

Understanding and Assessing Climate Change: Preparing for Nebraska's Future

2024 Climate Change Impact Assessment Report

Chapter 2 - Climate Change Contexts



Chapter 2

Climate Change Contexts: Global, National, and State

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Key messages

1. Climate change is happening, intensifying, and unprecedented.
2. Events outside Nebraska caused by climate change impact our state.
3. The effects of climate change are closely intertwined with society.

Introduction

Nebraska, where east meets west and north meets south, boasts unique landscapes and diverse ecosystems (Chapter 7). Nearly 80,000 miles of scenic rivers and the underlying High Plains Aquifer provide our state with abundant water resources (Chapter 5). Additionally, Nebraska ranks in the top five in the U.S. regarding wind resources (X. Yang et al., 2024) due to the generally flat terrain and location relative to the Rocky Mountains and the seasonal jet stream. With over 200 days of sunshine annually, Nebraska ranks thirteenth in the nation for solar potential (NDEE, 2024c). These natural resources are vital to our state's economy and way of life, supporting agricultural production (Chapter 8), industrial development, mineral extraction, power generation (Chapter 6), recreation, and tourism. Protecting and managing these resources is an integral part of our state's culture and is essential to long-term economic sustainability.

Nebraska transitions between humid conditions in the eastern part of the state and semi-arid conditions in the west. Characteristics include warm, humid summers and cold winters (Chapter 3). The state's continental position, located far from the moderating effects of the ocean, means that we experience large swings in the weather from day to day and season to season. Weather and climate-related hazards include severe thunderstorms, tornadoes, hail, flooding rains, droughts, heat waves, and blizzards. Personal observations and scientific data show that Nebraska's climate is changing, making it harder to maintain our way of life (IPCC, 2023b; Pytlík Zyllig, 2024; USGCRP, 2023).

Climate change intensifies extreme weather events, impacting crop yields (Chapter 8), displacing communities, damaging infrastructure (Chapter 10), and disrupting tourism. The increased frequency of droughts and the lengthening of the fire season contribute to a higher risk of wildfires. Fire suppression and firefighting efforts increase federal and state budgets, while smoke reduces air quality and impacts human health (Chapter 9). Additionally, climate change drives the spread of invasive species (Chapter 7) and shifts disease patterns from ticks and mosquitoes that carry and spread illness (Chapter 9).

Climate change is happening, intensifying, and unprecedented

Climate change is evident across more than 50 indicators (Figure 2.1), including historical data and observed trends related to its causes or effects. These indicators describe how the environment has changed and help communicate the climate's impacts, risks, and vulnerabilities (EPA, 2024a). This report presents indicators as maps and graphs based on historical observations and measurements. These indicators provide compelling evidence that climate change is increasingly affecting both nature and society.

Temperature

While the Earth's climate has always changed, recent warming (1994 to 2023) has been much faster than the long-term trend (1901 to 2023). Each of the last 10 consecutive years has been the warmest 10 since record-keeping began in 1880 (Blunden & Boyer, 2024). When weather station records are extended with proxy data (such as ice cores, rocks, coral reefs, and tree rings), scientists conclude that the current rate of warming is roughly 10 times faster than the average rate of warming after the last Ice Age (Gulev et al., 2021). Earth's rapid warming has resulted in other large-scale global changes, including reductions in snow and ice, sea level rise, rising ocean heat content, changing rainfall patterns, higher humidity, and shifts in the timing of seasonal events. Many of these climate impacts have been unprecedented for thousands of years (Figure 2.2) (Blunden & Boyer, 2024; Gulev et al., 2021; Marvel et al., 2023).

Human activities have altered the chemistry of the Earth's atmosphere by increasing the emission of greenhouse gases, such as carbon dioxide, methane, and nitrous oxide. As a result, the average global surface temperature has risen by approximately 2°F since the pre-industrial era (Figure 2.3) (Hawkins, n.d.). While a two-degree increase may not seem significant, the Earth's oceans, like a swimming pool on a hot day, can absorb a significant amount of heat with only a

Evidence for Climate Change Across Multiple Variables

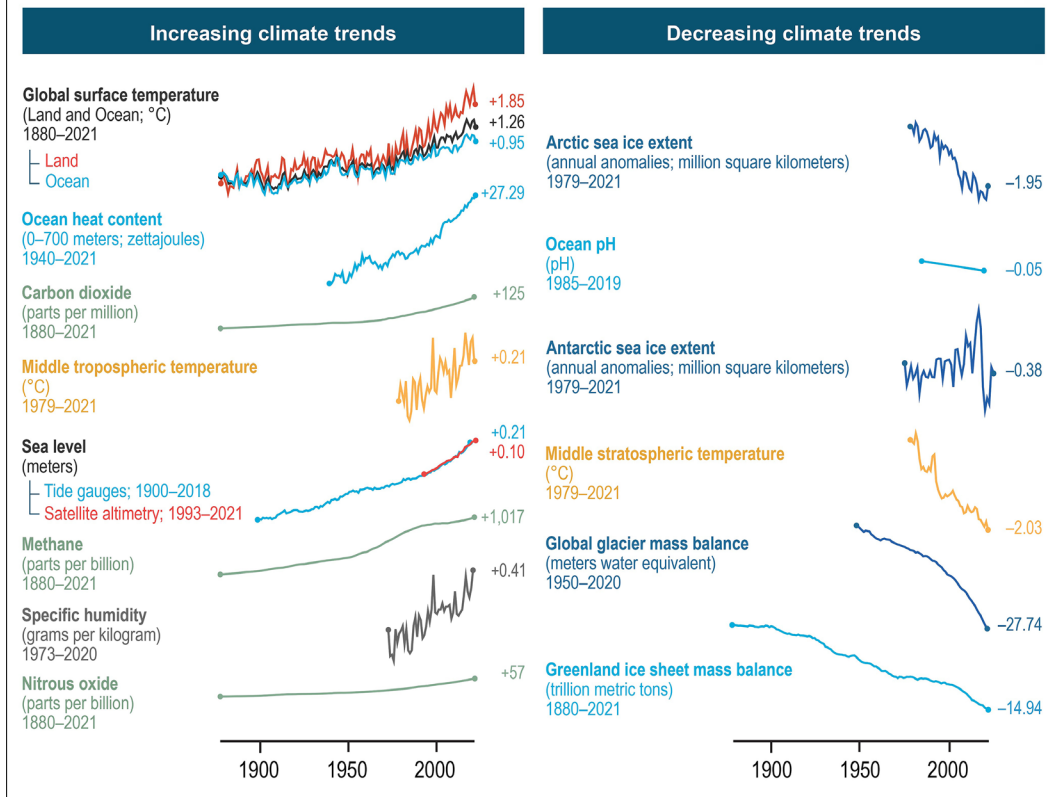


Figure 2.1. Indicators demonstrating evidence of climate change across various aspects of the Earth system between 1880 and 2021. (Source: Marvel et al., 2023)

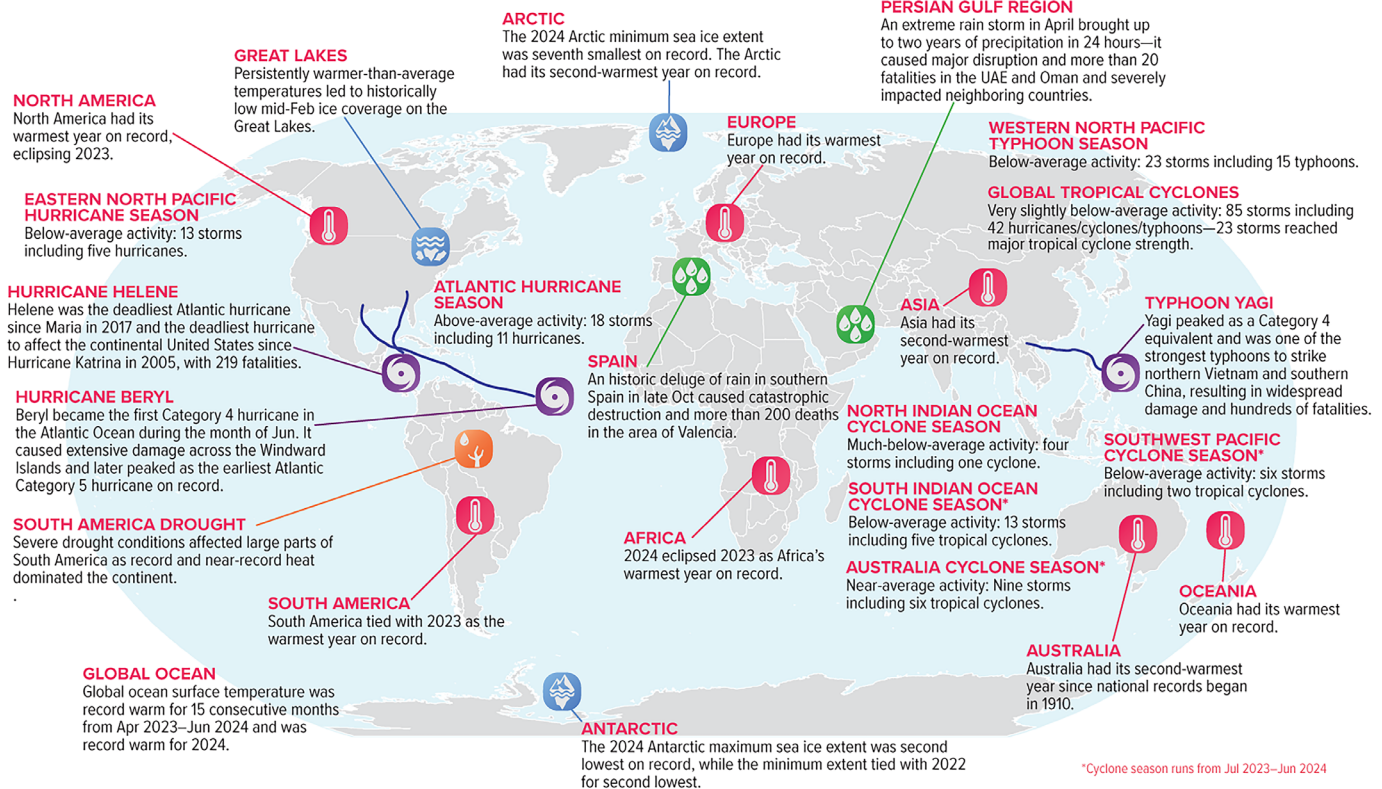
Figure 2.2. Global records set in 2023. (Sources: Blunden & Boyer, 2023; Gulev et al., 2021; Marvel et al., 2023)

Selected Significant Climate Anomalies and Events: Annual 2024



GLOBAL AVERAGE TEMPERATURE

The Jan–Dec global surface temperature ranked warmest since global records began in 1850.



small temperature change. Over 90% of the excess heat generated from rising greenhouse gas emissions has been absorbed by the oceans due to their vast volume, estimated at 352 quintillion gallons of water, and high heat-storage capacity. Without this absorption, the Earth would warm much more rapidly, and the impacts of climate change would be even more severe. However, the oceans have a limited capacity to absorb carbon dioxide; as the ocean temperatures rise, their ability to absorb carbon dioxide decreases (Gruber et al., 2023).

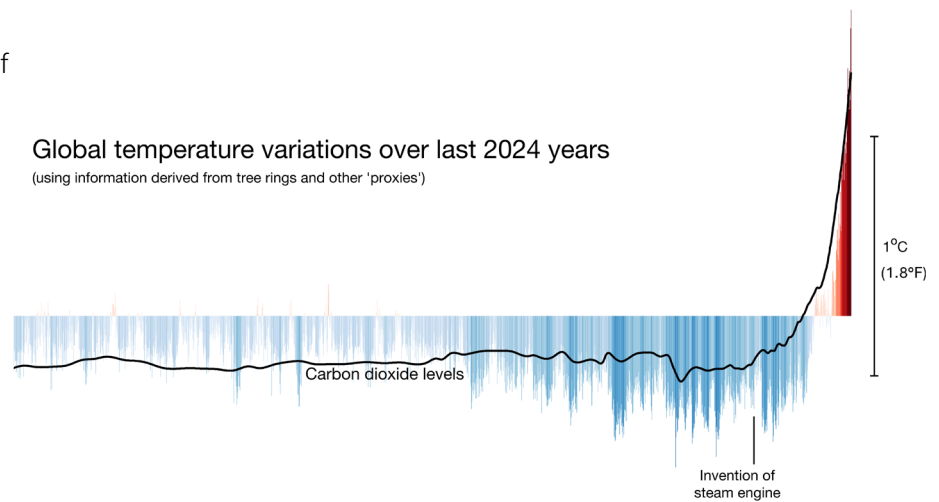


Figure 2.3. Global temperature anomalies over the last 2,024 years, using proxy data in combination with instrumentation. (Adapted from Hawkins, n.d.)

This global average surface temperature increase, referred to as global warming, is not uniform (Figure 2.4). Most regions are experiencing warming, particularly in the higher latitudes over land, while a few areas show isolated cooling (Lindsey & Dahlman, 2025). In the U.S., temperatures have risen more quickly than the global average. Since 1970, temperatures in the contiguous U.S. have increased by 2.5°F; in Alaska, they have risen by 4.2°F (Figure 2.5) (Marvel et al., 2023). Although these increases may seem minor, even small changes in average temperature can significantly impact temperature and precipitation extremes (Box 2.1).

Seasonally, winter is warming nearly twice as fast as summer in many northern states. Temperatures in some areas east of the Rocky Mountains, including parts of Nebraska, have decreased in summer. Studies have linked these regional trends to natural climate variability, irrigation, and aerosol pollution (Marvel et al., 2023). Additionally, the number of frost-free days, or the days between the last occurrence of 32°F in the spring and the first occurrence of 32°F in the fall, has been increasing in the U.S. over the last 40 years (Figure 2.6) (USGCRP, 2023). The length of the frost-free season is an important factor in determining the potential growing season for vegetation, so the increasing length means that the growing season is also increasing.

As temperatures rise, many other changes occur in the climate system. For example, many parts of the water cycle depend on temperature (Figure 2.7) (USGCRP,

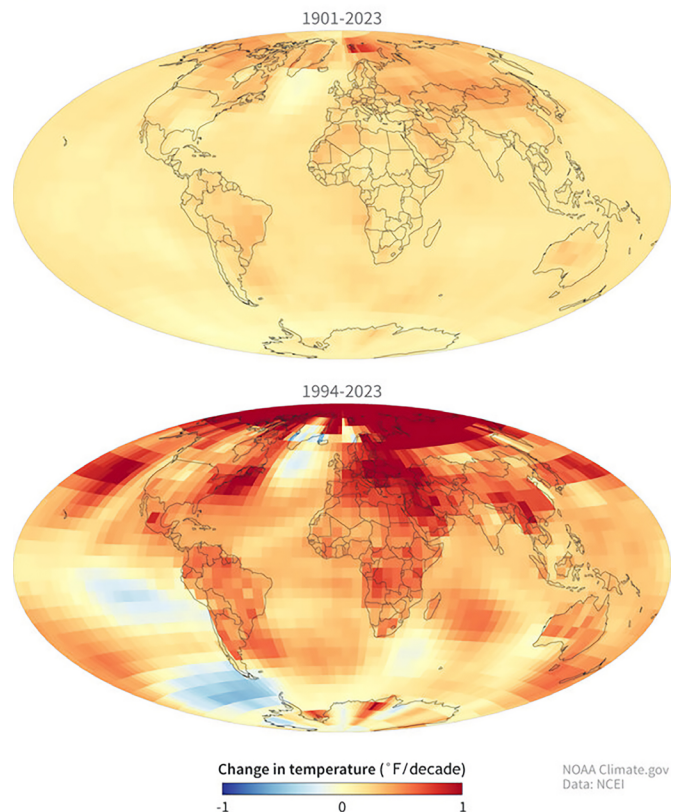


Figure 2.4. Trends in annual surface temperature over the past few decades (1994–2023, bottom) compared to the trend since the start of the 20th century (1901–2023, top). Recent warming is much faster than the longer-term average, with some locations warming 1°F or more per decade. Differences are most dramatic in the Arctic, where the loss of reflective ice and snow amplifies the rate of warming. (Source: Lindsay & Lindsay, 2024)

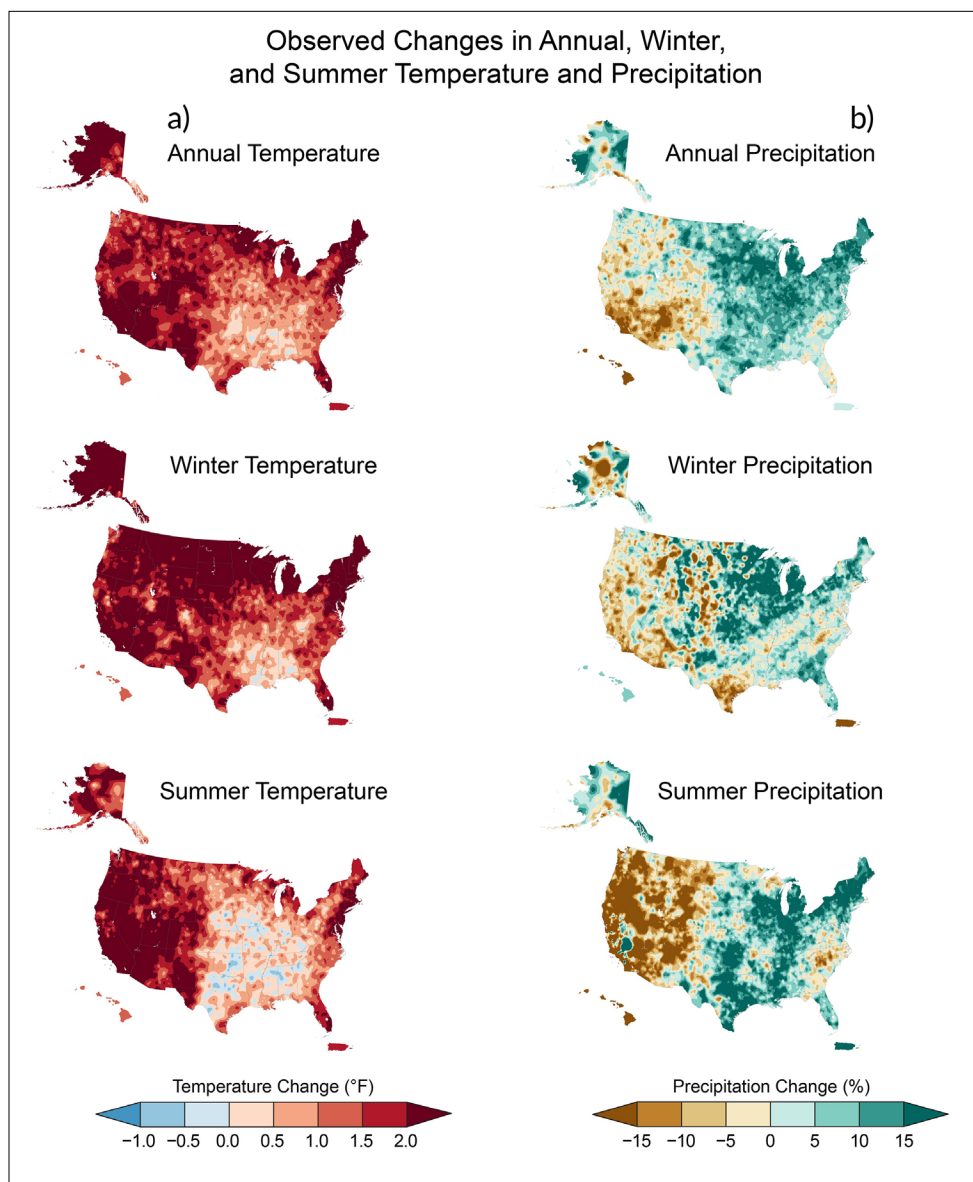


Figure 2.5. Changes shown are the difference between the annual average or seasonal temperatures (left column) and precipitation totals (right column) for the present day (2002–2021) compared to the average for the first half of the last century (1901–1960) for the contiguous United States, Hawaii, and Puerto Rico; and 1925–1960 for Alaska. (Source: Marvel et al., 2023)

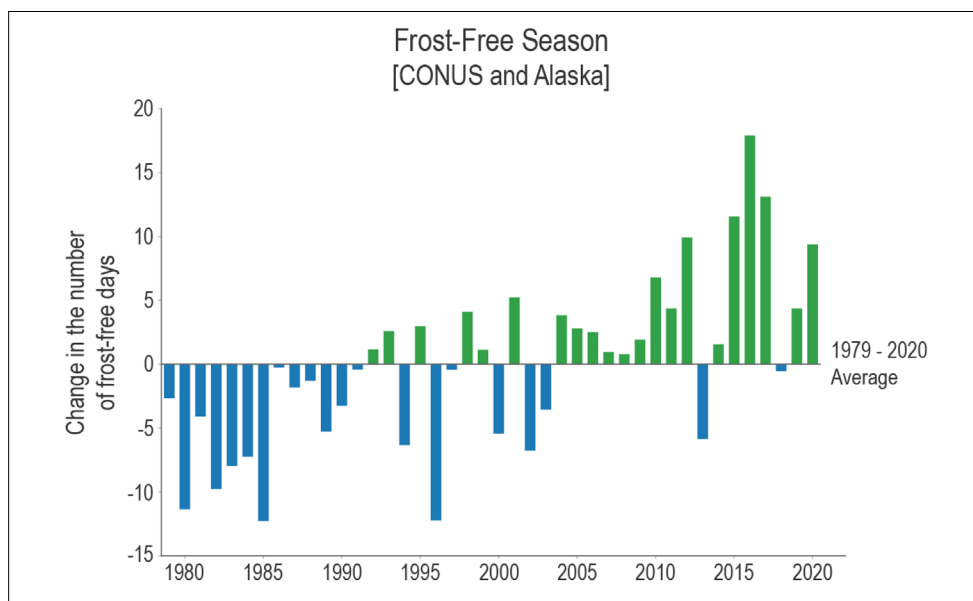
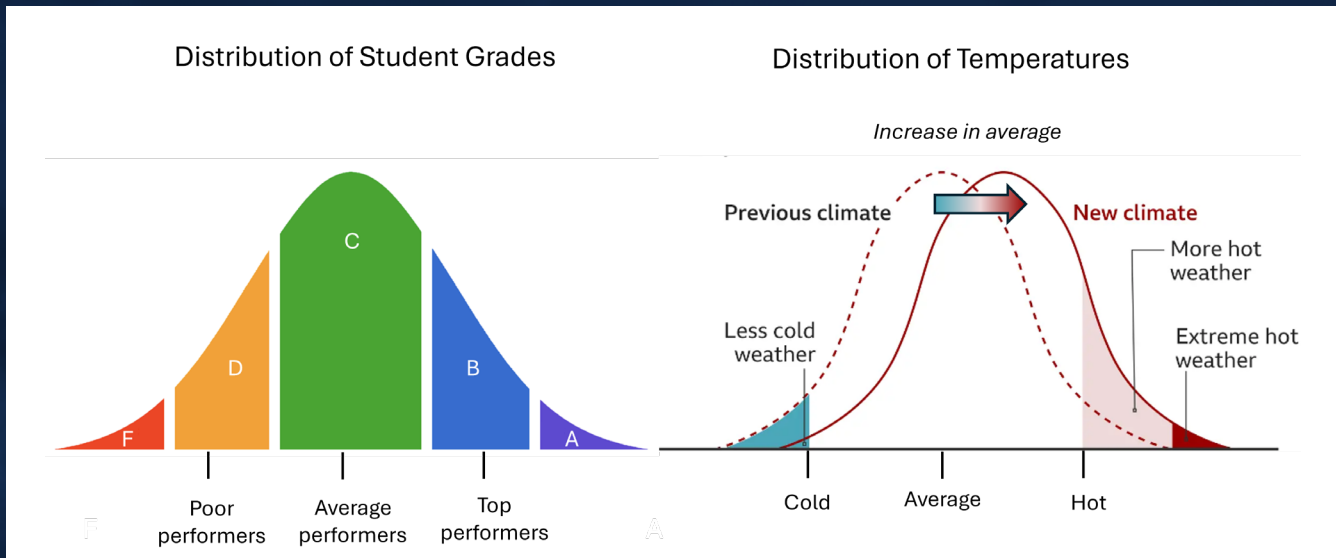


Figure 2.6. The difference between the number of frost-free days each year and the average number from 1979 to 2020 for the contiguous U.S. and Alaska. (Source: USGCRP, 2023)

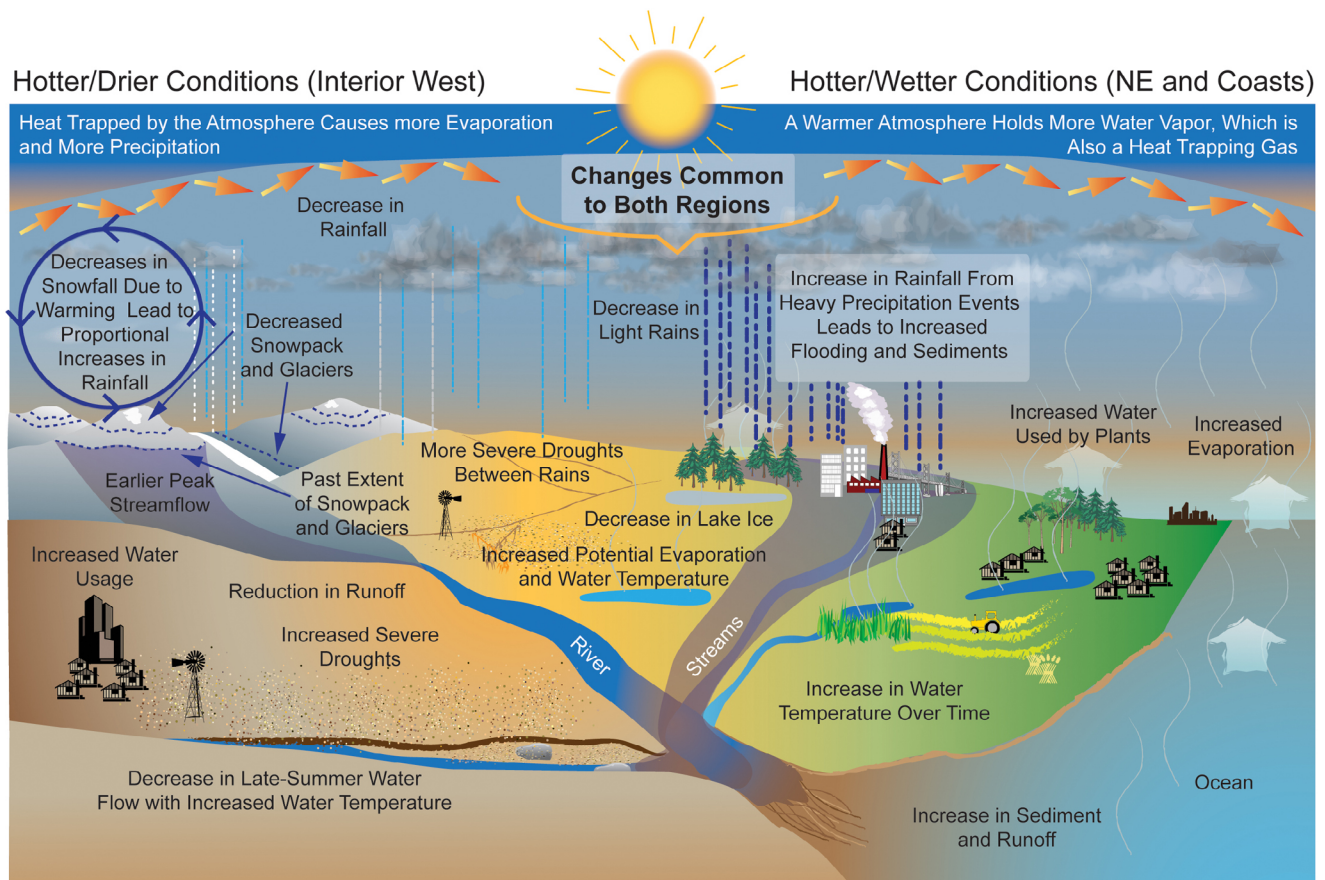
Box 2.1. How does a small shift in climate affect extreme heat events?

Even small increases in average temperature can make a big difference to heat extremes. For example, high school and college teachers often grade using a bell curve to evaluate students' performance. Within this system, everyone's grade is relative to the rest of the class. Using the figure below, we can see that most students fall in the middle, while the top and poor performers land in the "tails" of the curve. Considering temperature using the same curve, most values fall in the middle, while the coldest and warmest temperatures fall in the tails.

A teacher may want to adjust the curve so failing students can pass. Similarly, shifting the temperature curve to the right, indicating an increase in the average temperature, could result in more hot and extremely hot temperatures.



The effect of extreme heat on climate. (Adapted from EPA, 2016)



NOAA/NCDC

The water cycle exhibits many changes as the earth warms. Wet and dry areas respond differently.

Figure 2.7. Changes to the water cycle caused by a warming planet. (Source: USGCRP, 2009)

2009), affecting the timing and amount of rain and snow. From 1901 to 2023, the average global yearly rainfall has increased, and the rate of increase has become faster since the 1980s (Figure 2.8). Monitoring these changes is important because they can disrupt many natural processes. Sparse weather station networks, poor data, and short record lengths, combined with the highly variable nature of precipitation across space and time, make it difficult to understand changes, particularly on a global scale. For instance, 76 nations and territories are represented by fewer than five weather stations (Jaffrés, 2019). In the U.S., which has the highest density of stations worldwide, each station represents roughly 400 square miles (NASA, n.d.).

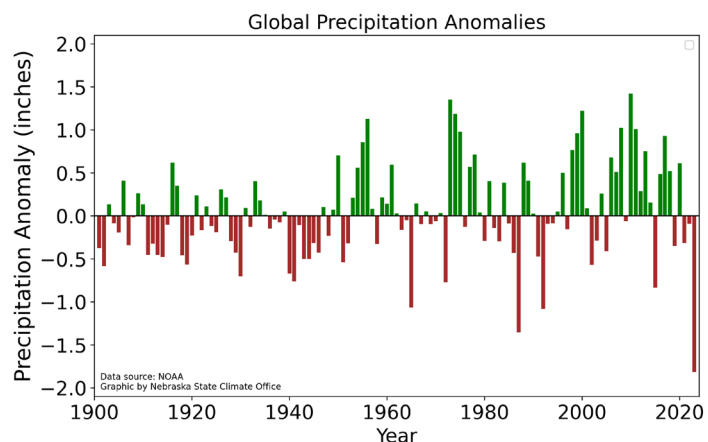


Figure 2.8. Annual global precipitation anomalies, 1901–2021. This graph uses the 1901–2000 average as a baseline to depict change. (Source: NOAA, 2022)

Rain and snow

Annual average precipitation has also increased in the U.S., differing across seasons and regions (Easterling et al., 2017; Marvel et al., 2023). Much of the eastern half of the U.S. is getting wetter, while parts of the Southwest are getting drier (Figure 2.5b). While the Northeast and Midwest have seen wetter conditions in all seasons, other areas, such as the Southeast, have seen a shift in the timing of precipitation. Across the northern Great Plains, precipitation shows drying in the region's western part in winter and summer.

Snow cover is declining globally as temperatures warm (Blau et al., 2024). In the Northern Hemisphere, satellite records show that the largest declines are in the spring (Easterling et al., 2017). These declines are partly due to warmer temperatures shortening snow time on the ground, reflecting an earlier spring snowmelt. River basins across the U.S. are experiencing rapid declines in snow in response to human-caused warming (Figure 2.9). The largest declines are in the Southwest and Northeast. Snow loss in the larger Mississippi basin, of which Nebraska is a part, has been estimated at 5% to 6% per decade since 1980 (Gottlieb & Mankin, 2024; Kelly, 2024). As snow melts, it releases water into rivers, streams, and reservoirs, infiltrates soil, and recharges groundwater. Changes in the amount of snow or the timing of melt can lead to water shortages and increased drought risks, threatening the water supply of the ecosystems and hundreds of millions of people.

Climate Change Effect on Spring Snowpack, 1981-2020

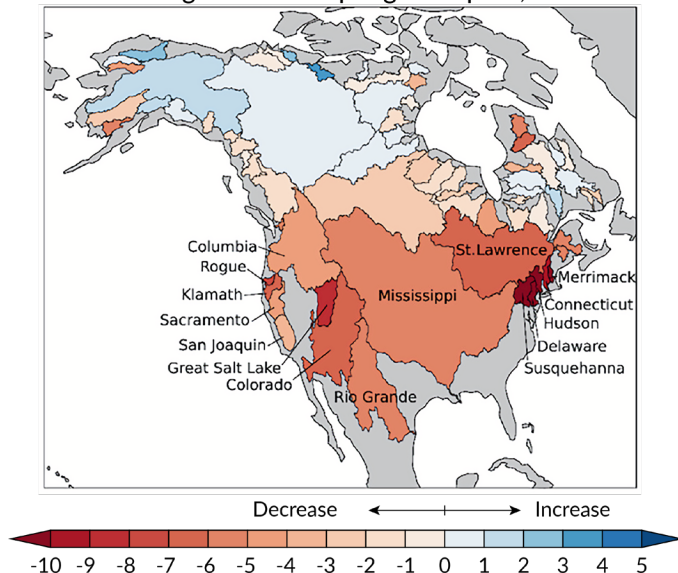


Figure 2.9. Climate change effects on spring snowpack, 1981–2020. (Source: Kelly, 2024)

Extreme weather and climate events

Extreme events are rare occurrences of severe weather conditions such as heat waves, heavy rainfall, drought, and severe thunderstorms. Due to their infrequent nature and historical data constraints, detecting and attributing trends to climate change can be challenging. Projecting future changes is also challenging because, due to their coarse resolution, climate models struggle to adequately represent the small-scale physical processes that drive these changes in extreme events. Despite this, many new developments have been made since the release of Nebraska's last climate assessment report (Bathke et al., 2014) that provide evidence of change and the influence of human-induced warming on these events (Seneviratne et al., 2021).

Extreme heat and cold

Globally, the frequency and intensity of extreme heat have increased, and those of extreme cold have decreased since 1950 (Sheridan & Lee, 2018; Seneviratne et al., 2021). In the western U.S., the risk of hot days where the temperature is at or above 95°F has increased (Figure 2.10). Warm nights where the temperature does not drop below 70°F have increased nearly everywhere except for the northern Plains; here in Nebraska, they have remained nearly constant. The number of cold days where the temperature is at or below 32°F has decreased everywhere except in the Southeast, where the number of days below freezing is already relatively small (Marvel et al., 2023).

Heavy precipitation and flooding

The frequency and intensity of heavy precipitation events have likely increased (66% to 100% probability) globally in places with good observational coverage, though significant regional and seasonal variations exist (Seneviratne et al., 2021). Since the 1950s, heavy precipitation events have become more frequent and intense across much of the country (Figure 2.11) (Marvel et al., 2023). In the northern Plains, a 24% increase in extreme precipitation days (defined as the top 1% of heaviest precipitation events) has occurred. These changes have contributed to increasing trends in large flood frequency (Figure 2.12) (Stevens et al., 2023).

Observed Changes in Hot and Cold Extremes

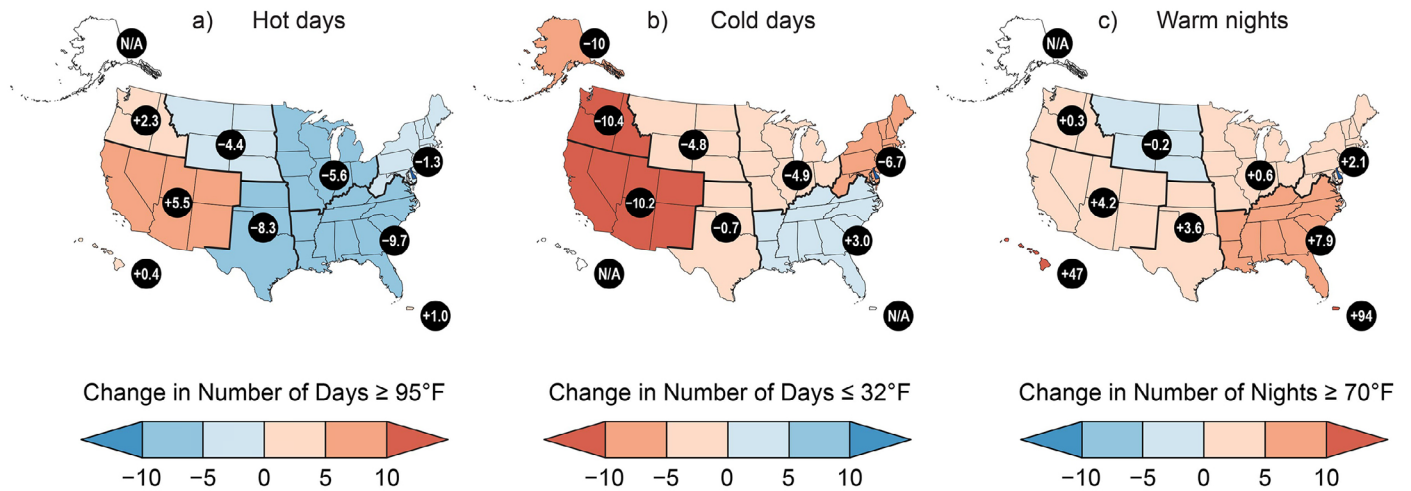


Figure 2.10. Over much of the country, the risk of warm nights has increased, while the risk of cold days has decreased. The risk of hot days has also increased across the western U.S. This figure shows the observed change in the number of (a) hot days (at or above 95°F), (b) cold days (at or below 32°F), and (c) warm nights (at or above 70°F) over the period of 2002–2021, relative to 1901–1960 (1951–1980 for Alaska and Hawai'i and 1956–1980 for Puerto Rico). (Source: Marvel et al., 2023)

Observed Changes in the Frequency and Severity of Heavy Precipitation Events

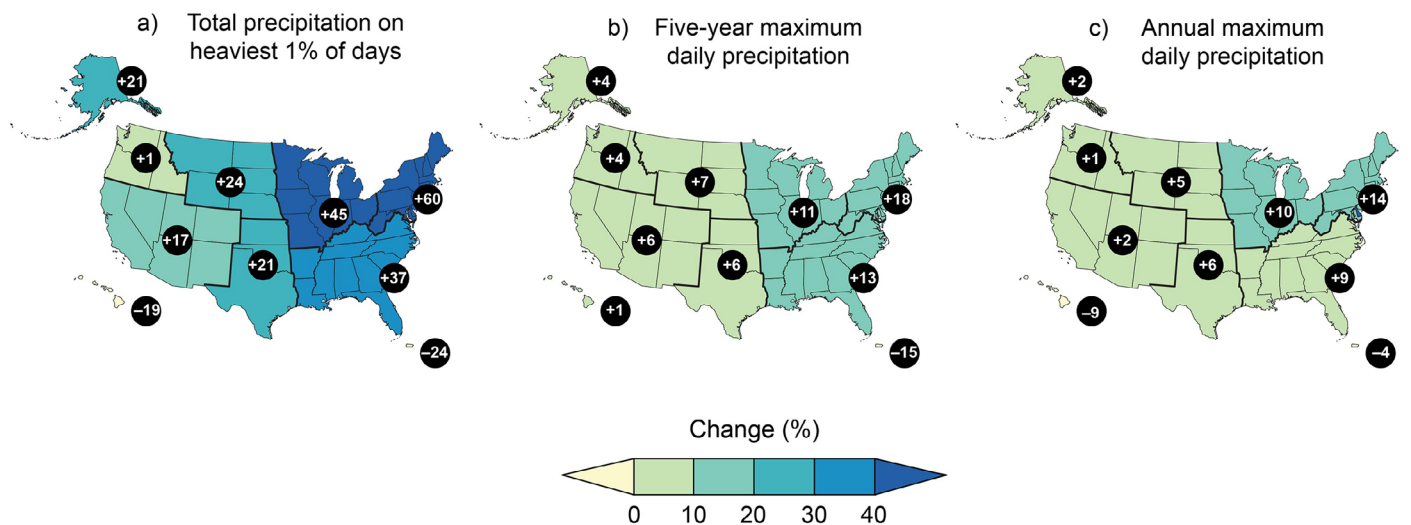
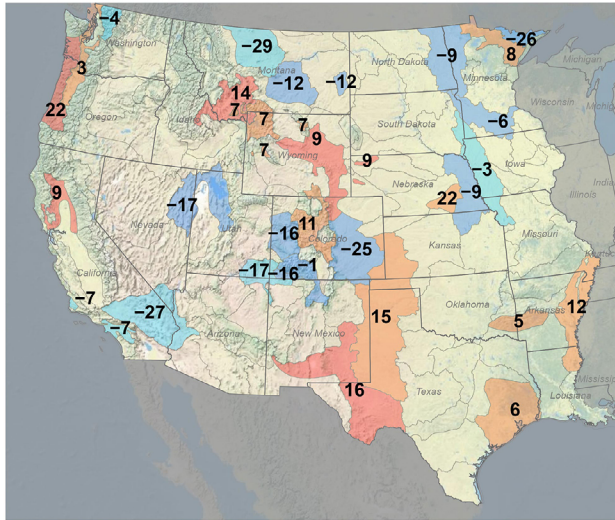


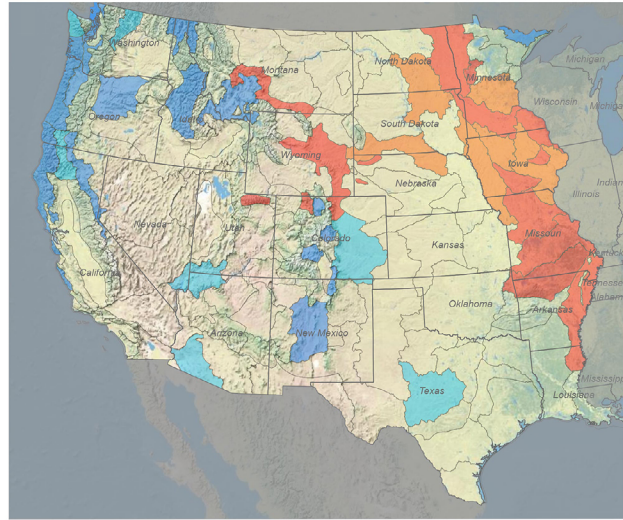
Figure 2.11. The frequency and intensity of heavy precipitation events have increased across much of the U.S., particularly the eastern part of the continental U.S., with implications for flood risk and infrastructure planning. Maps show observed changes in three measures of extreme precipitation: (a) total precipitation falling on the heaviest 1% of days, (b) daily maximum precipitation in a five-year period, and (c) the annual heaviest daily precipitation amount over 1958–2021. Numbers in black circles depict changes in percentage at the regional level. (Source: Marvel et al., 2023)

Flood Frequency and Magnitude West of the Mississippi River

a) Trends in large flood magnitude (%)



b) Trends in large flood frequency



Trends
(period of record varies by flood potential zone)

■ Statistically significant decreasing trend
 ■ Decreasing trend
 ■ No trend
 ■ Increasing trend
 ■ Statistically significant increasing trend

Figure 2.12. Trends in the (a) magnitude and (b) frequency of large floods in the western U.S. 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. The (a) percentage of 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 from 1945 to about 2020. (Source: Stevens et al., 2023)

Drought

Drought is a complex phenomenon that is difficult to define. It looks different based on where and when it occurs, how long it lasts, and whom it affects. Scientists have identified more than 150 definitions of drought (Wilhite & Glantz, 1985), and dozens of indicators exist to measure its severity (Svoboda & Fuchs, 2016). Some drought indicators consider water availability as measured by precipitation, streamflow, groundwater, reservoir levels, soil moisture, and other variables. Other indicators consider factors that represent demand, such as temperature and evapotranspiration. Despite this complexity, scientists can detect some trends in drought events. Global-scale trends indicate that drought has increased on all continents. These increases generally result from increased atmospheric demand caused by high temperatures rather than

decreases in precipitation (Seneviratne et al., 2021). The rapid onset and intensification of drought, also known as flash drought, is likely to increase across much of the globe (Christian et al., 2023). The Standardized Precipitation Evapotranspiration Index (SPEI) shows that since the early 20th century, the eastern half of the U.S. has generally experienced wetter conditions. In comparison, portions of the West have experienced drier conditions (Figure 2.13) (Stevens et al., 2023). The SPEI determines drought severity through a combination of precipitation and evapotranspiration, making it suitable for studies of the effect of climate change on drought severity (Nwayor & Robeson, 2024).

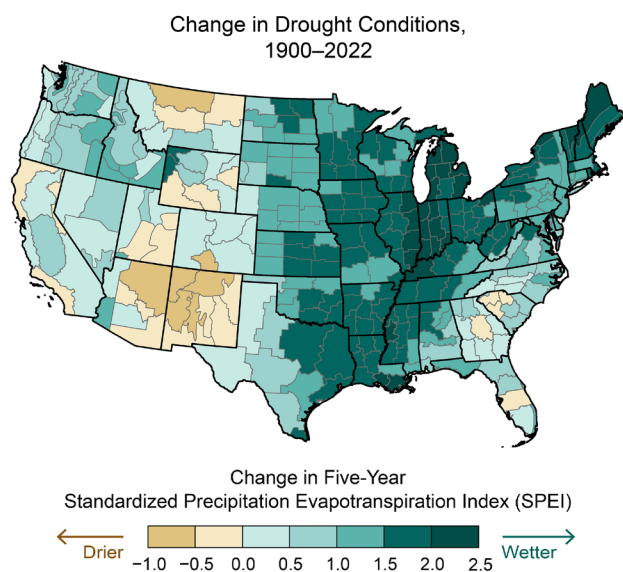


Figure 2.13. This map shows the total change in drought conditions across the contiguous United States, based on the long-term average rate of change in the five-year Standardized Precipitation Evapotranspiration Index (SPEI) from 1900 to 2022. As defined by NOAA, data are displayed for small regions called climate divisions. The 45 teal-shaded areas represent wetter conditions, and brown areas represent drier conditions. (Source: Stevens et al., 2023)

Wildfire

Fueled by higher temperatures and drier conditions, wildfires are becoming more extreme and burning for more prolonged periods across the globe in response to climate change (Jones et al., 2022). Hotter temperatures dry out the landscape, making it more prone to fires. As wildfires burn, they release billions of tons of carbon dioxide into the atmosphere, cause billions of dollars in property damage, displace thousands of people from their homes, threaten ecosystems, and release air pollution across continents (MacCarthy et al., 2023).

The annual average number of acres burned in the U.S. has increased since the mid-1980s (Figure 2.14a). An increase in the wildland-urban interface—where development meets or mixes with natural areas—has increased rapidly since 1990. Together, these changes show that many areas across the U.S. have experienced an increased risk of loss of life and property damage from wildfires (Figure 2.14b) (Stevens et al., 2023).

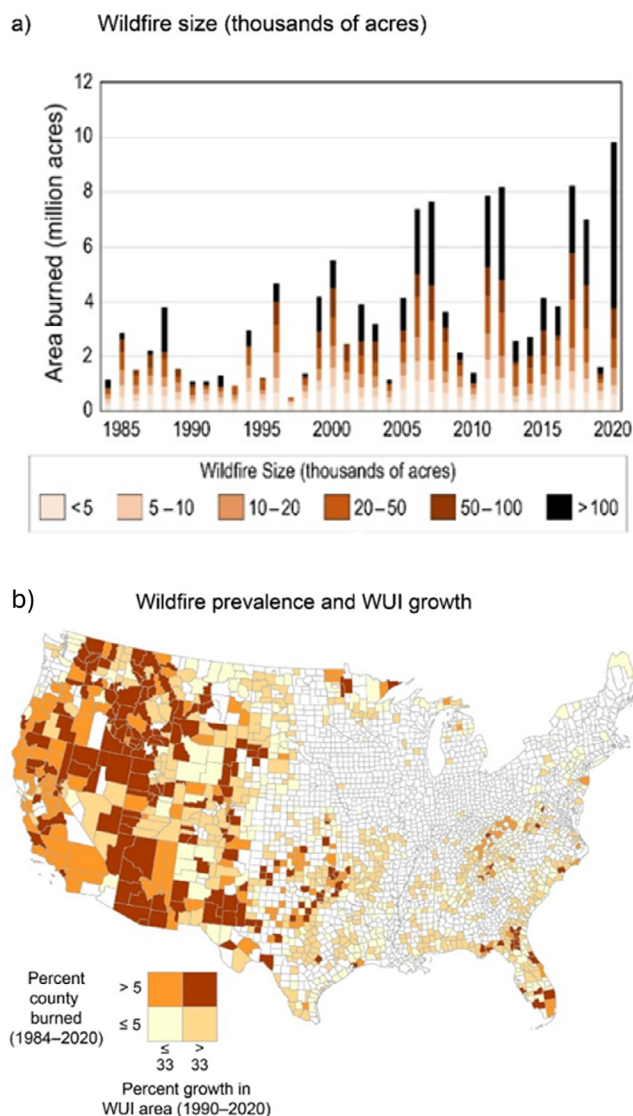


Figure 2.14. The (a) chart shows the number of acres burned between 1984 and 2020 for the contiguous U.S. The different shades within each bar indicate the proportional contribution of different fire size classes to the total for that year. The (b) map portrays U.S. counties where wildland-urban interface (WUI) growth and wildfires are most prevalent. Counties are categorized by their level of WUI growth between 1990 and 2020 and areas burned between 1984 and 2020. Counties are not categorized where wildfires do not meet the minimum size requirements for monitoring trends in burn severity mapping or where percent growth in WUI area is less than zero. (Source: Stevens et al., 2023)

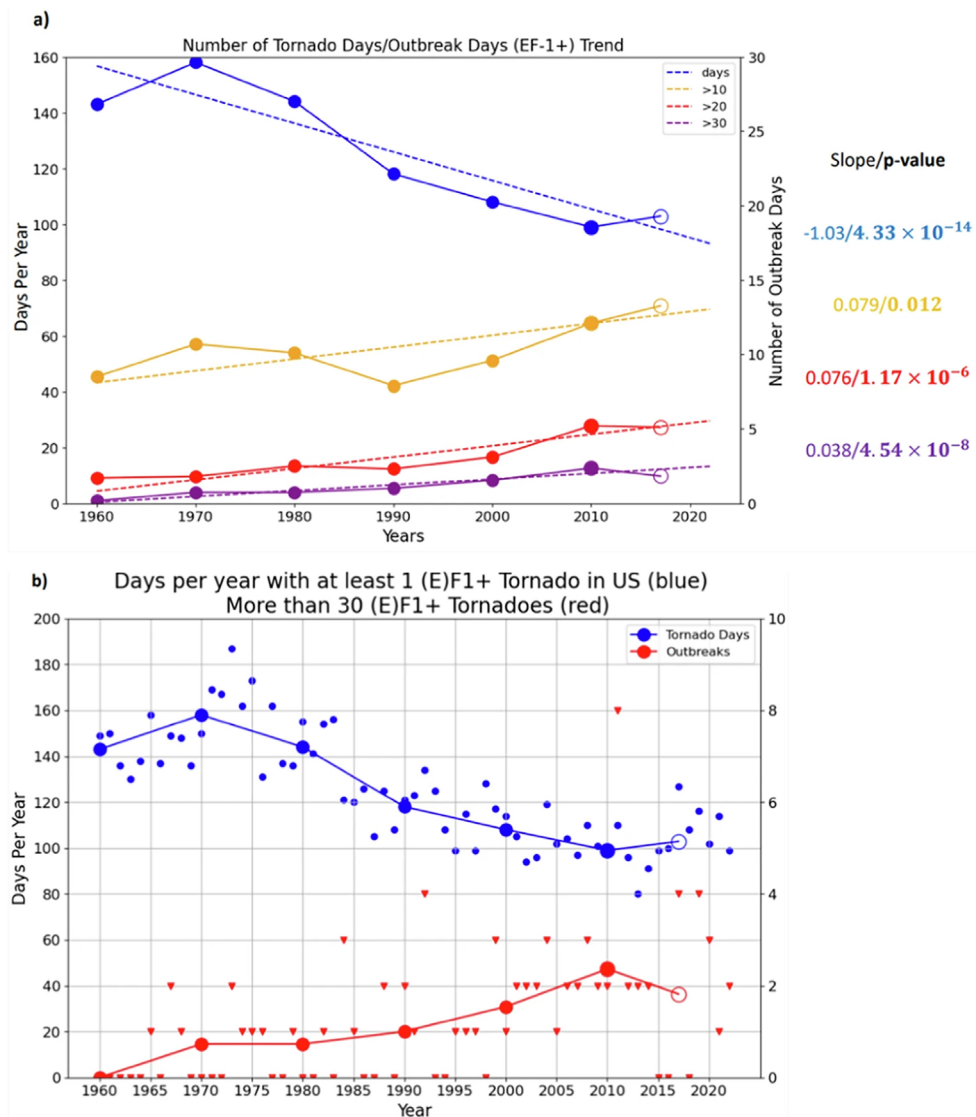


Figure 2.15. Linear trends (a) (dashed lines) of tornado days and of tornado outbreak days with >10, >20, and >30 (E)F-1+ tornadoes with corresponding slopes/p-values. The (b) number of days per year with at least one (E)F-1+ tornado (small circles) and >30 (E)F-1+ tornadoes (small triangles). Large circles and solid lines are decadal means centered on the decade (e.g., 1965–1975 for 1970). The open circles represent the final decadal mean taken in 2017 (i.e., 2012–2022). (Source: Graber et al., 2024, <http://creativecommons.org/licenses/by/4.0>)

Tornadoes and hail

Changes in small-scale, short-lived weather events, such as thunderstorms, tornadoes, and hail, are challenging to assess and have greater uncertainty than other aspects of the environment like larger-scale temperature changes (Taszarek et al., 2021). On a global scale, scientists have low confidence (limited agreement or evidence in research findings) in observed trends in tornadoes and hail due to inadequate observation networks and inconsistencies in observational practices (Seneviratne et al., 2021).

In the U.S., recent research suggests that the average annual number of tornadoes has remained relatively constant since 1950 (Coleman et al., 2024; Guo & Bluestein, 2016). Other research indicates that while tornadoes are occurring less frequently, the number of tornadoes occurring in outbreaks is increasing (Figure 2.15) (Gensini & Brooks, 2018; Graber et al., 2024). A recent example is the April 26, 2024, outbreak in Nebraska and Iowa, which saw 25 tornadoes (NOAA NWS, 2024). Data also show a change in the seasonality of tornadoes, with fewer warm-season (March to

August) tornadoes in the Great Plains. Nebraska has lost about one tornado day per decade over the period 1960–2022 (Moore, 2018; Coleman et al., 2024; Graber et al., 2024). Meanwhile, tornadoes in parts of the Midwest and Southeast are showing increasing trends, particularly in the cool season, suggesting an eastward shift in “Tornado Alley” (Figure 2.16) (Gensini & Brooks, 2018; Graber et al., 2024).

Thunderstorms are associated with other important hazards, including hail and lightning. As with tornadoes, identifying trends for these hazards is challenging due to observer biases, the limited length of the record, and changes in the observing systems (Stevens et al., 2023). However, days with environmental conditions favorable for producing large hail—greater than two inches in diameter or about the size of a pool ball—have become more frequent over the central and eastern parts of the U.S. (Figure 2.17) (B. Tang et al., 2019).

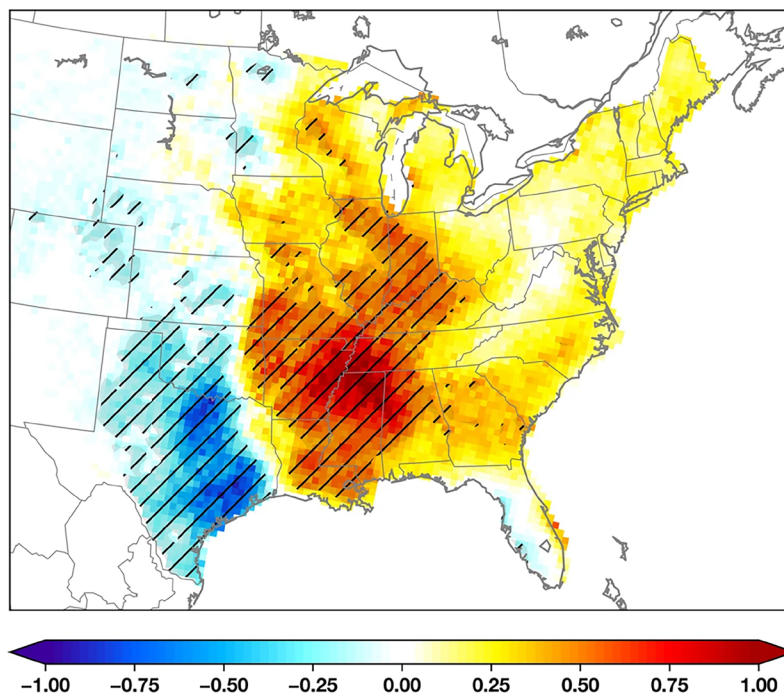


Figure 2.16. Tornado environment frequency trends. Warm colors indicate increasing trends in tornado frequency based on the analysis of the Significant Tornado Parameter, an index that relates environmental conditions to tornado occurrence. (Source: Gensini and Brooks, 2018, <http://creativecommons.org/licenses/by/4.0>)

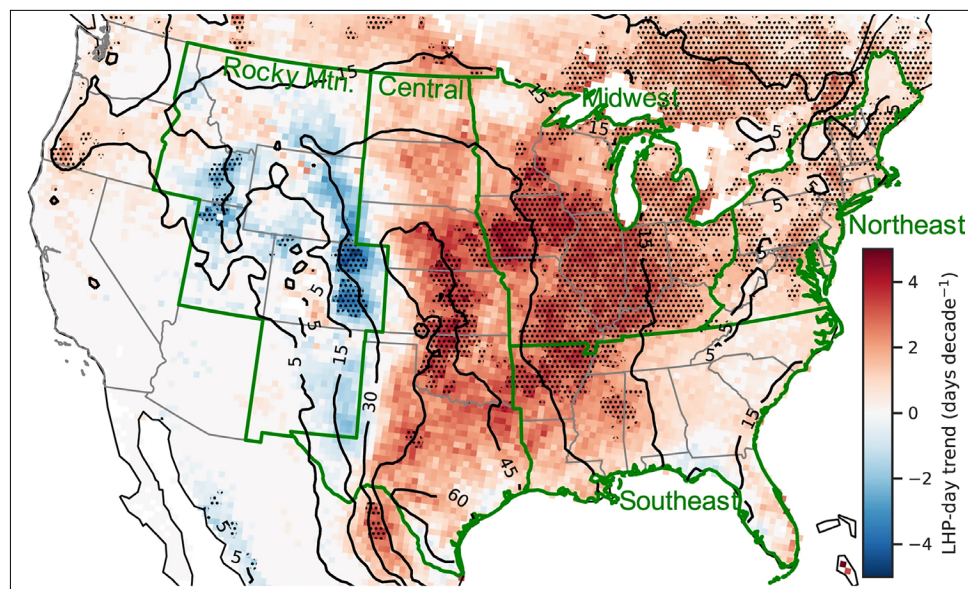


Figure 2.17. Hail environment frequency trends for hail greater than 2 inches. Shading represents trends in the number of days, with warm colors indicating increasing trends in hail frequency based on the analysis of the Large Hail Parameter. This index relates environmental conditions to hail size. (Source: Tang et al., 2019, <http://creativecommons.org/licenses/by/4.0>)

Summary of observed changes across the U.S.

Table 2.1 summarizes the observed changes in climate across the U.S. and the corresponding confidence level as indicated in the Fifth National Climate Assessment (Box 1.3). Confidence levels are based on the amount of evidence and the level of consensus (Marvel et al., 2023).

Table 2.1. Observed changes in the U.S. climate and the associated confidence level.

Note: Confidence levels align with those indicated in the Fifth National Climate Assessment (Box 1.3), reflecting the amount of evidence and level of consensus. (Marvel et al., 2023)

OBSERVED CHANGE	CONFIDENCE
Observed warming over the continental United States and Alaska is higher than the global average.	High confidence
Heat waves have become more common and severe in the West since the 1980s.	High confidence
Drought risk has been increasing in the Southwest over the past century.	Very high confidence
Rainfall has become more extreme in recent decades, especially to the east of the Rockies.	Very high confidence
Hurricanes have been intensifying more rapidly since the 1980s, causing heavier rainfall and higher storm surges.	Very high confidence
Over the past few decades, more frequent and extensive wildfires have been burning in the West.	Very high confidence
Tornado outbreaks have become more frequent, tornado power has increased, tornado activity is increasing in the fall, and Tornado Alley has shifted eastward.	Low confidence, but evidence is increasing.
Changes in extreme events are driven by human-caused climate change	Increasing confidence

Events outside Nebraska caused by climate change impact our state

Earth is a complex, interconnected system, meaning changes in faraway regions affect the U.S. and Nebraska. Direct climate impacts refer to the immediate and observable effects of climate changes, like rising temperatures, increased precipitation, or more extreme weather events. In contrast, indirect climate impacts are the cascading effects that occur because of these direct changes. They often affect ecosystems, food chains, and human societies in more complex ways, potentially even exceeding the severity of the initial direct impact. Examples are highlighted in Case Study 1, “Warming in the Arctic Causes Heat Waves and Cold Snaps in Nebraska,” and Case Study 2, “Warming and Cooling in the Tropics Affects Nebraska’s Temperature and Precipitation,” which demonstrate how changes in the Arctic and tropics cause direct impacts to Nebraska’s weather and climate by altering atmospheric circulation.



The effects of climate change are complex and interconnected with society

The interconnectedness of the Earth’s climate system with society can lead to cascading effects. Changes in one area can significantly impact others and impact national security, water availability, human health, economic stability, and migration patterns. Outcomes can be unpredictable and significantly disrupt the social systems we rely on, leading to a cascade of issues across different sectors of society (Figure 2.18). The most vulnerable populations often experience the harshest consequences (Chapter 12). Three case studies demonstrate how initial direct climate impacts lead to indirect impacts that affect society and ecosystems in complex ways. Each relates to Nebraska. Case Study 3 discusses how climate change threatens national security. Case Study 4 highlights the cascading and surprising effects of hurricanes. Finally, Case Study 5 features wildfires in Nebraska.

Case studies

Case Study 1: Warming in the Arctic causes heat waves and cold snaps in Nebraska

A jet stream is a narrow band of strong winds in the upper atmosphere. Located between four and eight miles above the Earth's surface, they can reach more than 275 miles per hour. Jet streams exist in both the Northern and Southern hemispheres and are formed at the boundaries between warm air near the equator and cold air at the poles. The jet stream's location and seasonal movement drive weather patterns, shift storm tracks, and cause temperature extremes. For example, when the jet stream dips southward, it brings cold Arctic air into lower latitudes, causing winter cold snaps. When it moves northward, warm air from the tropics may flow into regions that typically experience cooler weather.

Research suggests climate change influences the behavior of jet streams (Francis & Vavrus, 2015). As the Arctic warms up to four times faster than the global average (Rantanen et al., 2022), temperature differences between the cold polar regions and warmer air to the south break down, leading to a weaker and more wavy jet stream (Figure 2.19). This can result in extreme

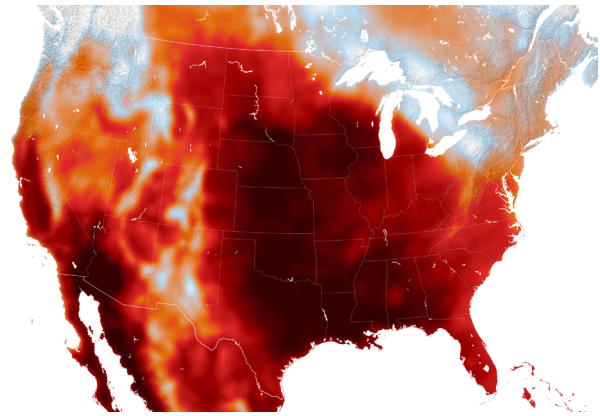


Figure 2.20. Air temperatures at 6.5 feet above the ground at approximately 3:00 p.m. Central Daylight Time on August 23, 2023. Image produced by combining satellite observations with temperatures predicted by a version of the Goddard Earth Observing System (GEOS) model. The darkest reds indicate areas where temperatures exceeded 104°F. (Source: Doermann, 2023, NASA Earth Observatory image by Lauren Dauphin, using GEOS-5 data from the Global Modeling and Assimilation Office at NASA GSFC)

weather events like the prolonged heat wave over North America in August 2023 (Figure 2.20) (Doermann, 2023). This heat wave shattered high-temperature records across the central U.S., affected millions of people, burned crops to a crisp, killed hundreds of cattle in Nebraska and Kansas, and strained utility providers, including record energy usage in Lincoln (Bernt, 2023;

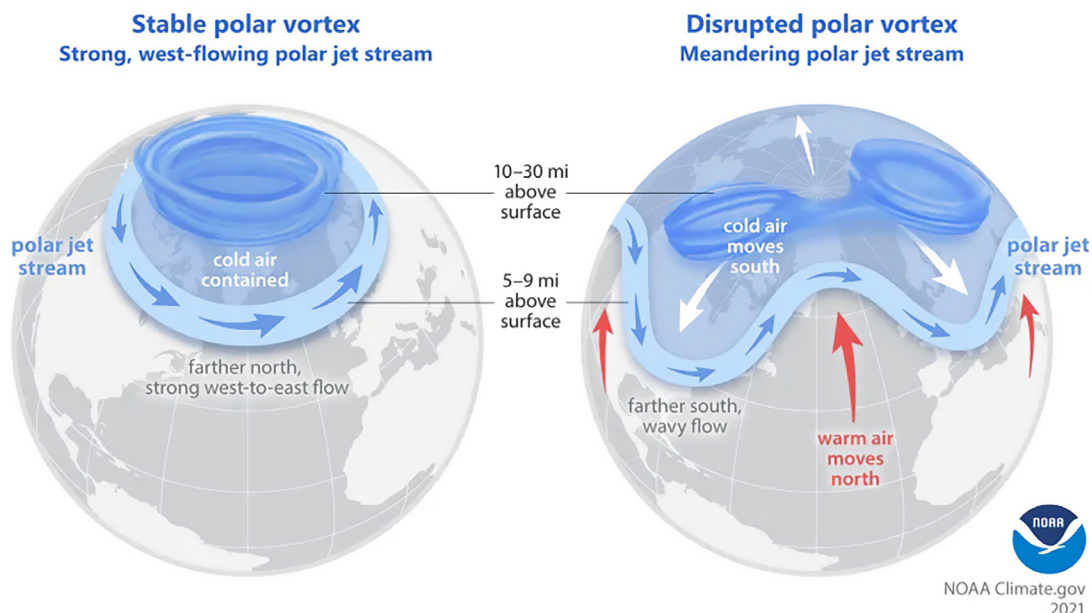


Figure 2.19. When the Arctic warms, the jet stream weakens and becomes more wavy, allowing cold Arctic air to move to the south and warm tropical air to move to the north. (Source: Lindsey, 2021)

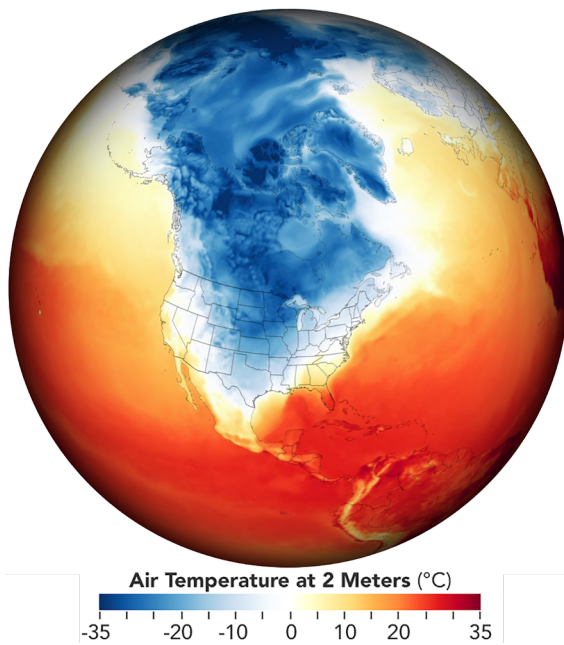


Figure 2.21. Record cold in mid-February 2021. (Source: NOAA NWS, 2021)

Hunt, 2023; NOAA NCEI, 2023; USDA FSA, 2023). In winter, a slower, wavier jet stream can cause severe winter weather outbreaks, such as the February 2021 Arctic Blast (Figure 2.21), which brought snow, ice, and extremely cold temperatures to the central U.S. Frigid Arctic air spilled southward over the U.S. as far as the Gulf Coast. Temperatures as much as 50°F below average strained the power grid and froze pipelines, leading millions to lose power for days, killing nearly 300 people, and costing an estimated \$27.2 billion. That week, cities in Nebraska, including Lincoln (-31°F), Valentine (-33°F), North Platte (-29°F), and Broken Bow (-33°F), set daily record low temperatures. The lowest temperature reported in the state was Imperial at -39°F, while the warmest was -13 °F in Elgin. The brutally cold temperatures, dangerous wind chills, and heavy snow created hardship for livestock and impacted residents as rolling blackouts were implemented in response to increased power demand (Beach, 2024a; Diaz, 2021; NSCO, 2021; NOAA NWS, 2021).

Case Study 2: Warming and cooling in the tropics affects Nebraska's temperature and precipitation.

Changes in sea surface temperatures in the tropical Pacific Ocean have far-reaching impacts on regional temperature and precipitation because they can change atmospheric circulation. The El Niño–Southern Oscillation (ENSO) is a natural climate phenomenon that occurs when the ocean and atmosphere work together to cause fluctuations in the global climate. ENSO consists of three phases: El Niño (warm phase), La Niña (cool phase), and ENSO-neutral. During an ENSO event, the surface temperature of the tropical Pacific Ocean warms (or cools) by 1.8°F to 5.4°F compared to normal phases, then swings back and forth every two to seven years on average. They vary in intensity and duration, impacting global circulation patterns such as the position of the Pacific jet stream, which serves as a large driver of weather across the United States (Figure 2.22).

The ENSO is linked to changes in temperature and precipitation across the globe. In general, ENSO-related temperature and precipitation impacts across

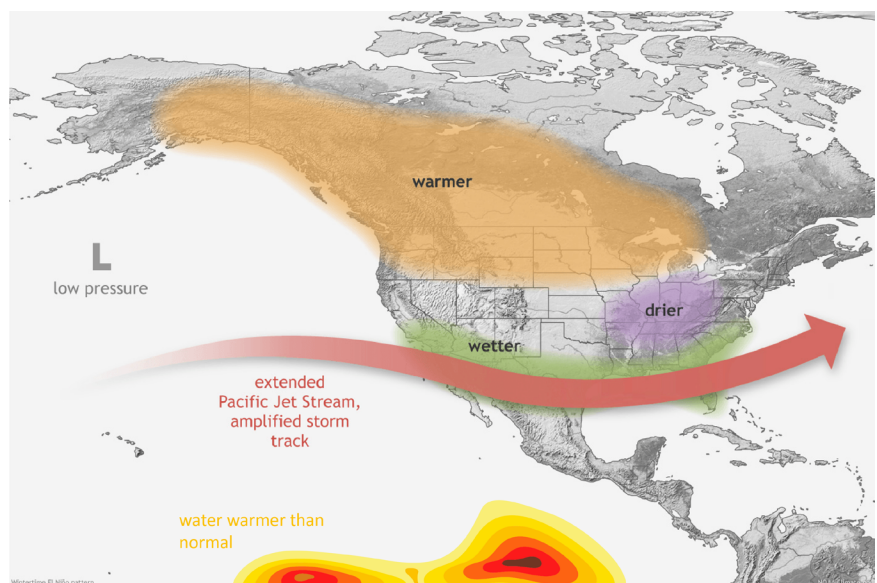


Figure 2.22. The typical impacts of El Niño and La Niña on U.S. winter weather. During El Niño, the jet stream tends to shift southward and steer storms across the southern third of North America. During La Niña, the jet usually shifts toward the poles. (Adapted from Climate.gov, 2016)

the United States are strongest during the cold half of the year (October through March). ENSO events heavily influence temperature and precipitation across the U.S.-affiliated Pacific islands and continental U.S. regions. During El Niño events, when tropical ocean temperatures are warmer than average, winter temperatures in Nebraska are typically warmer, and precipitation is higher than average (Figure 2.23) (NOAA NWS, n.d.). This tendency is stronger in the southern half of the state. During La Niña events, when tropical ocean temperatures are colder than average, winter temperatures in Nebraska are typically cooler, and precipitation is lower than average. (Lee et al., 2023; Zhang et al., 2024). El Niño and La Niña events are not simple mirror images of one another. They exhibit asymmetry in their spatial pattern, seasonal evolution, and duration (Cole et al., 2002). For example, El Niño events tend to be shorter-lived (about 9 to 2 months), while La Niña events can persist for 2 to 3 years.

Scientists have linked multiyear La Niña events to an increased probability of drought events in the Great Plains (Okumura et al., 2017; Zhang et al., 2024). For example, the historic 2012–13 drought (Figure 2.24) followed back-to-back La Niña events (NDMC, 2024; Rippey, 2015). Likewise, the 2022–23 drought followed nearly three consecutive years of La Niña events. Both droughts negatively affected agricultural productivity, leading to the worst and second-worst years in the state's wildfire history (Martens, 2017; Nebraska Farm Bureau, 2023; NFS, 2022; Rippey, 2015).

Other weather and climate events linked to ENSO include heavy rainfall events, the timing and magnitude of tornado season, and the frequency of hail events (Allen et al., 2015; Dommo et al., 2024). These links do not mean particular weather and climate events will occur with every ENSO event. Each event is somewhat different due to the tropical sea surface temperature pattern and strength, the shifting of the jet stream, and random climate variability. In other words, the effect of an ENSO phase on Nebraska is not absolute; instead, it increases the odds of particular weather and climate conditions.

In addition to changing regional weather and climate, El Niño events can increase global temperatures as warmer waters in the tropical Pacific Ocean release heat into the atmosphere, increasing global average

temperatures. Conversely, the La Niña phase of ENSO usually results in cooler global temperatures. Generally, the warmest year of any decade will be an El Niño year, and the coldest a La Niña one. For example, El Niño contributed to record-breaking global temperatures in 2023 (Blunden & Boyer, 2024). While La Niña tends to cool global temperatures, it is not enough to offset global warming. Evidence suggests that ENSO characteristics are changing, with climate change compounding its impacts (McPhaden et al., 2020). Instrumental and paleoclimate records show that the strength and frequency of high-magnitude strong ENSO events have increased since the 1950s and possibly as far back as 1400 (Lee et al., 2023). In recent La Niña years, global-averaged temperatures have been warmer than El Niño years in earlier decades (Allen et al., 2015). These findings suggest that scientists may need to revisit and revise the frameworks and models used to understand and predict ENSO and its impacts (Yu et al., 2017).

Case Study 3: Climate change risks to national security

The Arctic region provides a vivid example of the interconnection of climate change with society, even in places seemingly far away. Here, temperatures are increasing at a rate more than twice that of the rest of the world, glaciers and ice sheets are melting, and sea levels are rising. This rapidly changing region poses new risks for national security as the Arctic becomes warmer and increasingly navigable due to receding sea ice, adding to the military risks already present (Goodman, 2021). For example, China and Russia are already working together to develop Arctic shipping routes as Russia seeks to deliver more oil and gas to China amid Western sanctions (DOD, 2024a). The Pentagon also reports that China is looking to leverage “changing dynamics in the Arctic to pursue greater influence and access, take advantage of Arctic resources, and play a larger role in regional governance” (DOD, 2024b). China and Russia have also increased their military cooperation with joint exercises in the Arctic in 2022 and 2023. The increasing politicization of the Arctic with climate change introduces significant uncertainties to peace and stability in the region.

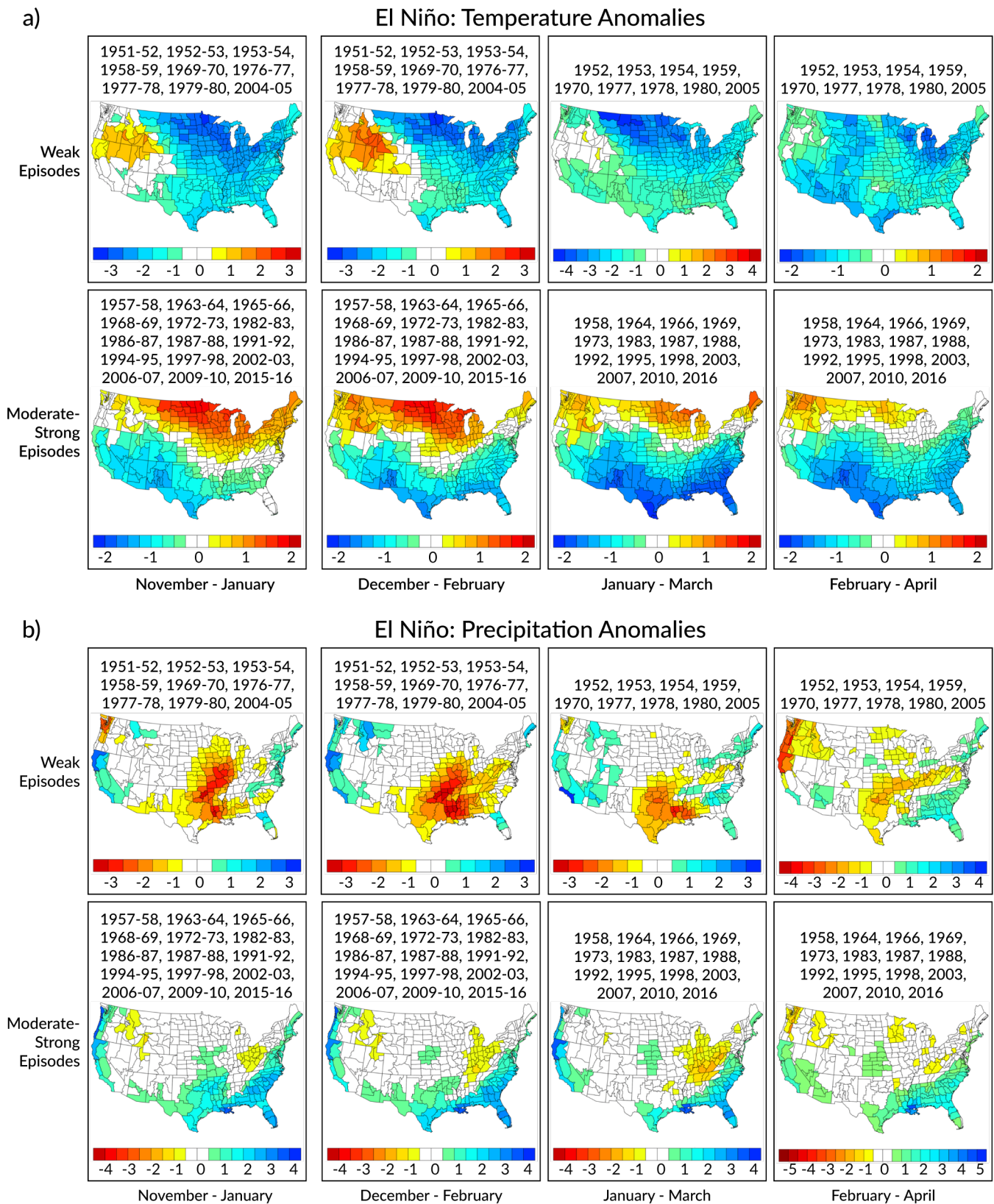


Figure 2.23. The three-month averaged (a) temperature and (b) precipitation anomalies from November through April for weak, moderate, and strong El Niño episodes since 1950. The anomalies are based on the official 1981–2010 normals. These composites are not intended to be a forecast of expected conditions; instead, they use historical data to highlight locations where ENSO can potentially impact temperature and precipitation. (Source: NOAA NWS, n.d., National Weather Service, Newport/Morehead City, NC, Forecast Office)

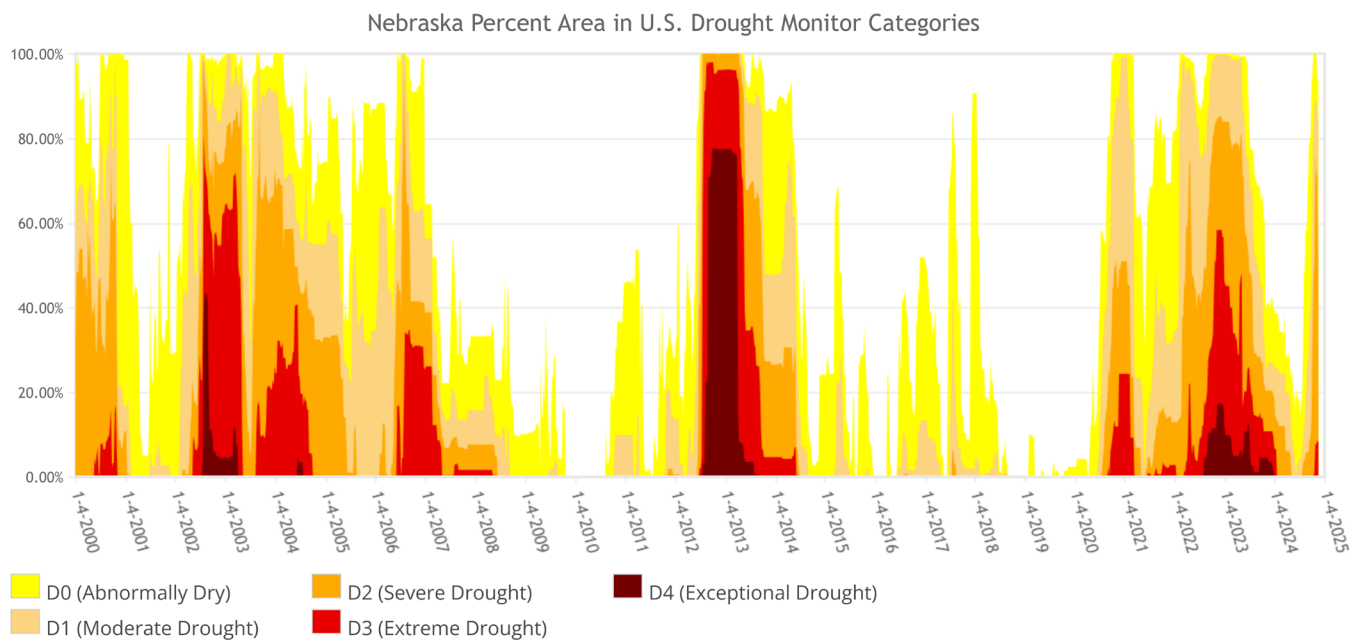


Figure 2.24. U.S. Drought Monitor Time Series. (Source: NDMC, 2024)

U.S. military forces must be prepared to respond in this remote region. Home to Offutt Air Force Base, with over 6,500 active-duty personnel and over 8,500 National Guard and reserve members at units around the state (Military One Source, 2024), Nebraska would likely feel the consequences of increased tensions. Military personnel from Offutt and from National Guard units in the state train in the Arctic to test readiness in the event of an emergency or threat (Bingaman, 2007; Tourtellotte, 2023). Research documents the impacts on the health and well-being of military personnel and their families as well as the economy of surrounding communities, including sectors such as food, housing, retail, transportation, health care, and entertainment (Board on the Health of Select Populations et al., 2013; Gregory, 2008; Kriesel & Gilbreath, 1994).

Responding to climate crises redirects time, attention, and resources away from the military. For example, in the past two years alone, U.S. troops have deployed domestically more than 70 times in response to climate-related hazards, including fighting fires, rescuing citizens from floods, or delivering water (Sikorsky, 2024). The U.S. Department of Defense also noted, "The number of personnel days the National Guard spent on firefighting increased from 14,000 in the fiscal year 2016 to 176,000 days in fiscal 2021. . . . That is more than

twelve-fold in just five years" (Garamone, 2023). This demand is almost certain to grow as temperatures rise.

Additionally, climate change directly affects the military's critical infrastructure (DOD, 2024c). In 2019, Offutt Air Force Base was hit by a devastating flood, crippling parts of the base, displacing personnel, and causing millions of dollars in damage (Losey, 2020). This marked the second time in less than 10 years (also in 2011) that flooding threatened base operations (Hasemyer, 2019). While climate change's exact role in the 2019 Nebraska floods is not clear, scientists worldwide agree that the science is clear: climate change is making natural disasters more frequent, stronger, and longer (IPCC, 2023a).

As the U.S. confronts more frequent and intense climate-driven threats at home and abroad, damage and disruptions to military facilities and capabilities have implications for the readiness of our armed forces (NATO, 2023). Attention is diverted away from readiness and preparation for future threats and is instead focused on dealing with urgent crises related to extreme weather and climate events (Garamone, 2023). In addition, military forces will need to operate in more extreme climate conditions, facing demanding operational requirements (NATO, 2023).

Case Study 4: The widespread and long-lasting toll of hurricanes

When a hurricane makes landfall, heavy rainfall, strong winds, storm surge, and flooding cause tremendous damage to coastal communities; trees and powerlines are downed; buildings, roads, and bridges are destroyed; beaches are eroded; and injuries and loss of life occur. Since 1980, 66 hurricanes have impacted the U.S., costing an estimated \$1.5 trillion in damages and over 7,000 deaths. Impacts cascade throughout communities, ripple out to a larger geographic area, and linger long after the event (NOAA NCEI, 2024c).

When hurricanes cause transportation systems to collapse—due to port closures, impassable roadways, and flight cancellations—so do supply chains (Kim & Bui, 2019). Floods in North Carolina caused by Hurricane Helene in September 2024 damaged a facility that produces about 60% of the intravenous (IV) fluids in the U.S. (Fortiér, 2024). The company had to stop production, which led to shortages. Hospitals across the country were forced to ration supplies and cancel surgeries. At Nebraska Medicine, doctors used about half of the IV fluid they would typically use, while rural hospitals in Nebraska were forced to cancel surgeries (Parsons, 2024; Ricketts, 2024).

Hurricanes Katrina and Rita in 2005 severely damaged the Gulf of Mexico region, destroying and damaging oil and gas production facilities in the Gulf of Mexico. The hurricanes caused a complete shutdown of oil production and 80% of gas production in the gulf. Repairing the platforms, refineries, and pipelines took weeks to months. The oil and gas industry suffered huge losses, and economic repercussions were felt worldwide (Cruz & Krausmann, 2008). Significant price increases triggered a public outcry over price gouging. In Nebraska, gas prices rose more than 50 cents per gallon the week after Hurricane Katrina; only five states and the District of Columbia had higher prices (Jenkins, 2005).

When Hurricane Katrina made landfall in New Orleans, floodwaters submerged 80% of the city, and catastrophic damage occurred along the Gulf Coast states of Alabama, Mississippi, and Louisiana. As a

result, over 1.5 million people were abruptly displaced from their homes (Serraglio & Adaawen, 2023). People fled to every state in the country, including 547 residents who moved to Nebraska (Figure 2.25) (Katrina +10, 2015). About one-third of evacuees did not return to the areas where they were living before the storm. More recently, in the aftermath of Hurricane Maria in 2017, an estimated 130,000 people left the island and U.S. territory of Puerto Rico (Acosta et al., 2020). Nebraska once again received people displaced by the hurricane damage. While data is still being analyzed for September 2024's Hurricane Helene, which left a trail of destruction across Florida, Georgia, the Carolinas, and Tennessee, tens of thousands of people were displaced. They struggled to access food, power, and water (White House, 2004). Sometimes, an inability to recover and rebuild turns a temporary displacement into a permanent move (Serraglio & Adaawen, 2023).

When disasters like Hurricane Helene strike, Nebraskans answer the call for help. In 2024, Nebraskans' hurricane response efforts included military deployments, search and rescue teams, emergency response communications teams, utility restoration crews, food distribution teams, and faculty and student volunteers (10-11 Now, 2024; Gonzalez, 2024a; Jones, 2024.; LES, 2024a; NEMA, 2024; Office of the Governor, 2024).

As the climate warms, Atlantic hurricane activity is changing. Higher ocean temperatures provide more energy for storms, making them stronger. Observations show more hurricane activity, stronger storms, faster intensification, higher rainfall amounts, and bigger storm surges (Gilford et al., 2024; Marvel et al., 2023; Reed & Wehner, 2023; K. Reed et al., 2022). Warmer ocean temperatures fuel stronger winds and heavier rainfall in storms, leading to more destruction when these storms make landfall. Climate change is also raising the sea level (Figure 2.25) by more than eight inches along the Gulf and East Coasts. Combined with stronger and larger storms, it can lead to more catastrophic storm surges. These effects are particularly evident in the Atlantic basin. Research shows that human-caused climate change intensified the maximum wind speeds of roughly 80% of hurricanes between 2019 and 2023, increasing their intensity by an average of 18 miles per hour (Figure 2.26) (Climate Central, 2024; Gilford et al., 2024).



Figure 2.25. Relative sea level change along U.S. coasts, 1960–2021. (Source: Congressional Budget Office, 2024)

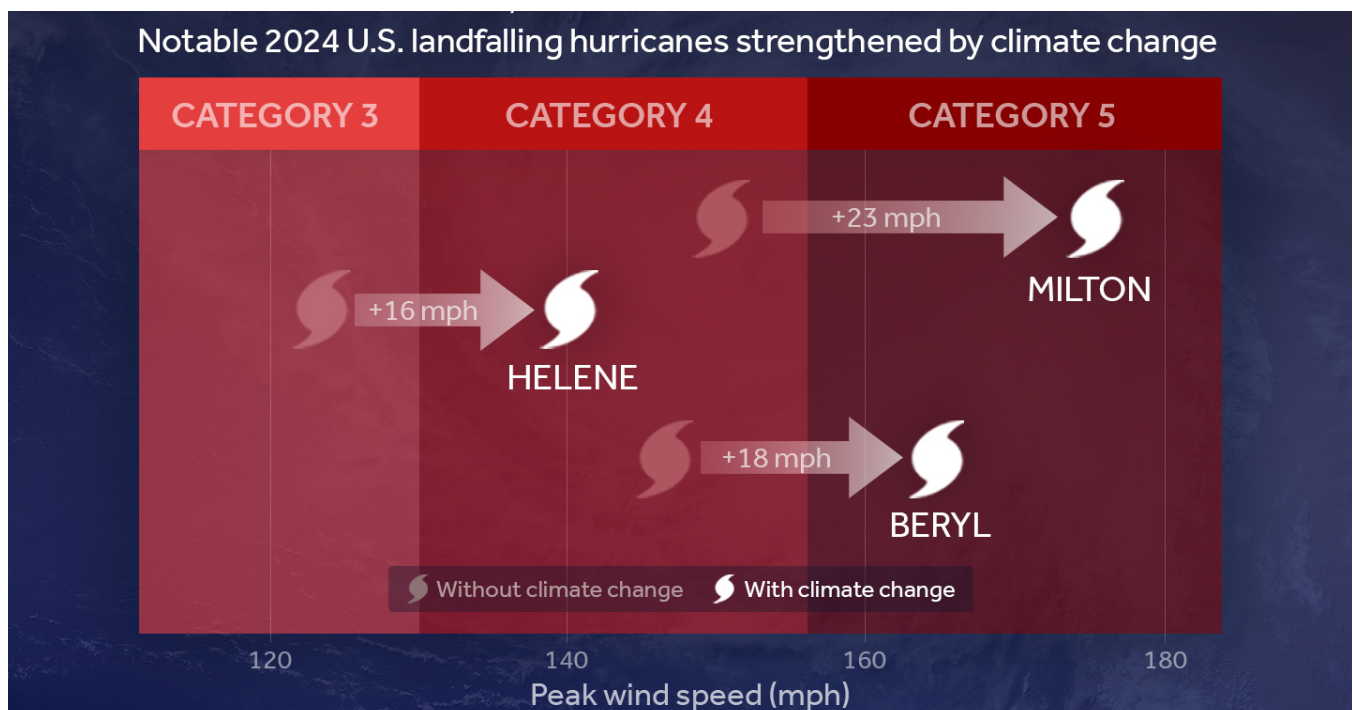


Figure 2.26. Change in peak wind speed and storm category due to climate-change-driven ocean-warming. (Source: Climate Central, 2024, <http://creativecommons.org/licenses/by/4.0>)



Nebraska National Forest after the October 2022 Bovee Wildfire. Photo courtesy: Marek Ulasz, Adobe Stock.

As climate change increases the threat from hurricanes, people across the U.S. must change how they perceive and prepare for storms. When storms intensify rapidly, communicating with, preparing for, and evacuating communities in time can be difficult. Additionally, as the climate continues to change and natural disasters grow, insurance companies are increasing the costs of policies, declining to renew policies, or exiting the market altogether (Congressional Budget Office, 2024).

Case Study 5: Nebraska wildfires

We do not have to look outside Nebraska to see how climate events can cascade through society. In 2012, 500,000 acres burned in Nebraska, making it the worst fire season in the state's recorded history (NEMA, 2012). This fire season coincided with the most severe summer drought in the observational record for that region (Hoerling et al., 2014). The hot, dry summer combined with high winds and low humidity led to an abundance of dry fuel in the form of parched cropland, prairies, and ponderosa pine stands. Firefighting included equipment from the Nebraska Army National Guard, mutual aid from more than 100 volunteer fire departments, and the response of hundreds of staff members from almost a dozen state agencies, with costs exceeding \$12 million (NEMA, 2012). These fires reduced air quality, burned dozens of structures, destroyed power lines, changed the landscape, strained the resources

of private landowners and rural fire departments, and highlighted the need for upgraded firefighting equipment (Stohs-Krause, 2012). Scientists partially attribute the unusually high temperatures (resulting in dry soil moisture) and vegetation accompanying this fire season to anthropogenic climate change (Diffenbaugh & Scherer, 2013). Nebraska's extraordinary 2012 fire season prompted changes in policy, such as the Nebraska Wildfire Control Act (Nebraska Revised Statutes, 2013), which increased the capacity of the state, thereby helping to reduce risks and enhancing training and management efforts. In 2022, Nebraska experienced its second-worst fire season in decades, with over 250,000 acres burned (NFS, 2022). Again, the fire season coincided with record-breaking heat, drought conditions, and low soil moisture (Christian et al., 2023). Notably included were the scorching of nearly a quarter of Nebraska's National Forest, the death of a volunteer firefighter, the destruction of the State 4-H Camp and nearby Scott Lookout Tower, the temporary closure of Nebraska Highway 2, and the evacuation of a nearby community (Vaughan, 2022). Studies have found that climate change has increased wildfire season length and frequency and burned areas due to warmer springs, longer summer dry seasons, and drier soils and vegetation (Ostoja et al., 2023; Westerling, 2016). Similarly, increases in climate change-driven fire season frequency, extent, and severity are expected to continue (Leung, 2023).