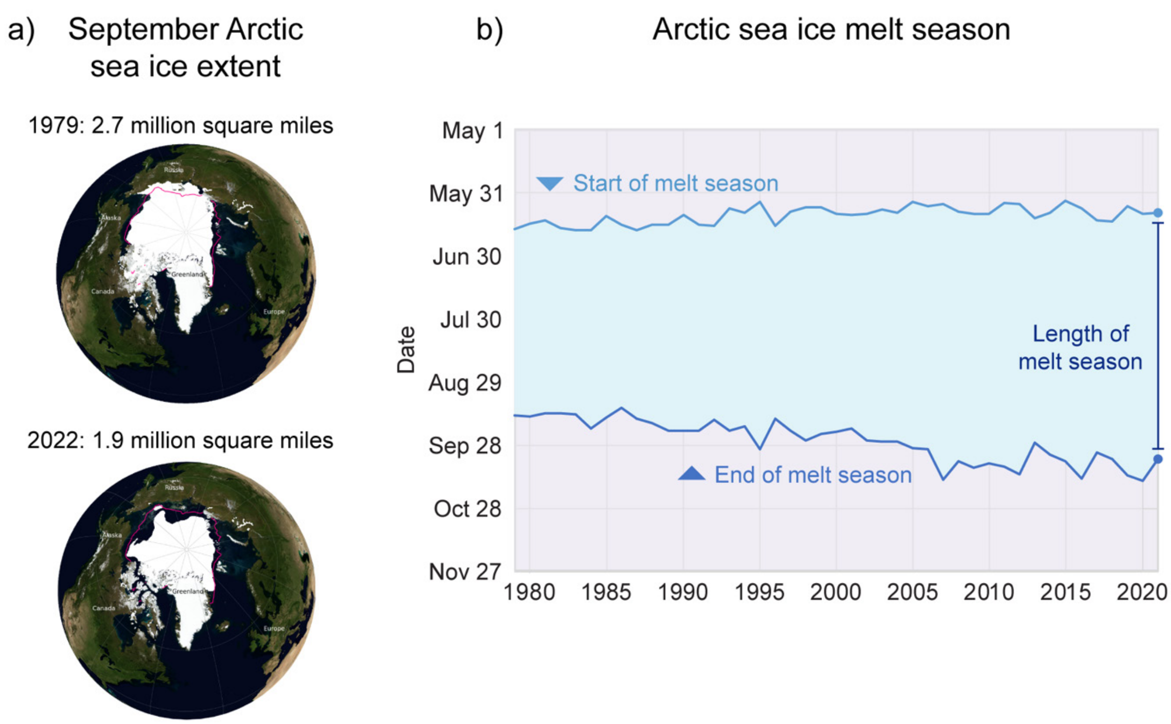
A4.3. Ice, Snow, and Water Indicators

Many parts of the US are experiencing intensified droughts or reduced snowpack, which are caused or exacerbated by rising temperatures (KMs 2.2, 4.1). These changes, combined with increasing water demand from growing populations, can reduce the reliability of water supplies,[31,32] and water-related indicators can help communities prepare for impacts. Also useful are indicators used to track changes in the cryosphere (the frozen parts of Earth's surface), as melting sea and land ice (e.g., ice sheets and glaciers) and thawing permafrost can contribute to sea level rise (KM 9.1; Figures 2.5, 9.1), affect water supply (KM 4.1), and have other negative impacts on humans and ecosystems (KM 8.2; Ch. 29).

Sea Ice

Changes in Arctic sea ice are some of the most visible and well-known indicators of a changing climate.[33,34,35] The steep decline of average Arctic sea ice extent in September, when the ice shrinks to its smallest area each year, is shown in Figure 2.3. Figure A4.6 illustrates how the total area of September sea ice has declined and how the overall length of the melt season is increasing over time. Melt location and timing is important, because as sea ice melts, it changes ocean and atmospheric circulation patterns, which can impact marine life and coastal economies (KM 10.1). Additionally, loss of sea ice is leading to increases in commercial shipping; exploration of oil, gas, and minerals; and geopolitical and global security issues (Ch. 17; KM 29.6).[36]

Changes in Arctic Sea Ice



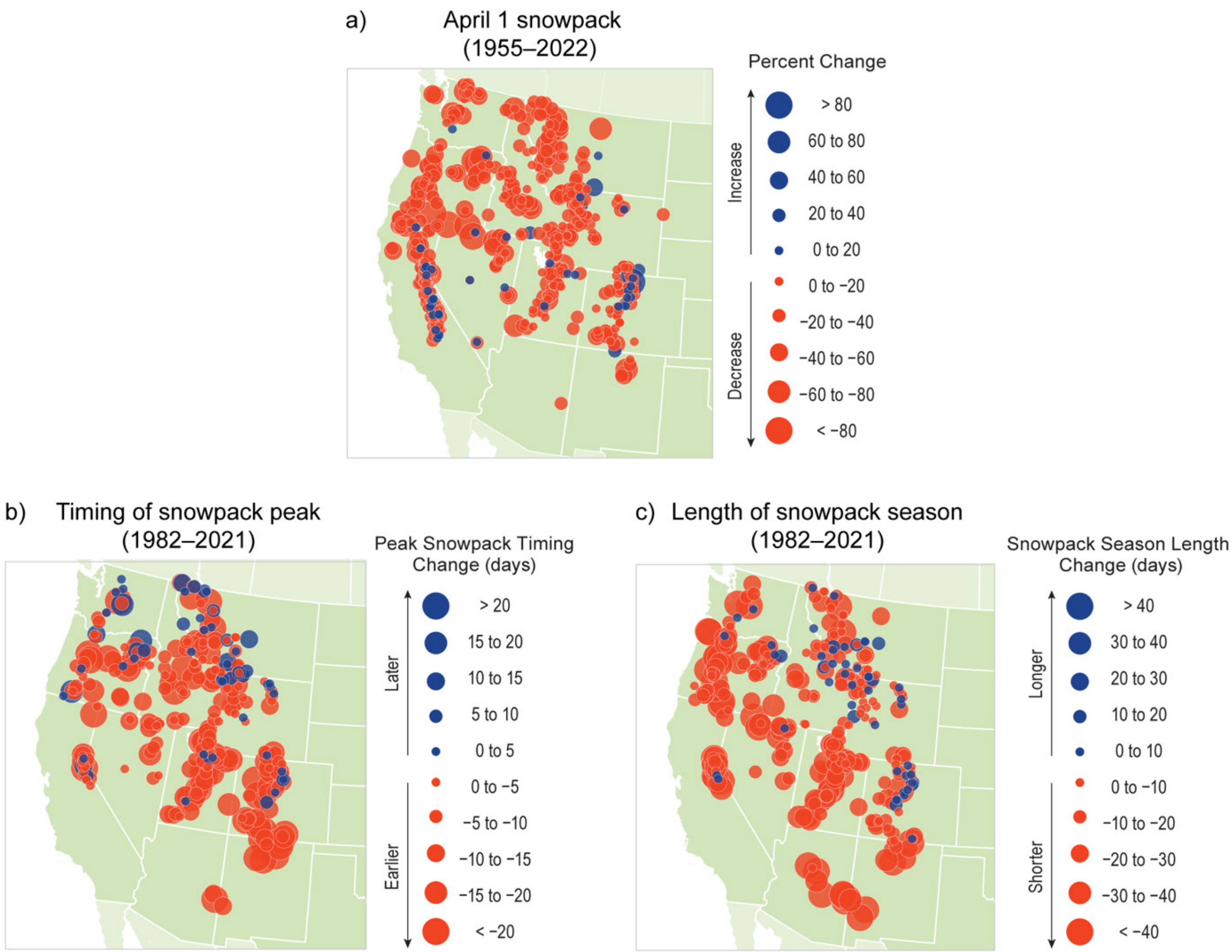
Arctic sea ice is shrinking as the melt season grows longer.

Figure A4.6. An increasingly later end to the melt season is the primary contributor to both the longer season and the declining ice extent. (**a**) This indicator compares the annual minimum sea ice extent—the smallest area of sea ice—measured in the Arctic in 1979 (the beginning of the record) and 2022 (the most recent year of observation). The pink line on each map represents the median ice edge for 1981 to 2010. (**b**) This indicator shows the annual length of the Arctic sea ice melt season from 1979 to 2021. The blue shaded area represents the amount of time between the date when ice begins to melt consistently (light blue line) and the date when it begins to refreeze (dark blue line). (a) Adapted from NSIDC 2023;[37] imagery from the Special Sensor Microwave Imager/Sounder (SSMIS) instrument, courtesy of NASA and NSIDC; (b) adapted from EPA 2023.[33]

Snowpack and Snow Cover

As US winters and springs warm, the amount and seasonality of snow is changing (KM 2.2). Higher temperatures cause snow to melt earlier, which affects timing and availability of water (KM 2.2).[38] A variety of indicators can be used to track changes in snowpack and snow cover (Figure A4.7). These indicators focus on the western US, where millions of people depend on the melting of mountain snowpack for drinking water, crop irrigation, and hydropower (Ch. 4; KM 28.1). Changes in snowpack and snow cover affect winter recreation, tourism, plants, and wildlife.[38]

Snowpack Changes in the West



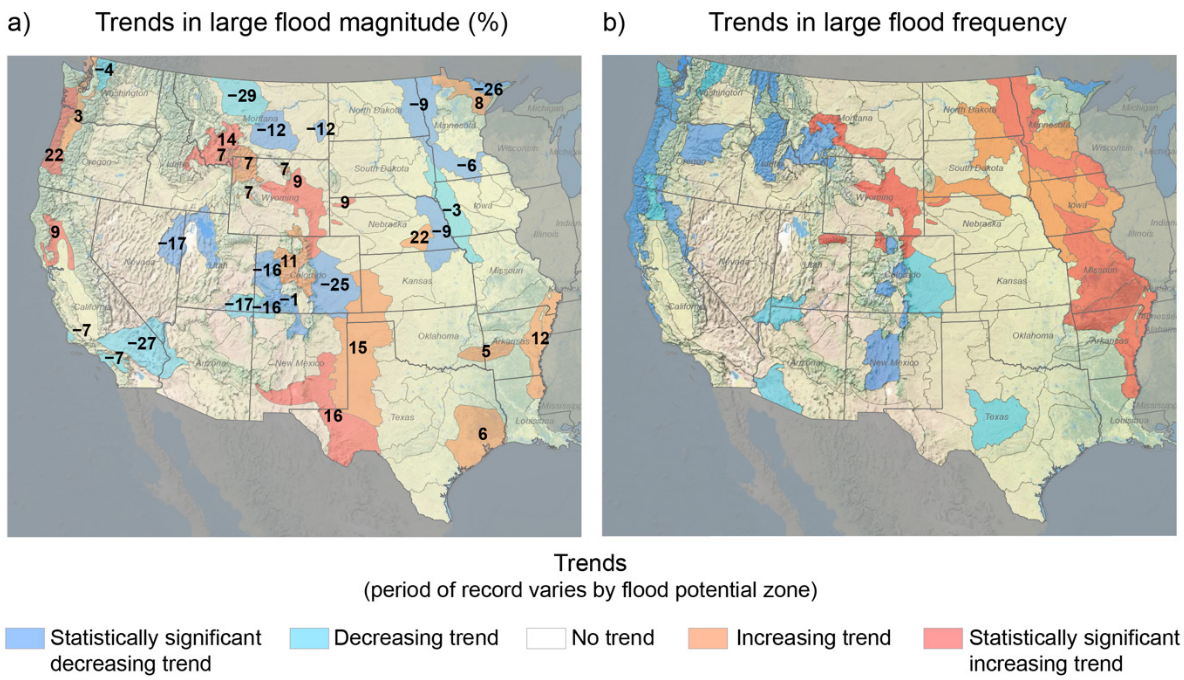
Western snowpack is declining, peak snowpack is occurring earlier, and the snowpack season is shortening in length.

Figure A4.7. The overall amount of snow has been declining across the western United States, as shown in three indicators: (**a**) trends in snowpack on April 1 (percent change) from 1955 to 2022 (red and blue circles represent a decrease and increase, respectively); (**b**) change in the annual date when snowpack reaches its maximum amount (days) from 1982 to 2021 (red and blue circles represent a shift to earlier and later timing, respectively); and (**c**) change in snowpack season length (days) from 1982 to 2021 (red and blue circles represent a shortening and lengthening of the snowpack season, respectively). Adapted from EPA 2023.[38]

Flooding

Indicators can be used to quantify trends in large floods, which is imperative for floodplain management and infrastructure design to maximize safety and resilience (KMs 4.2, 6.1, 12.4). For example, west of the Mississippi River, nearly 30% of monitored areas are experiencing increases in large flood frequency and/or magnitude (Figure A4.8). In contrast, other areas have recently experienced decreasing trends due to prevailing climate patterns such as the Southwest megadrought (KM 28.1).[39] Flood indicators are also used to track economic damage related to flooding (Figure 4.12) and monitor flood trends of individual streams.[40]

Flood Frequency and Magnitude West of the Mississippi River



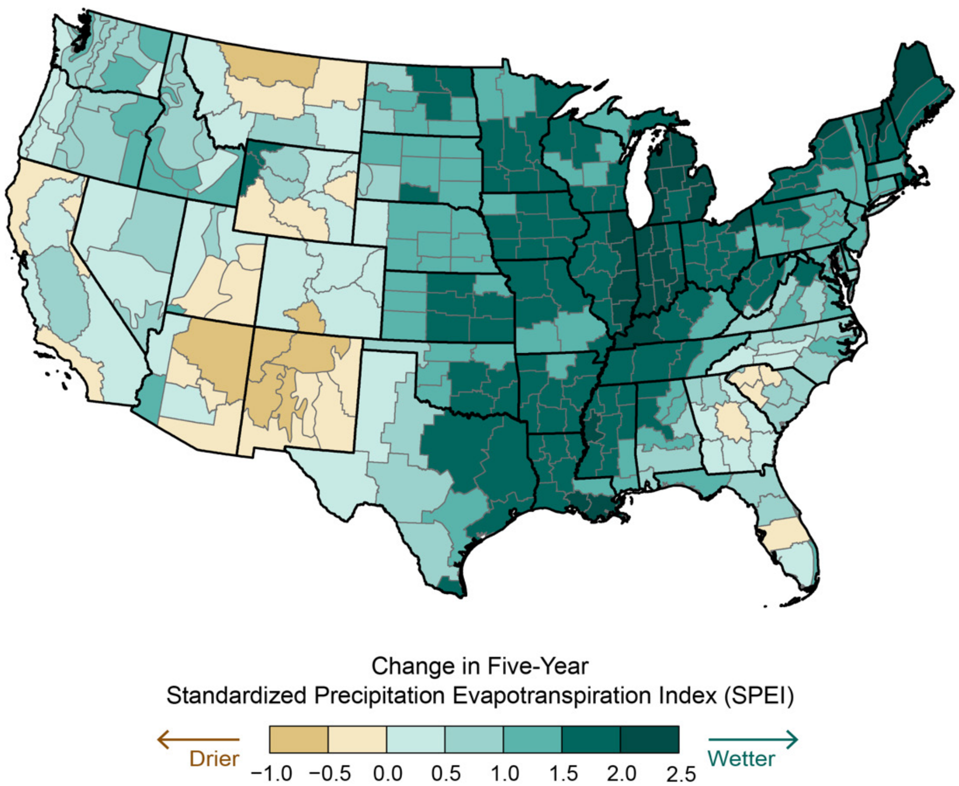
Trends in flood magnitude and frequency vary widely across the western US.

Figure A4.8. Flood magnitudes are increasing along the Oregon coastline, throughout large portions of the central Rockies and southern Great Plains, and in parts of the Gulf Coast, whereas flood frequencies are increasing across a large area east of the Rocky Mountain Front.[41] This indicator shows trends in (**a**) magnitude and (**b**) frequency of large floods in the western US within 117 flood potential zones. Shading in warm colors (reds) represents increasing trends, and shading in cool colors (blues) represents decreasing trends. Darker shades indicate where trends are statistically significant. (a) Percent change in annual flood magnitudes is indicated by black numbering. Trends in magnitudes vary by the available record length (most commonly from the early 1900s through 2020), while (b) trends in frequency are for 1945 to about 2020. Data are not yet available for the US Caribbean, Alaska, or Hawai'i and US-Affiliated Pacific Islands regions, as well as the contiguous US east of the Mississippi River. Additional information related to trends in large floods is provided in the Flood Potential Portal at https://floodpotential.erams.com/. Figure credit: USDA Forest Service.

Drought

The effects of drought can be far-reaching and long-lasting, posing risks to people and ecosystems and often contributing to other extreme events, such as drought-induced wildfire (KM 4.2; Focus on Western Wildfires). Several hydrologic measures exist for drought, and for certain applications, climate reanalyses can also be valuable in evaluating historical trends related to climate including drought metrics (e.g., Jasinski et al. 2019[42]). Some drought indicators consider water availability, measured by variables such as precipitation (Figure 4.10), streamflow, groundwater and reservoir levels, or soil moisture (Figure 28.2). Other drought indicators take into account different climatic factors, such as temperature, potential evapotranspiration, and solar radiation (Figure 3.12). For example, the Standardized Precipitation Evapotranspiration Index (SPEI; Figure A4.9) measures the combination of precipitation and evapotranspiration to determine whether a certain area is experiencing extreme drought, extreme moisture, or conditions in between.[43] SPEI is a valuable indicator when considering how droughts might affect activities that depend on a balance between water supply and demand, particularly those related to agriculture and ecosystems.[44]

Change in Drought Conditions, 1900–2022



Long-term records show conditions are becoming drier in many portions of the West and wetter elsewhere, particularly the East.

Figure A4.9. Since the early 20th century, the eastern US has generally experienced wetter conditions, while portions of the West—especially the Southwest—have experienced drier conditions. This map shows the total change in drought conditions across the contiguous United States, based on the long-term average rate of change in the five-year Standardized Precipitation Evapotranspiration Index (SPEI) from 1900 to 2022. Data are displayed for small regions called climate divisions, as defined by NOAA.[45] Teal-shaded areas represent wetter conditions, and brown areas represent drier conditions. Data are not available for the US Caribbean, Alaska, or Hawaiʻi and US-Affiliated Pacific Islands regions. Adapted from EPA 2023.[44]

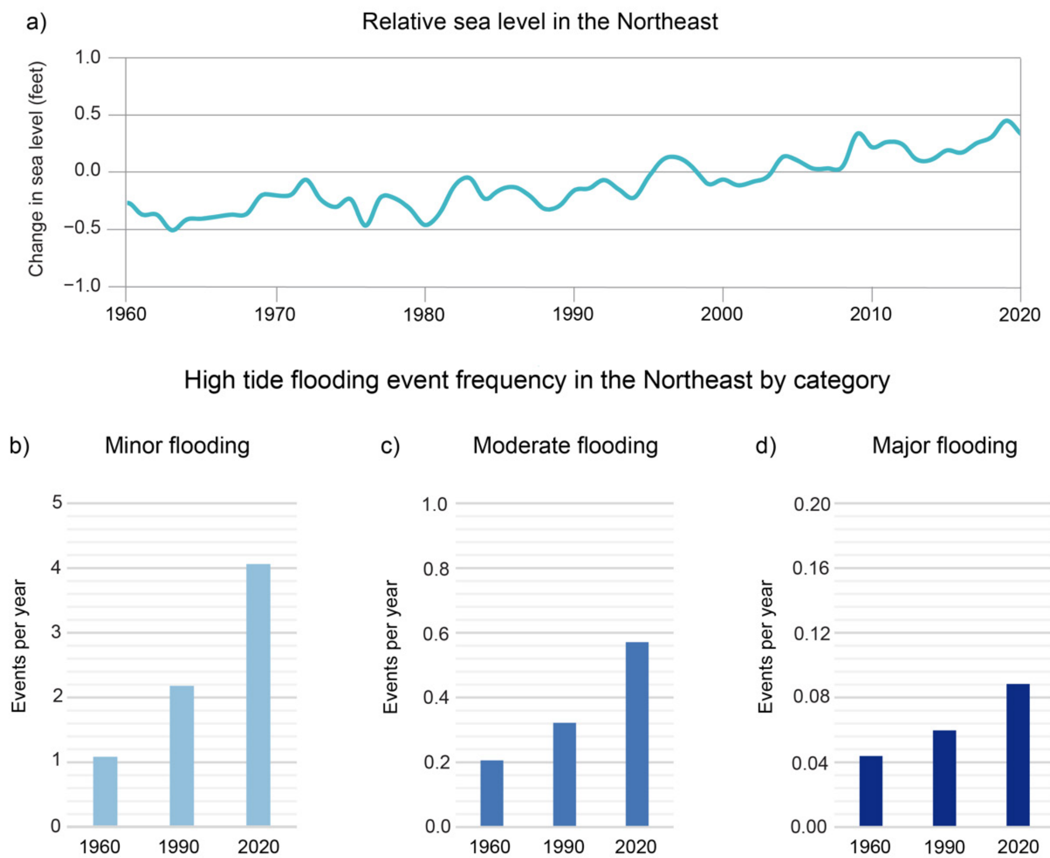
A4.4. Ocean and Coastal Indicators

Climate-driven changes to US oceans and coasts endanger marine ecosystems and coastal communities (Figures 10.1, 21.5) and threaten infrastructure and energy production (KMs 9.2, 10.1). Indicators can be used to track physical ocean conditions (e.g., sea surface temperatures, ocean acidification), ecological impacts (e.g., marine species shifts), and coastal impacts (e.g., high tide flooding). This information is used to evaluate risk, promote resilience, and increase the value of coastal and marine resources as ocean conditions change.

Sea Level Rise and Coastal Flooding

Global sea level is rising as warming ocean waters expand and glaciers and ice sheets melt. Along some US coastal areas, sea levels are rising faster than the global average, with the highest rates occurring along parts of the Atlantic coast and the Gulf of Mexico (Figures A4.10a, 2.5; KMs 21.2, 22.1, 26.1).[46] The increase in relative sea level is driving increases in physical and societal impacts such as high tide flooding (Figure A4.10b–d; KM 9.1).

Sea Level and Coastal Flooding in the Northeast



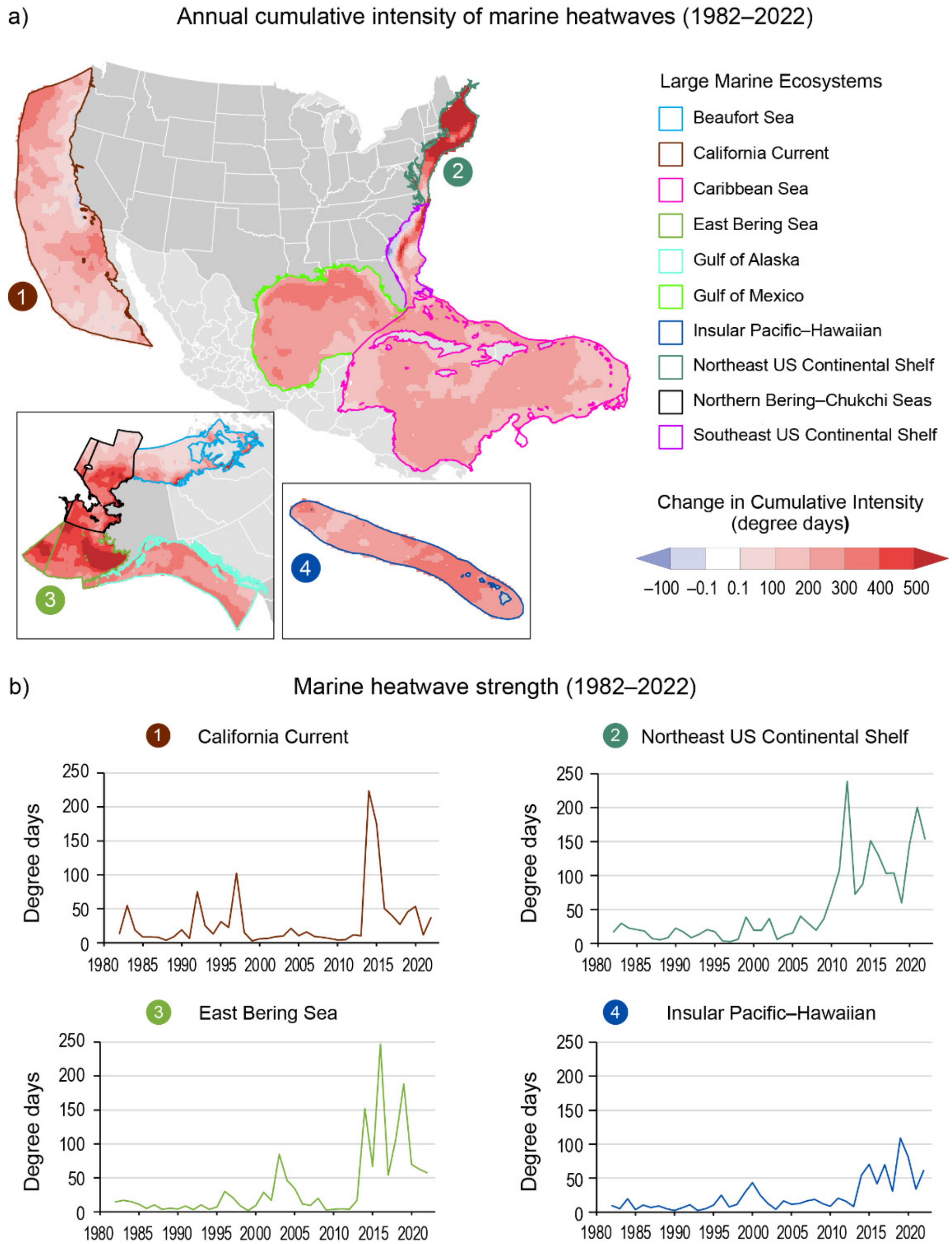
The combination of rising sea levels and the increased frequency of coastal flooding events exacerbates risk for coastal communities.

Figure A4.10. (**a**) The line chart shows the observed changes in relative sea level from 1960 to 2020 (compared to the 1991–2009 average), which is a combination of sea level changes and local uplift or subsidence of land, averaged along the Atlantic coast of the northeastern US. The bar graphs depict the frequency of (**b**) minor (disruptive), (**c**) moderate (damaging), and (**d**) major (destructive) high tide flooding events at 30-year intervals (1960, 1990, and 2020), also for the northeastern US (see Figure 9.3 for definitions of high tide flooding thresholds). The frequency of occurrence is expressed as the number of events per year, where a value of 0.1 is equivalent to a 10% annual chance of experiencing that type of flood event. See Chapter 9 for contiguous US data, including future projections. Figure credits: (a) adapted from Sweet et al. 2022;[47] (b, c, d) NOAA NCEI and NOAA.

Marine Heatwaves

Sea surface temperatures in oceans surrounding the US have risen steadily over time, as they have in most of the world's oceans (Figure 2.3).[48] Rising temperatures in these areas contribute to increases in marine heatwave frequency (KMs 10.1, 21.2), intensity (Figure A4.11), size, and duration.[49] These changes have detrimental impacts on surrounding ecosystems and economies, including shifts in the distributions of marine life (Figure A4.12; KMs 8.2, 10.1).

Marine Heatwaves



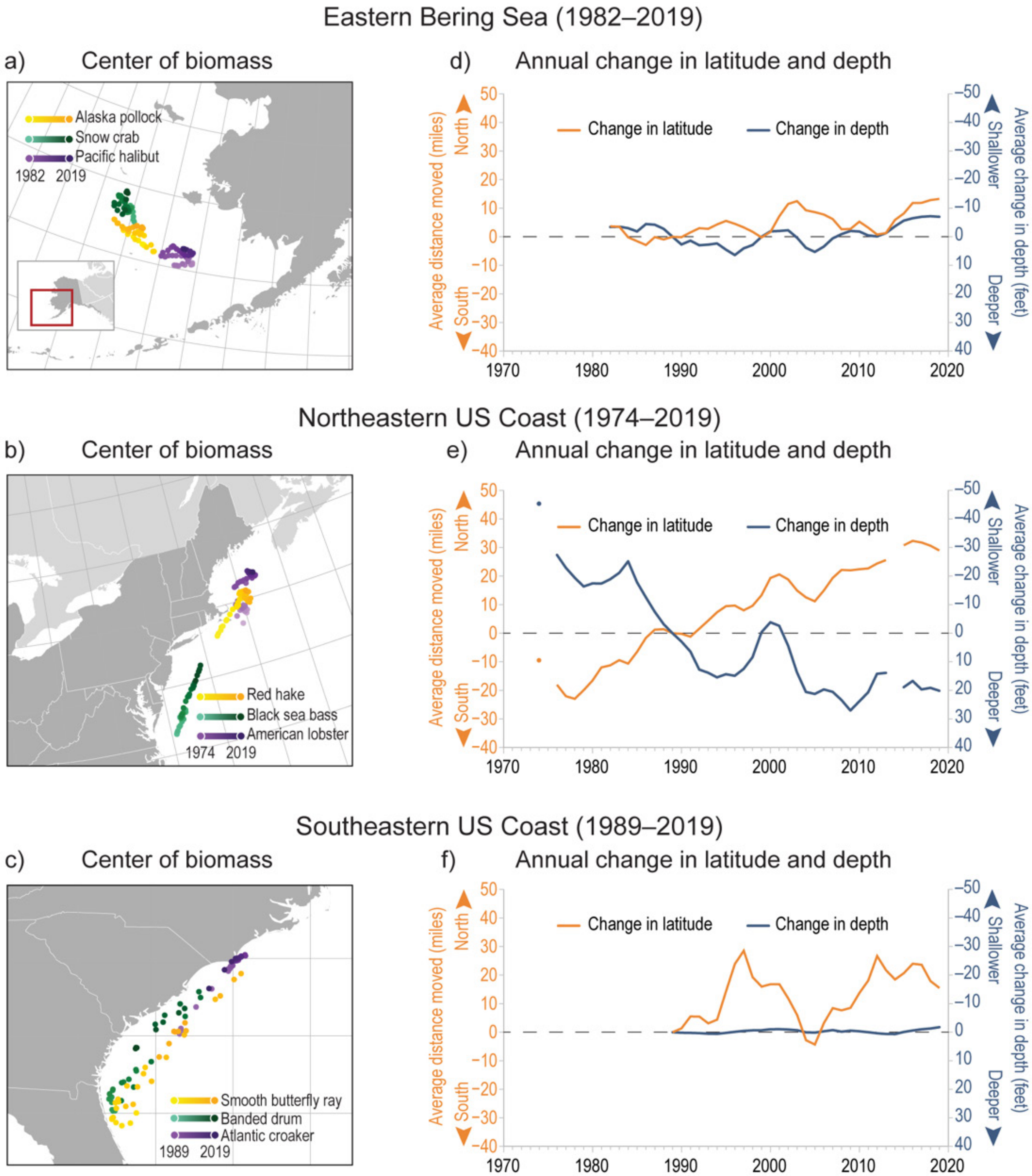
Extreme ocean temperatures are more common as ocean temperatures rise.

Figure A4.11. (**a**) The maps show the change in annual cumulative intensity of marine heatwaves (anomalously warm temperatures lasting five or more days) within large marine ecosystems surrounding the United States from 1982 to 2022. Cumulative intensity, or degree days, is determined by heatwave intensity multiplied by duration, compared to the 1982–2011 average. Areas with increases in cumulative intensity are shown in red, with darker colors indicating greater change. Areas in blue represent a decrease in cumulative intensity over time. (**b**) Charts show the heatwave strength in total degree days each year from 1982 to 2022 for select large marine ecosystems highlighted in the above maps. Figure credit: NOAA NCEI, University of Miami, DOE, and Eastern Research Group Inc.

Marine Species

Warming oceans have contributed to shifts in the geographic distribution of marine species (KM 10.1), which are extensively studied and tracked using indicators.[50] It is important to track climate-driven changes in the distribution, timing, and productivity of fishery-related species that can put marine fisheries and fishing communities at risk.[51] Many marine species are sensitive to environmental cues such as temperature ranges and track well with local climate velocities (the speed and direction at which species move in order to experience similar climate conditions).[52] However, several other factors can influence the abundance and geographic distribution of species, such as large-scale fishing practices, ocean currents, changes in habitats, and species' ability to adapt. Figure A4.12 depicts how multiple species adjacent to the Alaska, northeastern US, and southeastern US coasts have been shifting northward and, in some regions deeper, to cooler waters.

Marine Species Distribution



Marine species along US coasts are generally shifting northward to cooler waters.

Figure A4.12. (**left**) Maps show annual centers of biomass for three species in three regions: (**a**) the eastern Bering Sea (1982–2019) and the (**b**) northeastern (1974–2019) and (**c**) southeastern (1989–2019) US coasts. Species were chosen because they represent a variety of habitats and species types and are relatively abundant. Dots are shaded to show how species' locations have changed over time, with light shading representing earlier years and darker shading representing more recent years. (**right**) Charts show the annual change in latitude (orange lines; movement in miles) and depth (blue lines; change in feet) of several marine species in (**d**) the eastern Bering Sea (top; 64 species) and (**e**) the northeastern (middle; 53 species) and (**f**) southeastern (bottom; 63 species) US coasts, relative to 1989. Black dashed lines represent no overall change. Data were not available for 1975 or 2014 for the Northeast region. Adapted from EPA 2023.[50]

A4.5. Land and Ecosystems Indicators

Earth's land, food, and climate systems are inextricably intertwined (Figure 11.9). Climate and weather shape demand for and distribution of food, fish, and forest products. In turn, commodity production influences the climate via greenhouse gas exchange and land conservation or degradation. These feedbacks are driving the coupled climate–land system toward a host of outcomes for people and society, some undesirable.[53] Indicators can help land managers and policymakers identify optimal planning and solutions in the context of changing conditions.

Seasonal Change

Seasonality refers to recurring seasonal events or processes, such as the blooming of wildflowers in spring.[54] The timing, duration, and variability of many seasonal events are changing in response to changing temperature and moisture patterns (Chs. 2, 8; Figure 24.3). Indicators of seasonal change (Figure A4.13) are valuable for understanding relationships between climate and ecosystems and subsequent risks to environmental and social systems.[55] Knowledge of these changes is often generated by local and Indigenous populations, who have deep connections to local ecosystems because of their cultural and subsistence practices (Ch. 16).

Changes in Seasonality

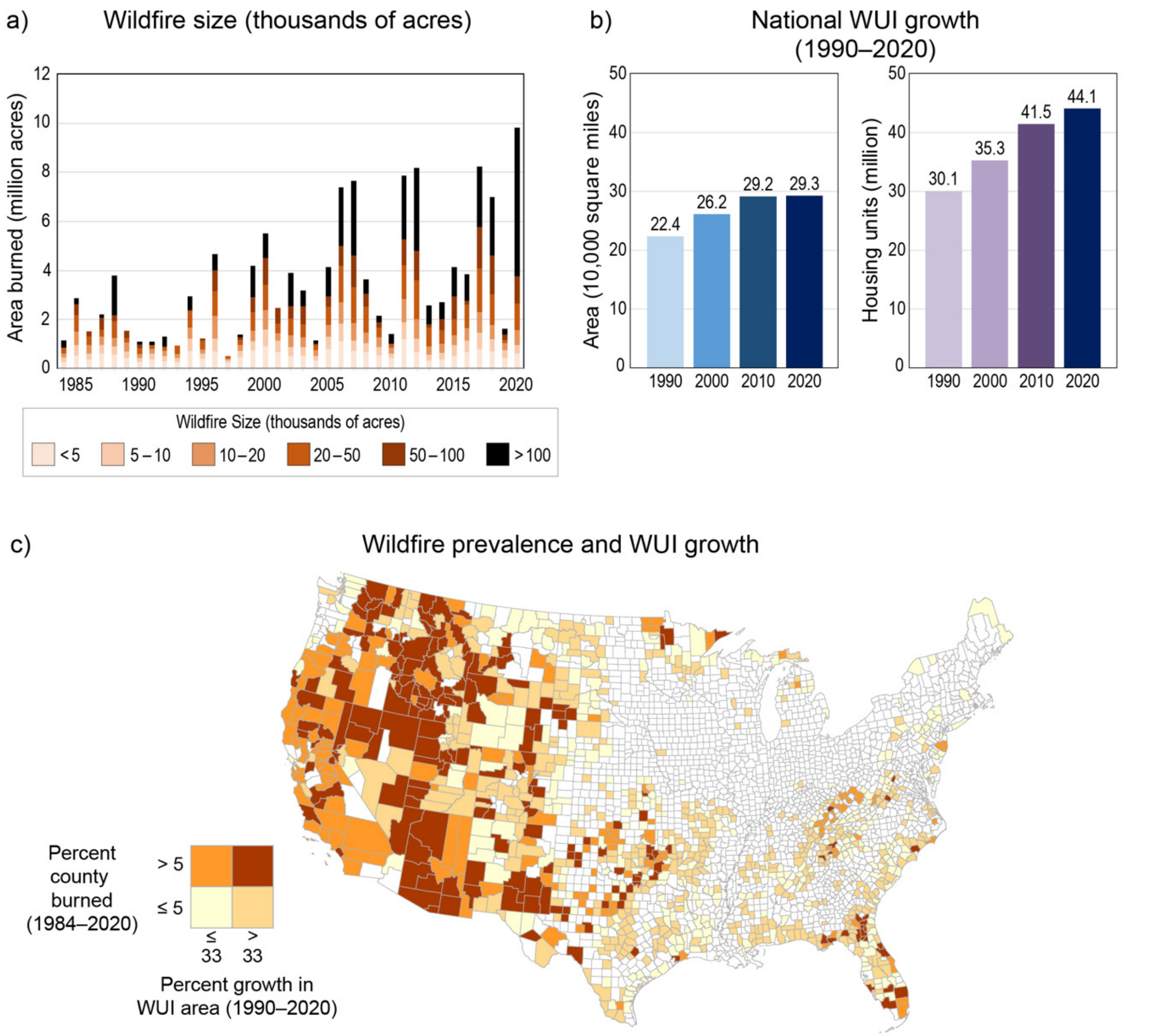
Observed evidence of changes in seasonality reflect a warming climate.

Figure A4.13. Many indicators show shifts in timing and duration of seasonal events or processes that are correlated with seasons. The length of the blue lines represents the approximate time of year when these events typically occur, and the direction of the arrows denotes earlier (⟵) and later (⟶) shifts in the season. Red line segments portray the observed change for illustrative purposes, whereas the actual observed values are provided as text above each line. Some of these indicators are limited to specific geographic regions. Adapted from EPA 2021.[54]

Wildland Fire and the Wildland–Urban Interface

Wildland fires affect carbon dynamics, ecosystems, biodiversity, and human health (Ch. 7; KMs 6.1, 14.2; Figures F2.1, 28.9). The wildland–urban interface (WUI) is the area where buildings and other developments meet or mix with undeveloped natural areas, including fire-prone vegetation. Over the past several decades, the WUI has grown rapidly,[56] expanding in both total area and number of homes. In addition, the annual average acreage burned by wildfires has increased since the mid-1980s.[57] Together, these changes have increased risks of loss of life and property damage in many areas across the United States (Figure A4.14). Other important wildfire-related indicators include greenhouse gas emissions resulting from wildfires and prescribed fires (Figure 7.2) and related socioeconomic indicators such as federal spending on wildfire suppression.[58]

Wildfires and Wildland–Urban Interface (WUI) Growth



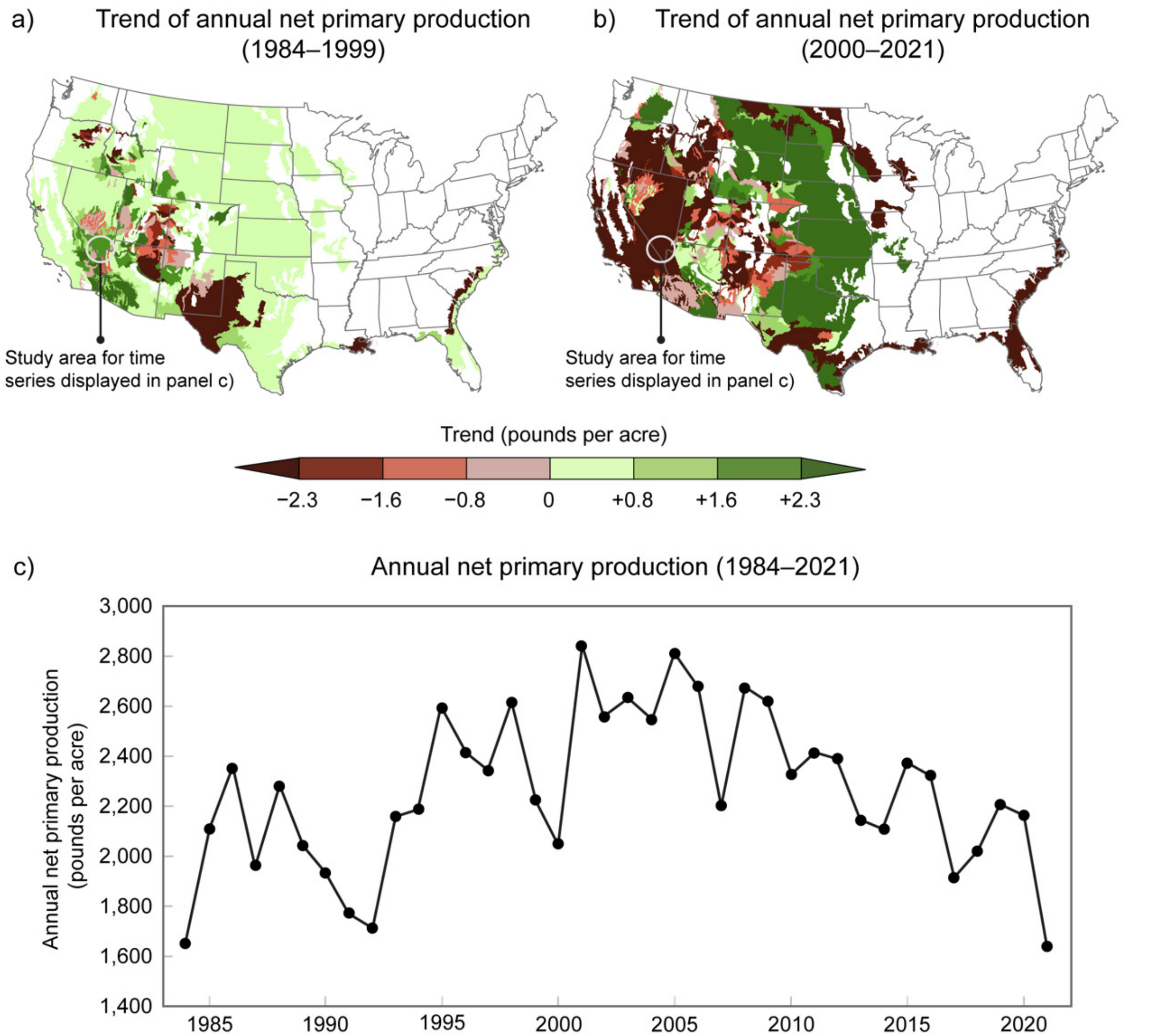
Area burned by wildfires is increasing and the wildland–urban interface is expanding in the contiguous US.

Figure A4.14. (**a**) The chart shows the number of acres burned between 1984 and 2020 for the contiguous US. The different shades within each bar indicate the proportional contribution of different fire size classes to the total for that year. (**b**) The two charts depict wildland–urban interface (WUI) growth in terms of area and number of housing units from 1990 to 2020 for the contiguous US. (**c**) The map portrays US counties where WUI growth and wildfires are most prevalent. Counties are categorized by their level of WUI growth between 1990 and 2020 and area burned between 1984 and 2020. Counties are not categorized where wildfires do not meet the minimum size requirements for Monitoring Trends in Burn Severity (MTBS) mapping[57] or where percent growth in WUI area is less than zero. WUI data are not available for the US Caribbean, Alaska, or Hawai‘i and US-Affiliated Pacific Islands regions. In Alaska, wildfires burned over 34 million acres between 1984 and 2020; during this period, eight of the nine wildfire seasons when more than one million acres burned have occurred since 2000. Twenty-one wildfires in Hawai‘i (more than 103,000 total acres) and four wildfires in Puerto Rico (about 6,300 total acres) were mapped between 1984 and 2020. MTBS wildfire data are not available for other parts of the US Caribbean and US-Affiliated Pacific Islands regions (wildfire data from another source for the US-Affiliated Pacific Islands region is presented in Figure 30.13). Figure credits: (a, c) USDA Forest Service; (b) adapted from Radeloff et al. 2018.[56]

Agriculture and Food Systems

The climate–agriculture–food system is complex (Figure 11.9). Agricultural production and natural resources face challenges from increasing climate variability and change. Optimized management and policy decisions require an integrated indicator system that communicates climate-driven production impacts; trends in the social-ecological systems underpinning agriculture (e.g., heat-related mortality of workers; Figure 11.1); crop insurance payments (KM 11.2);[5] how management performs in relation to desired social-ecological conditions;[59] degree of adaptation (KM 11.1); and the relationships among climate change, consumption, and production.[60] Currently, the most developed agriculture-related indicators are production-oriented (Ch. 11), such as range or crop yield, crop pathogens, animal heat stress, migration of plant hardiness zones (Figure 11.3), timing of budbreak in fruit trees, and ratios of outputs to inputs (total factor productivity).[5] The productivity of rangeland vegetation provides many valued ecosystem services,[61] but it has severely declined in some areas of the US in recent decades (Figure A4.15),[62] with a strong correlation to regional-scale climate change exposure.[63]

Rangeland Production



Rangeland vegetation production has severely declined in some areas and increased in others.

Figure A4.15. Rangeland annual net primary production (ANPP) measures the annual production of rangeland vegetation, which provides key ecosystem services supporting soil, air, and water quality and billions of dollars in commerce. This figure illustrates ANPP in pounds per acre on rangelands by ecological subsection (see Cleland et al. 2007[64]) during the periods (**a**) 1984–1999 and (**b**) 2000–2021. Positive values indicate areas where ANPP has increased over time, and negative values show where it has decreased. Areas in white are not classified as rangeland ecosystems. (**c**) The time series shows annual values of ANPP from 1984 to 2021 for a select location in the Mojave Desert (indicated by the circle on the maps). ANPP increased in this area over the first half of the time period but has since seen a steady decline. Data are not available for the US Caribbean, Alaska, or Hawai'i and US-Affiliated Pacific Islands regions. Adapted with permission from Reeves et al. 2021[62] [CC BY-NC-ND 4.0].

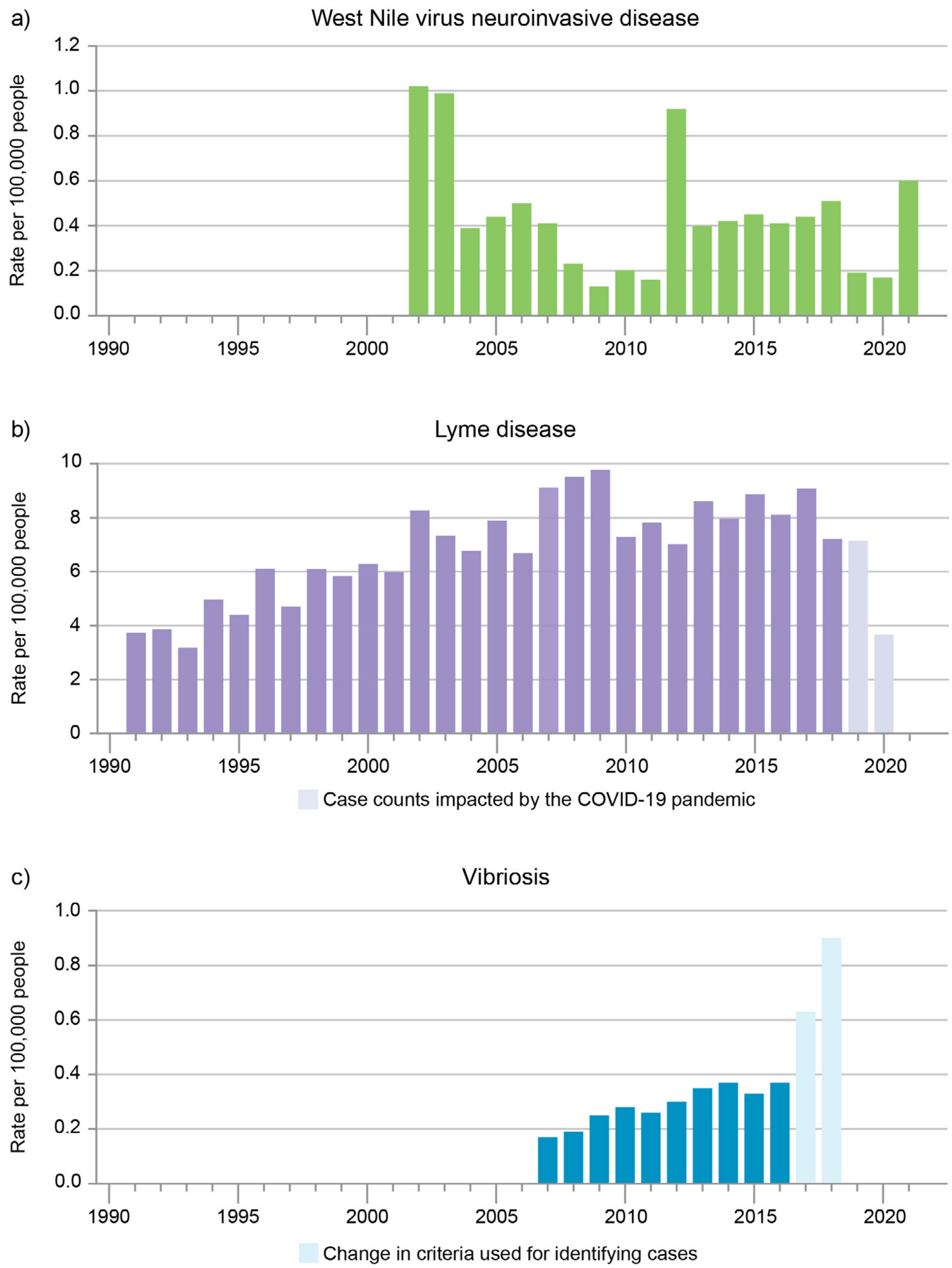
A4.6. Health Indicators

Climate change increases risks and impacts to human health and well-being by exacerbating existing health threats and creating new challenges based on multiple factors and pathways. A variety of health outcomes are affected by climate change, including mental health challenges as well as physical health issues such as cardiorespiratory conditions from poor air quality, injuries and mortality from extreme weather events, and malnutrition from changing climate and environmental factors.[15]

It is important that health indicators include more than just measures of health outcomes to understand how climate impacts and exposures influence health burdens. A broader approach is helpful because of the complex, often indirect relationships among climate drivers, environmental and social factors, and health outcomes, and because of challenges with collecting and reporting health data including lag times in availability. Some widely utilized health indicators include heat-related illnesses and deaths,[21,22,65] described in part in NCA4, which also details the impacts of a changing climate on vector-, water-, and foodborne diseases but without quantitative context.[66] To build upon this body of knowledge and to highlight robust examples of infectious disease metrics with 1) strong science supporting the linkages among climate, environment, and human risk factors; 2) national coverage; and 3) ample temporal extent, this appendix presents indicators for three nationally notifiable infectious diseases routinely reported to the CDC (Figure A4.16).

Changes in temperature, precipitation patterns, and extreme events can alter the seasonality, distribution, and prevalence of vector-, water-, and foodborne diseases (KM 15.1).[7] West Nile virus (WNV) neuroinvasive disease and Lyme disease are impacted by climate change through complex shifts in land use, vector ecology, and human behavior (Chs. 8, 15). Vibriosis, linked to warming marine and coastal waters, is an illness contracted through exposure to *Vibrio* bacterial species from contaminated seafood or from open skin wounds exposed to contaminated water.[7]

Infectious Diseases Impacted by Climate Change



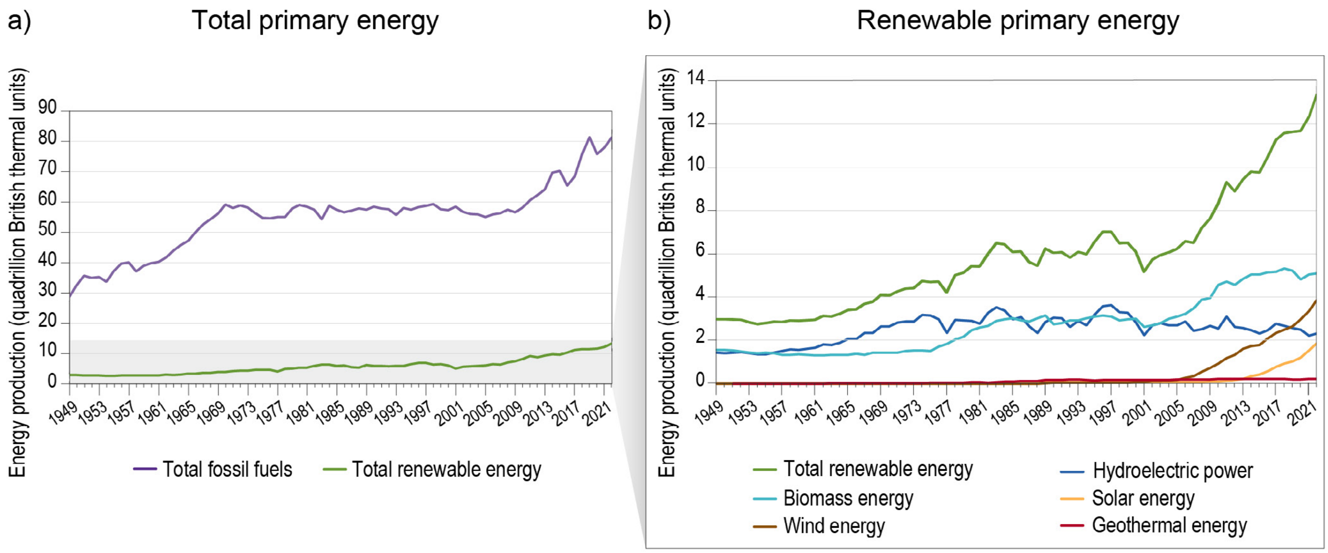
Climate, environmental, and social factors influence infectious disease rates.

Figure A4.16. Indicators of diseases widely recognized as being affected by climate change can provide a general gauge of the disease burden and help guide resources and public health actions. Incidence rates of (**a**) West Nile virus (WNV) neuroinvasive disease, (**b**) Lyme disease, and (**c**) vibriosis are presented for the years 2002–2021, 1991–2020, and 2007–2018, respectively. For WNV neuroinvasive disease, the pattern of incidence rates is variable, ranging from 1 per 100,000 people in 2002, when it became a nationally notifiable condition, to 0.6 per 100,000 people in 2021. Lyme disease incidence rates have trended upward from 4 cases per 100,000 people in 1991 to 7 cases per 100,000 in 2018. Similarly, trends in vibriosis have risen since 2007. Confirmed and probable cases are collected by state and local health departments and reported to the National Notifiable Diseases Surveillance System or the COVIS (Cholera and Other *Vibrio* Illness Surveillance) system. Annual counts and rates for each state are compiled by the CDC. Surveillance data for Lyme disease in 2019 and 2020 were markedly affected by the COVID-19 pandemic (light purple bars). Case definitions are occasionally revised, but because the vibriosis case definition changed significantly in 2017, trends before (dark blue bars) and after (light blue bars) are not comparable. (a) Adapted from EPA 2023;[67] (b) adapted from EPA 2023;[68] (c) adapted from Sheahan et al. 2022.[69]

A4.7. Adaptation and Mitigation Indicators

Adaptation to promote climate resilience of populations, ecosystems, and infrastructure as well as mitigation to reduce emissions are critical, particularly for protecting human well-being and the environment (Chs. 31, 32). Indicators of adaptation and mitigation are important tools that help track and assess progress[70,71,72], as well as evaluate adaptation decisions and improve resilience (KM 31.5). This can be done, for example, by aggregating the number of documented adaptation activities by state over a certain time period (Figures 1.3, 31.1, 32.20). Although valuable for decision-making and evaluating effectiveness, indicators of resilience, adaptation responses, and adaptive capacity remain relatively limited.[72,73,74] Figure A4.17 is an example of a mitigation indicator showing how US energy production from renewables has increased in recent years (KM 32.1; Figures 26.6, 32.3).

Energy Production by Source



US energy production from renewables is increasing.

Figure A4.17. The figure shows annual time series of US energy production for (**a**) total primary energy (which includes both fossil fuels and renewable energy) and (**b**) categories of renewable energy (biomass, wind, hydroelectric, solar, and geothermal) for 1949–2022. US energy production from renewable sources (dark green line) has increased since the 1960s, reaching a record high in 2022, primarily due to increases in wind (brown line) and biomass (light blue line) energy. Energy production from fossil fuels (purple line) also increased during this same time period, although with increased use of cleaner fossil fuels (KM 5.3). Adapted from EIA 2023.[75]

Climate change disproportionately impacts certain communities and populations (Ch. 20). Social, environmental, and economic factors[76,77,78] contribute to disparities experienced by groups at greater risk of climate change stressors (KM 15.2). Indices that combine multiple variables have been developed to capture complex issues affecting communities that are overburdened (e.g., Figures 15.5, 22.12). Furthermore, indicators that couple human and social dimensions with climate data (e.g., Figures 11.13, 12.6, 22.18) are necessary to better assess who is at highest risk from impacts and to prioritize and evaluate response decisions.

A4.8. Knowledge Gaps and New Approaches

It is vital to recognize data specific to Indigenous communities to adequately address the disproportionate impacts of climate change (Ch. 16).[79] Indicators drawing from Indigenous Knowledge (KM 16.3)[80] and focusing on the concept of cultural keystone indicator species[81] may better represent the perspectives of Indigenous Peoples affected by climate change than the indicators featured in this appendix.

Indicators are used to evaluate community response and preparedness,[82] as well as the capacity for socio-ecological systems to build resilience.[83] However, it is difficult to incorporate consistent indicators of resilience and adaptation (e.g., Brooks 2014;[84] Keenan and Maxwell 2021[85]). Distilling best practices at the community scale remains a challenge.[86] The emerging understanding of compound events and their impacts (Ch. 18) will likely inform new indicator development. Confidence in attributing outcomes to climate change varies among physical climate indicators, especially for societal and ecosystem indicators (e.g., IPCC 2022[15]).

Data sharing and transparency standards arising from the Information Quality Act (IQA; App. 2), are well established for geophysical information and are reliably compiled in several recurring volumes,[2,9,87] whereas biological and health information is typically built on local and less-federated data. For health, limitations in sharing data, due to privacy concerns or cost, hinder the creation of nationally consistent indicators.[8] Advances in applying IQA standards to nonphysical data will increase the availability and credibility of this information.

Newer observing systems and sensors and community-led (“citizen”) science bring additional data options. In recent years, broader public participation in data collection and curation has played an increasingly important role in contributing to existing or potential indicators. Such efforts include improvements in documenting physical climate variables at finer scales,[88] capturing the impacts on or responses of ecosystems, and recording climate-related influences on human health.[89]

While indicators provide valuable information on past changes, it is important that they be well positioned to provide information on how these changes may continue in the future, to assist with planning, adaptation, and strategic policy decisions. For example, national surveillance systems, such as the National Notifiable Diseases Surveillance System,[90] could integrate indicators into existing data collection and analysis processes to advance interpretation of observed data, trends, and impacts. New indicators that track how compound events are changing over time would potentially help communities become more climate resilient (see Focus on Compound Events).

Looking ahead, indicator systems that reflect the coupled nature of climate systems and management systems will be needed for optimal planning and policymaking. This will require integration across disciplines, stakeholder groups, government agencies, and nations.[91]

References

1. Jay, A., D.R. Reidmiller, C.W. Avery, D. Barrie, B.J. DeAngelo, A. Dave, M. Dzaugis, M. Kolian, K.L.M. Lewis, K. Reeves, and D. Winner, 2018: Ch. 1. Overview. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 33–71. https://doi.org/10.7930/nca4.2018.ch1

2. EPA, 2023: Climate Change Indicators in the United States. U.S. Environmental Protection Agency, accessed February 14, 2023. https://www.epa.gov/climate-indicators

3. Di Napoli, C., A. McGushin, M. Romanello, S. Ayeb-Karlsson, W. Cai, J. Chambers, S. Dasgupta, L.E. Escobar, I. Kelman, T. Kjellstrom, D. Kniveton, Y. Liu, Z. Liu, R. Lowe, J. Martinez-Urtaza, C. McMichael, M. Moradi-Lakeh, K.A. Murray, M. Rabbaniha, J.C. Semenza, L. Shi, M. Tabatabaei, J.A. Trinanes, B.N. Vu, C. Brimicombe, and E.J. Robinson, 2022: Tracking the impacts of climate change on human health via indicators: Lessons from the Lancet Countdown. *BMC Public Health*, **22** (1), 663. https://doi.org/10.1186/s12889-022-13055-6

4. Kenney, M.A., A.C. Janetos, and M.D. Gerst, 2020: A framework for national climate indicators. *Climatic Change*, **163** (4), 1705–1718. https://doi.org/10.1007/s10584-018-2307-y

5. Walsh, M.K., P. Backlund, L. Buja, A. DeGaetano, R. Melnick, L. Prokopy, E. Takle, D. Todey, and L. Ziska, 2020: Climate Indicators for Agriculture. USDA Technical Bulletin 1953. U.S. Department of Agriculture, Washington, DC, 70 pp. https://doi.org/10.25675/10217/210930

6. Romanello, M., C. Di Napoli, P. Drummond, C. Green, H. Kennard, P. Lampard, D. Scamman, N. Arnell, S. Ayeb-Karlsson, L.B. Ford, K. Belesova, K. Bowen, W. Cai, M. Callaghan, D. Campbell-Lendrum, J. Chambers, K.R. van Daalen, C. Dalin, N. Dasandi, S. Dasgupta, M. Davies, P. Dominguez-Salas, R. Dubrow, K.L. Ebi, M. Eckelman, P. Ekins, L.E. Escobar, L. Georgeson, H. Graham, S.H. Gunther, I. Hamilton, Y. Hang, R. Hänninen, S. Hartinger, K. He, J.J. Hess, S.-C. Hsu, S. Jankin, L. Jamart, O. Jay, I. Kelman, G. Kiesewetter, P. Kinney, T. Kjellstrom, D. Kniveton, J.K.W. Lee, B. Lemke, Y. Liu, Z. Liu, M. Lott, M.L. Batista, R. Lowe, F. MacGuire, M.O. Sewe, J. Martinez-Urtaza, M. Maslin, L. McAllister, A. McGushin, C. McMichael, Z. Mi, J. Milner, K. Minor, J.C. Minx, N. Mohajeri, M. Moradi-Lakeh, K. Morrissey, S. Munzert, K.A. Murray, T. Neville, M. Nilsson, N. Obradovich, M.B. O'Hare, T. Oreszczyn, M. Otto, F. Owfi, O. Pearman, M. Rabbaniha, E.J.Z. Robinson, J. Rocklöv, R.N. Salas, J.C. Semenza, J.D. Sherman, L. Shi, J. Shumake-Guillemot, G. Silbert, M. Sofiev, M. Springmann, J. Stowell, M. Tabatabaei, J. Taylor, J. Triñanes, F. Wagner, P. Wilkinson, M. Winning, M. Yglesias-González, S. Zhang, P. Gong, H. Montgomery, and A. Costello, 2022: The 2022 report of the *Lancet* Countdown on health and climate change: Health at the mercy of fossil fuels. *The Lancet*, **400** (10363), 1619–1654. https://doi.org/10.1016/s0140-6736(22)01540-9

7. USGCRP, 2016: *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. Crimmins, A., J. Balbus, J.L. Gamble, C.B. Beard, J.E. Bell, D. Dodgen, R.J. Eisen, N. Fann, M.D. Hawkins, S.C. Herring, L. Jantarasami, D.M. Mills, S. Saha, M.C. Sarofim, J. Trtanj, and L. Ziska, Eds. U.S. Global Change Research Program, Washington, DC, 312 pp. https://doi.org/10.7930/j0r49nqx

8. Liu, A.Y., J.M. Trtanj, E.K. Lipp, and J.M. Balbus, 2021: Toward an integrated system of climate change and human health indicators: A conceptual framework. *Climatic Change*, **166** (3), 49. https://doi.org/10.1007/s10584-021-03125-w

9. USGCRP, 2023: USGCRP Indicators Platform. U.S. Global Change Research Program, accessed October 3, 2023. https://www.globalchange.gov/indicators/

10. CDC, 2020: National Environmental Public Health Tracking: Climate Change. Centers for Disease Control and Prevention, accessed April 5, 2023. https://www.cdc.gov/nceh/tracking/topics/climatechange.htm

11. EPA, n.d.: EPA Climate Indicator Map Viewer. U.S. Environmental Protection Agency, accessed May 20, 2023. https://experience.arcgis.com/experience/bdd9567a847a4b52abd20253539143df

12. NASA, 2023: Global Climate Change—Vital Signs of the Planet: Understanding Our Planet to Benefit Humankind. National Aeronautics and Space Administration. https://climate.nasa.gov/

13. NOAA, 2023: National Marine Ecosystem Status: Assessing Our Marine and Great Lakes Ecosystems. National Oceanic and Atmospheric Administration, accessed May 5, 2023. https://ecowatch.noaa.gov/

14. Kunkel, K.E., R. Frankson, J. Runkle, S.M. Champion, L.E. Stevens, D.R. Easterling, B.C. Stewart, A. McCarrick, and C.R. Lemery, 2022: State Climate Summaries for the United States 2022. NOAA Technical Report NESDIS 150. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Silver Spring, MD. https://statesummaries.ncics.org/

15. IPCC, 2022: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp. https://doi.org/10.1017/9781009325844

16. UN Environment Programme, n.d.: About Montreal Protocol. United Nations Environment Programme. https://www.unep.org/ozonaction/who-we-are/about-montreal-protocol

17. USGCRP, 2023: USGCRP Indicators Platform: Annual Greenhouse Gas Index. U.S. Global Change Research Program, accessed May 25, 2023. https://www.globalchange.gov/indicators/annual-greenhouse-gas-index

18. EPA, 2023: Climate Change Indicators: Seasonal Temperature. U.S. Environmental Protection Agency, accessed February 14, 2023. https://www.epa.gov/climate-indicators/climate-change-indicators-seasonal-temperature

19. Raymond, C., T. Matthews, R.M. Horton, E.M. Fischer, S. Fueglistaler, C. Ivanovich, L. Suarez-Gutierrez, and Y. Zhang, 2021: On the controlling factors for globally extreme humid heat. *Geophysical Research Letters*, **48** (23), e2021GL096082. https://doi.org/10.1029/2021gl096082

20. Rogers, C.D.W., M. Ting, C. Li, K. Kornhuber, E.D. Coffel, R.M. Horton, C. Raymond, and D. Singh, 2021: Recent increases in exposure to extreme humid-heat events disproportionately affect populated regions. *Geophysical Research Letters*, **48** (19), e2021GL094183. https://doi.org/10.1029/2021gl094183

21. EPA, 2023: Climate Change Indicators: Heat Related Illneses. U.S. Environmental Protection Agency, accessed February 14, 2023. https://www.epa.gov/climate-indicators/heat-related-illnesses

22. EPA, 2023: Climate Change Indicators: Heat Related Deaths. U.S. Environmental Protection Agency, accessed February 14, 2023. https://www.epa.gov/climate-indicators/climate-change-indicators-heat-related-deaths

23. USGCRP, 2023: USGCRP Indicators Platform: Heat Waves. U.S. Global Change Research Program, accessed May 25, 2023. https://www.globalchange.gov/indicators/heat-waves

24. Xian, G., H. Shi, Q. Zhou, R. Auch, K. Gallo, Z. Wu, and M. Kolian, 2022: Monitoring and characterizing multi-decadal variations of urban thermal condition using time-series thermal remote sensing and dynamic land cover data. *Remote Sensing of Environment*, **269**, 112803. https://doi.org/10.1016/j.rse.2021.112803

25. Kunkel, K.E., T.R. Karl, M.F. Squires, X. Yin, S.T. Stegall, and D.R. Easterling, 2020: Precipitation extremes: Trends and relationships with average precipitation and precipitable water in the contiguous United States. *Journal of Applied Meteorology and Climatology*, **59** (1), 125–142. https://doi.org/10.1175/jamc-d-19-0185.1

26. EPA, 2023: Climate Change Indicators: Heavy Precipitation. U.S. Environmental Protection Agency, accessed February 14, 2023. https://www.epa.gov/climate-indicators/climate-change-indicators-heavy-precipitation

27. USGCRP, 2023: USGCRP Indicators Platform: Atlantic Tropical Cyclone Days. U.S. Global Change Research Program, accessed May 25, 2023. https://www.globalchange.gov/indicators/atlantic-tropical-cyclone-days

28. Smith, A.B., 2022: 2021 U.S. Billion-Dollar Weather and Climate Disasters in Historical Context. National Oceanic and Atmospheric Administration, National Centers for Environmental Information. https://www.climate.gov/news-features/blogs/beyond-data/2021-us-billion-dollar-weather-and-climate-disasters-historical

29. NCEI, 2023: U.S. Billion-Dollar Weather and Climate Disasters. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, National Centers for Environmental Information. https://www.ncei.noaa.gov/access/billions/

30. USGCRP, 2023: USGCRP Indicators Platform: Billion Dollar Disasters. U.S. Global Change Research Program, accessed May 25, 2023. https://www.globalchange.gov/indicators/billion-dollar-disasters

31. Peters-Lidard, C.D., K.C. Rose, J.E. Kiang, M.L. Strobel, M.L. Anderson, A.R. Byrd, M.J. Kolian, L.D. Brekke, and D.S. Arndt, 2021: Indicators of climate change impacts on the water cycle and water management. *Climatic Change*, **165** (1-2), 36. https://doi.org/10.1007/s10584-021-03057-5

32. Stevens, L.E., T.K. Maycock, and B.C. Stewart, 2021: Climate change in the human environment: Indicators and impacts from the Fourth National Climate Assessment. *Journal of the Air & Waste Management Association*, **71** (10), 1210–1233. https://doi.org/10.1080/10962247.2021.1942321

33. EPA, 2023: Climate Change Indicators: Arctic Sea Ice. U.S. Environmental Protection Agency, accessed February 14, 2023. https://www.epa.gov/climate-indicators/climate-change-indicators-arctic-sea-ice

34. NOAA, 2023: Arctic Report Card. National Oceanic and Atmospheric Administration, accessed May 5, 2023. https://www.arctic.noaa.gov/report-card

35. USGCRP, 2023: USGCRP Indicators Platform: Arctic Sea Ice Extent. U.S. Global Change Research Program, accessed May 25, 2023. https://www.globalchange.gov/indicators/arctic-sea-ice-extent

36. CRS, 2023: Changes in the Arctic: Background and Issues for Congress. CRS Report R41153. Congressional Research Service. https://crsreports.congress.gov/product/pdf/r/r41153

37. NSIDC, 2023: Sea Ice Index Daily and Monthly Image Viewer. University of Colorado Boulder, National Snow and Ice Data Center, Boulder, CO, accessed March 6, 2023. https://nsidc.org/data/seaice_index/data-and-image-archive

38. EPA, 2023: Climate Change Indicators: Snowpack. U.S. Environmental Protection Agency, accessed February 14, 2023. https://www.epa.gov/climate-indicators/climate-change-indicators-snowpack

39. Williams, A.P., B.I. Cook, and J.E. Smerdon, 2022: Rapid intensification of the emerging southwestern North American megadrought in 2020–2021. *Nature Climate Change*, **12** (3), 232–234. https://doi.org/10.1038/s41558-022-01290-z

40. EPA, 2023: Climate Change Indicators: River Flooding. U.S. Environmental Protection Agency, accessed February 14, 2023. https://www.epa.gov/climate-indicators/climate-change-indicators-river-flooding

41. USFS, 2022: National Stream and Aquatic Ecology Center: Flood Potential. U.S. Department of Agriculture, Forest Service, accessed March 31, 2022. https://www.fs.usda.gov/biology/nsaec/projects-floodpotential.html

42. Jasinski, M.F., J.S. Borak, S.V. Kumar, D.M. Mocko, C.D. Peters-Lidard, M. Rodell, H. Rui, H.K. Beaudoing, B.E. Vollmer, K.R. Arsenault, B. Li, J.D. Bolten, and N. Tangdamrongsub, 2019: NCA-LDAs: Overview and analysis of hydrologic trends for the National Climate Assessment. *Journal of Hydrometeorology*, **20** (8), 1595–1617. https://doi.org/10.1175/jhm-d-17-0234.1

43. Vicente-Serrano, S.M., S. Beguería, and J.I. López-Moreno, 2010: A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration Index. *Journal of Climate*, **23** (7), 1696–1718. https://doi.org/10.1175/2009jcli2909.1

44. EPA, 2023: Climate Change Indicators: Drought. U.S. Environmental Protection Agency, accessed February 14, 2023. https://www.epa.gov/climate-indicators/climate-change-indicators-drought

45. NCEI, n.d.: CONUS Climate Divisions. National Oceanic and Atmospheric Administration, National Centers for Environmental Information, accessed August 16, 2023. https://www.ncei.noaa.gov/access/monitoring/reference-maps/conus-climate-divisions

46. NOAA, 2023: Tides & Currents: Relative Sea Level Trends. National Oceanic and Atmospheric Administration, accessed May 5, 2023. https://tidesandcurrents.noaa.gov/sltrends/

47. Sweet, W.V., B.D. Hamlington, R.E. Kopp, C.P. Weaver, P.L. Barnard, D. Bekaert, W. Brooks, M. Craghan, G. Dusek, T. Frederikse, G. Garner, A.S. Genz, J.P. Krasting, E. Larour, D. Marcy, J.J. Marra, J. Obeysekera, M. Osler, M. Pendleton, D. Roman, L. Schmied, W. Veatch, K.D. White, and C. Zuzak, 2022: Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines. NOAA Technical Report NOS 01. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 111 pp. https://oceanservice.noaa.gov/hazards/sealevelrise/sealevelrise-tech-report-sections.html

48. NOAA, 2023: National Marine Ecosystems Status: Sea Surface Temperature. National Oceanic and Atmospheric Administration, accessed May 5, 2023. https://ecowatch.noaa.gov/thematic/sea-surface-temperature

49. Oliver, E.C.J., M.G. Donat, M.T. Burrows, P.J. Moore, D.A. Smale, L.V. Alexander, J.A. Benthuysen, M. Feng, A. Sen Gupta, A.J. Hobday, N.J. Holbrook, S.E. Perkins-Kirkpatrick, H.A. Scannell, S.C. Straub, and T. Wernberg, 2018: Longer and more frequent marine heatwaves over the past century. *Nature Communications*, **9** (1), 1324. https://doi.org/10.1038/s41467-018-03732-9

50. EPA, 2023: Climate Change Indicators: Marine Species Distribution. U.S. Environmental Protection Agency, accessed March 3, 2023. https://www.epa.gov/climate-indicators/climate-change-indicators-marine-species-distribution

51. USGCRP, 2023: USGCRP Indicators Platform: Marine Species Distribution. U.S. Global Change Research Program, accessed May 25, 2023. https://www.globalchange.gov/indicators/marine-species-distribution

52. Pinsky, M.L., B. Worm, M.J. Fogarty, J.L. Sarmiento, and S.A. Levin, 2013: Marine taxa track local climate velocities. *Science*, **341** (6151), 1239–1242. https://doi.org/10.1126/science.1239352

53. Wieland, A., 2021: Dancing the supply chain: Toward transformative supply chain management. *Journal of Supply Chain Management*, **57** (1), 58–73. https://doi.org/10.1111/jscm.12248

54. EPA, 2021: Seasonality and Climate Change: A Review of Observed Evidence in the United States. EPA 430-R-21-002. U.S. Environmental Protection Agency. https://www.epa.gov/system/files/documents/2021-12/30339_epa_report_climate_change_and_seasonality_v12_release_508.pdf

55. Weltzin, J.F., J.L. Betancourt, B.I. Cook, T.M. Crimmins, C.A.F. Enquist, M.D. Gerst, J.E. Gross, G.M. Henebry, R.A. Hufft, M.A. Kenney, J.S. Kimball, B.C. Reed, and S.W. Running, 2020: Seasonality of biological and physical systems as indicators of climatic variation and change. *Climatic Change*, **163** (4), 1755–1771. https://doi.org/10.1007/s10584-020-02894-0

56. Radeloff, V.C., D.P. Helmers, H.A. Kramer, M.H. Mockrin, P.M. Alexandre, A. Bar-Massada, V. Butsic, T.J. Hawbaker, S. Martinuzzi, A.D. Syphard, and S.I. Stewart, 2018: Rapid growth of the US wildland-urban interface raises wildfire risk. *Proceedings of the National Academy of Sciences of the United States of America*, **115** (13), 3314–3319. https://doi.org/10.1073/pnas.1718850115

57. Monitoring Trends in Burn Severity, 2022: MTBS Data Access: Fire Level Geospatial Data. U.S. Department of Agriculture, Forest Service, and U.S. Geological Survey, accessed March 31, 2022. http://mtbs.gov/direct-download

58. CBO, 2022: Wildfires. Congressional Budget Office. https://www.cbo.gov/publication/58212

59. Ahlering, M.A., C. Kazanski, P.E. Lendrum, P. Borrelli, W. Burnidge, L. Clark, C. Ellis, K. Gadzia, J. Gelbard, S. Gennet, J. Goodwin, J.E. Herrick, E. Kachergis, C. Knapp, N. Labbe, K. Maczko, E. Porzig, D. Rizzo, S. Spiegal, and C. Wilson, 2021: A synthesis of ranch-level sustainability indicators for land managers and to communicate across the US beef supply chain. *Rangeland Ecology & Management*, **79**, 217–230. https://doi.org/10.1016/j.rama.2021.08.011

60. van Selm, B., A. Frehner, I.J.M. de Boer, O. van Hal, R. Hijbeek, M.K. van Ittersum, E.F. Talsma, J.P. Lesschen, C.M.J. Hendriks, M. Herrero, and H.H.E. van Zanten, 2022: Circularity in animal production requires a change in the EAT-Lancet diet in Europe. *Nature Food*, **3** (1), 66–73. https://doi.org/10.1038/s43016-021-00425-3

61. Havstad, K.M., D.P.C. Peters, R. Skaggs, J. Brown, B. Bestelmeyer, E. Fredrickson, J. Herrick, and J. Wright, 2007: Ecological services to and from rangelands of the United States. *Ecological Economics*, **64** (2), 261–268. https://doi.org/10.1016/j.ecolecon.2007.08.005

62. Reeves, M.C., B.B. Hanberry, H. Wilmer, N.E. Kaplan, and W.K. Lauenroth, 2021: An assessment of production trends on the Great Plains from 1984 to 2017. *Rangeland Ecology and Management*, **78**, 165–179. https://doi.org/10.1016/j.rama.2020.01.011

63. Briske, D.D., L.A. Joyce, H.W. Polley, J.R. Brown, K. Wolter, J.A. Morgan, B.A. McCarl, and D.W. Bailey, 2015: Climate-change adaptation on rangelands: Linking regional exposure with diverse adaptive capacity. *Frontiers in Ecology and the Environment*, **13** (5), 249–256. https://doi.org/10.1890/140266

64. Cleland, D.T., J.A. Freeouf, J.E. Keys, G.J. Nowacki, C.A. Carpenter, and W.H. McNab, 2007: Ecological Subregions: Sections and Subsections for the Conterminous United States. Gen. Tech. Report WO-76D. Department of Agriculture, Forest Service, Washington, DC. https://doi.org/10.2737/wo-gtr-76d

65. CDC, 2023: Heat & Health Tracker. Centers for Disease Control and Prevention, accessed April 5, 2023. https://ephtracking.cdc.gov/Applications/heatTracker/

66. Ebi, K.L., J.M. Balbus, G. Luber, A. Bole, A. Crimmins, G. Glass, S. Saha, M.M. Shimamoto, J. Trtanj, and J.L. White-Newsome, 2018: Ch. 14. Human health. In: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. Reidmiller, D.R., C.W. Avery, D. Easterling, K. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, Eds. U.S. Global Change Research Program, Washington, DC, USA, 539–571. https://doi.org/10.7930/nca4.2018.ch14

67. EPA, 2023: Climate Change Indicators: West Nile Virus. U.S. Environmental Protection Agency, accessed March 3, 2023. https://www.epa.gov/climate-indicators/climate-change-indicators-west-nile-virus

68. EPA, 2023: Climate Change Indicators: Lyme Disease. U.S. Environmental Protection Agency, accessed March 3, 2023. https://www.epa.gov/climate-indicators/climate-change-indicators-lyme-disease

69. Sheahan, M., C.A. Gould, J.E. Neumann, P.L. Kinney, S. Hoffmann, C. Fant, X. Wang, and M. Kolian, 2022: Examining the relationship between climate change and vibriosis in the United States: Projected health and economic impacts for the 21st century. *Environmental Health Perspectives*, **130** (8), 087007. https://doi.org/10.1289/ehp9999a

70. Cutter, S.L., B.J. Boruff, and W.L. Shirley, 2003: Social vulnerability to environmental hazards. *Social Science Quarterly*, **84** (2), 242–261. https://doi.org/10.1111/1540-6237.8402002

71. Hicke, J.A., S. Lucatello, L.D. Mortsch, J. Dawson, M.D. Aguilar, C.A.F. Enquist, E.A. Gilmore, D.S. Gutzler, S. Harper, K. Holsman, E.B. Jewett, T.A. Kohler, and K. Miller, 2022: Ch. 14. North America. In: *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Pörtner, H.-O., D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, and B. Rama, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 1929–2042. https://doi.org/10.1017/9781009325844.016

72. Vogel, J., M.J. Kolian, A.S. Juliana, H. Hosterman, J. Peers, D. Krishland, and K. Carney, 2020: Past is prologue: A case study exploration of the role of climate indicators in adaptation in the United States. *Climate Services*, **20**, 100202. https://doi.org/10.1016/j.cliser.2020.100202

73. Ebi, K., C. Boyer, K. Bowen, H. Frumkin, and J. Hess, 2018: Monitoring and evaluation indicators for climate change-related health impacts, risks, adaptation, and resilience. *International Journal of Environmental Research and Public Health*, **15** (9), 1943. https://doi.org/10.3390/ijerph15091943

74. Kenney, M.A. and M.D. Gerst, 2021: Synthesis of indicators, datasets, and frameworks available to establish resilience and adaptation indicators: Case study of Chesapeake Bay region, USA. *Current Climate Change Reports*, **7** (2), 35–44. https://doi.org/10.1007/s40641-021-00170-6

75. EIA, 2023: Total Energy. U.S. Energy Information Administration, accessed April 13, 2023. https://www.eia.gov/totalenergy/data/browser/?tbl=t01.02#/?f=a

76. Colburn, L.L., M. Jepson, C. Weng, T. Seara, J. Weiss, and J.A. Hare, 2016: Indicators of climate change and social vulnerability in fishing dependent communities along the Eastern and Gulf Coasts of the United States. *Marine Policy*, **74**, 323–333. https://doi.org/10.1016/j.marpol.2016.04.030

77. Ebi, K.L. and J.J. Hess, 2020: Health risks due to climate change: Inequity in causes and consequences. *Health Affairs*, **39** (12), 2056–2062. https://doi.org/10.1377/hlthaff.2020.01125

78. Thomas, K., R.D. Hardy, H. Lazrus, M. Mendez, B. Orlove, I. Rivera-Collazo, J.T. Roberts, M. Rockman, B.P. Warner, and R. Winthrop, 2019: Explaining differential vulnerability to climate change: A social science review. *WIREs Climate Change*, **10** (2), e565. https://doi.org/10.1002/wcc.565

79. STACCWG, 2021: The Status of Tribes and Climate Change Report. Marks-Marino, D., Ed. Northern Arizona University, Institute for Tribal Environmental Professionals, Flagstaff, AZ. http://nau.edu/stacc2021

80. Reyes-García, V., Á. Fernández-Llamazares, M. Guèze, A. Garcés, M. Mallo, M. Vila-Gómez, and M. Vilaseca, 2016: Local indicators of climate change: The potential contribution of local knowledge to climate research. *WIREs Climate Change*, **7** (1), 109–124. https://doi.org/10.1002/wcc.374

81. Wyllie de Echeverria, V.R. and T.F. Thornton, 2019: Using traditional ecological knowledge to understand and adapt to climate and biodiversity change on the Pacific coast of North America. *Ambio*, **48** (12), 1447–1469. https://doi.org/10.1007/s13280-019-01218-6

82. FEMA, 2022: Community Resilience Indicator Analysis: Commonly Used Indicators from Peer-Reviewed Research: Updated for Research Published 2003–2021. U.S. Department of Homeland Security, Federal Emergency Management Agency. https://www.fema.gov/sites/default/files/documents/fema_2022-community-resilience-indicator-analysis.pdf

83. Cabell, J.F. and M. Oelofse, 2012: An indicator framework for assessing agroecosystem resilience. *Ecology and Society*, **17** (1). https://doi.org/10.5751/es-04666-170118

84. Brooks, N., 2014: Indicators for the Monitoring and Evaluation of Adaptation. IIED Briefing. International Institute for Environment and Development, 4 pp. https://www.iied.org/17273iied

85. Keenan, J.M. and K. Maxwell, 2021: Rethinking the design of resilience and adaptation indicators supporting coastal communities. *Journal of Environmental Planning and Management*, **65** (12), 2297–2317. https://doi.org/10.1080/09640568.2021.1971635

86. Brown, C., R.R. Shaker, and R. Das, 2018: A review of approaches for monitoring and evaluation of urban climate resilience initiatives. *Environment, Development and Sustainability*, **20** (1). https://doi.org/10.1007/s10668-016-9891-7

87. Blunden, J. and T. Boyer, 2021: State of the Climate in 2020. *Bulletin of the American Meteorological Society*, **102** (8). https://doi.org/10.1175/2021bamsstateoftheclimate.1

88. Reges, H.W., N. Doesken, J. Turner, N. Newman, A. Bergantino, and Z. Schwalbe, 2016: CoCoRaHS: The evolution and accomplishments of a volunteer rain gauge network. *Bulletin of the American Meteorological Society*, **97** (10), 1831–1846. https://doi.org/10.1175/bams-d-14-00213.1

89. Crimmins, T.M. and M.A. Crimmins, 2022: Large-scale citizen science programs can support ecological and climate change assessments. *Environmental Research Letters*, **17** (6), 065011. https://doi.org/10.1088/1748-9326/ac72b7

90. CDC, 2022: National Notifiable Diseases Surveillance System (NNDSS). Centers for Disease Control and Prevention. https://www.cdc.gov/nndss/index.html

91. Beauchamp, E., M. Hirons, K. Brown, and E.J. Milner-Gulland, 2020: Twenty priorities for future social-ecological research on climate resilience. *Environmental Research Letters*, **15** (10), 105006. https://doi.org/10.1088/1748-9326/abb157