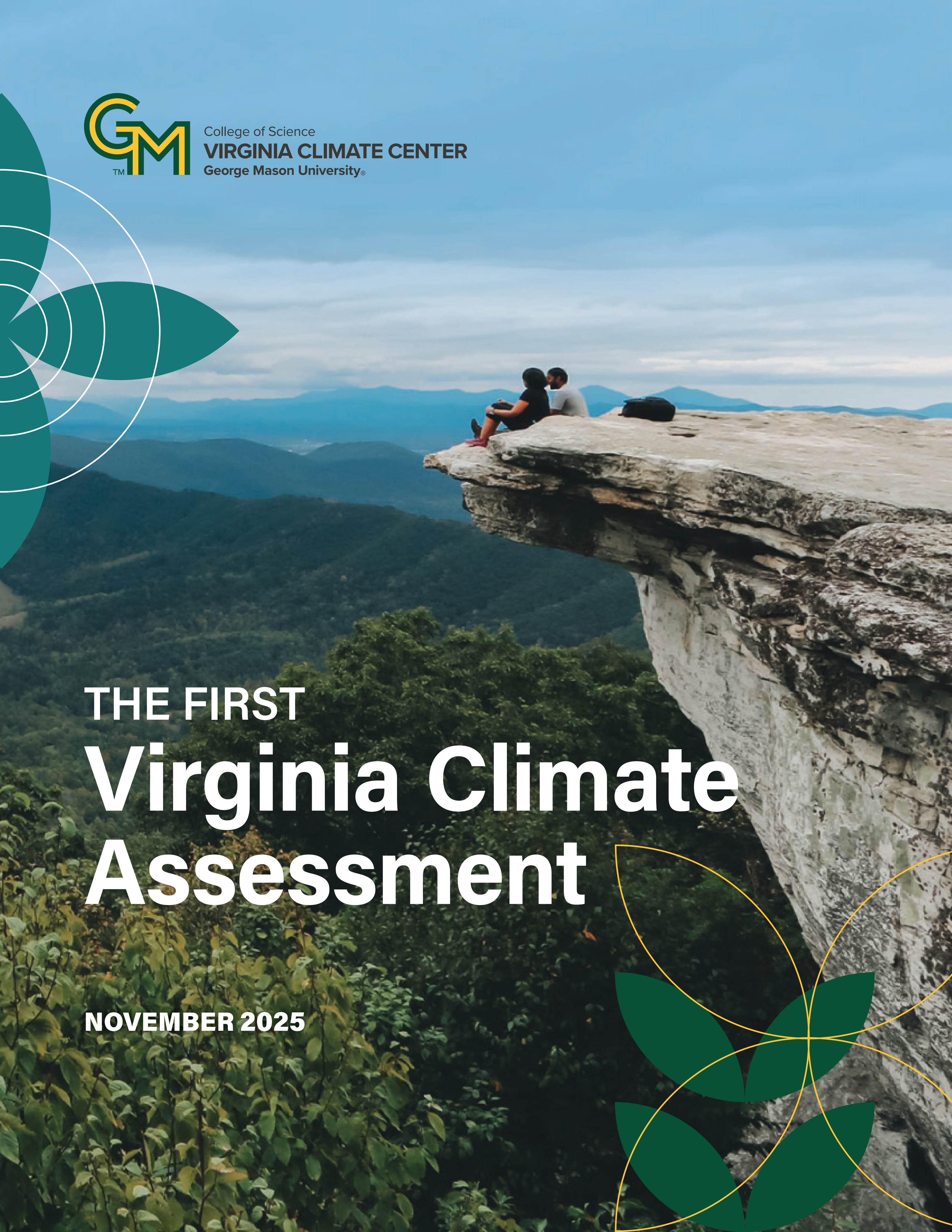

College of Science
VIRGINIA CLIMATE CENTER
George Mason University

THE FIRST

Virginia Climate Assessment

NOVEMBER 2025

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SECTION 1

Executive Summary

What is the VCA?

This report marks the inaugural comprehensive assessment of climate conditions across the Commonwealth of Virginia. While Virginia's diverse weather and climate patterns have been examined in both local and broader national and global contexts, no prior effort has synthesized the wealth of scholarly research specific to Virginia into a unified resource.

The Virginia Climate Assessment provides a science-based evaluation of the ways past, current, and anticipated climates have and will impact Virginia and its people. As the first report of its kind for the state, it provides a collection of evidence-based key messages that have been prepared and extensively reviewed by technical and scientific experts across Virginia and beyond. It is expected to be the first in a series of such assessments, establishing a baseline against which future changes and impacts can be measured and understood, and adaptation effectiveness and resilience can be evaluated.

About Virginia:

Virginia is changing, and so are the challenges facing its communities. Since the mid 1970s, Virginia's urban areas have grown substantially, and communities across the Commonwealth have become more diverse. At the same time, Virginia's economy has shifted from agriculture and manufacturing to include technology, defense, education, and service industries.

These changes bring new opportunities, but also new vulnerabilities, especially as climate impacts become more severe: Rising temperatures, heavier rainfall, coastal erosion, and stronger storms are already affecting infrastructure, housing, transportation, and public services.

State Climate Assessments play a critical role in preparing for these risks. This baseline evaluation of Virginia's climate can ensure that Virginia's climate history can help inform decisions made today about land use, infrastructure, and development. By integrating climate pasts and evidence-based projections into planning and implementation, communities can build resilience, protect public investments, and ensure long-term safety and economic stability.

Virginia's climate has changed and is still changing, but the impacts appear differently across the state (2A)

Virginia is a climatically diverse state comprised of 27 different ecoregions and 6 climate divisions that span across state and county borders. These ecoregions span plains, mountains, and coasts. As a result, changes in temperature, humidity, and wind produce different impacts on these regions simultaneously, emphasizing the importance of local and regional data collection and strategic planning. In fact, Thomas Jefferson started the practice of measuring climate locally in 1776. His meteorological journal has provided evidence of significant warming (about 4.5°C or 8°F) in Monticello since 1776.

Virginia today is different from the Virginia Thomas Jefferson knew. The long-term view sets the stage for understanding the scale of climate change and contextualizing the changes in temperature, precipitation, and sea level rise that this report identifies now and anticipates in the future. Overall, the data collected over these long periods of time shows that Virginia has become warmer and wetter, but the scale and consequences of this trend vary from place to place and season to season due to the diversity of Virginia's climate. Highlights of the findings of this Assessment are given below, including the chapter numbers in which they are explained.

Large temperature changes (3A) and increasing extreme heat events (2B) pose increased health risks, labor disruptions, and crop stress

Virginia is experiencing larger temperature swings throughout each month. Last January (2024), for example, Charlottesville residents experienced a daytime high of 79°F (26°C) and a daytime high of 28°F (-2°C) within 11 days, the largest January range on record. Rapid and extreme temperature changes can adversely affect Virginia's major economic outputs, especially related to crop production and livestock.

As extreme heat events occur more frequently, adverse health effects, infrastructure failure, and ecosystem stress also become more common. The health risks increase the longer someone spends in direct sunlight and higher humidity, as it is more challenging for the body to cool itself as moisture in the air increases. When heat waves increase in duration, intensity, and frequency, disruptions to productivity, construction, recreation, and transportation will become more costly and more common.

Virginia is experiencing wetter conditions overall, with more frequent and intense precipitation events (2C)

Severe weather events are increasing in frequency and duration in Virginia, causing heavier precipitation (rain, snow, hail). Spring and Fall are becoming wetter, but the number of rainy days remains the same. This signals that rainfall is heavier on those rainy days, increasing the likelihood of flash floods and standing water in low-lying roadways, fields and yards. This is leading to transportation disruptions, diminished crop yields, and increased pest presence. Increasing variability in rainfall may require costly public investments and result in the loss of property as river-based water storage needs to be augmented with new reservoirs.

In the drier seasons of Summer and Winter, in addition to rain- and snowmelt-driven floods that continue to be a serious hazard, quick-onset and short-term flash droughts—droughts that occur quickly and end quickly—are becoming increasingly frequent. Owing to limited monitoring and prediction capabilities, flash droughts are particularly difficult to respond to, providing new challenges to unprepared regions. In Northern Virginia, drought-induced disruptions to water availability in the Potomac River could reduce economic output by more than $4.5 billion in just one month (see Traceable Accounts for KM3 in chapter 3C).

Virginia is experiencing a faster sea level rise than the global rate due to the combination of land erosion and rising waters (2D)

Sea level rise remains one of the most pressing issues for coastal Virginia. Sea level rise can adversely affect key economic and cultural assets, including the Chesapeake ecosystem. However, these ecological impacts also range further inland as evidence of salinity changes can be seen in the York River that are migrating inland towards the river source.

All of Virginia's people, places, businesses, and ecosystems are vulnerable to climate change (3D, 4)

Extreme weather and weather-related events, including hail, floods, heatwaves, and wildfires, are made worse by the increasing duration, frequency, and severity of both too much and too little precipitation, and bigger temperature swings. These hazards pose serious threats to the economy, property, natural resources, and ways of living in the Commonwealth. When combined with factors such as Virginia's aging infrastructure and rising sea levels, impacts such as road closures and power blackouts can quickly overwhelm emergency responders and turn even moderate weather hazards into disasters. Virginia's ability to prevent and respond to potential negative outcomes and future risks depends on its ability and willingness to invest in infrastructure, nature-based solutions, monitoring and communication, and coordinated action.

Challenges & future needs:

The successful completion of the *Virginia Climate Assessment* was dependent upon the generosity of talented researchers across the Commonwealth and beyond, voluntarily writing and reviewing this document. Topics that appeared in this assessment were chosen based on the most readily available evidence and subject matter expertise.

To enhance the value of future assessments, it will be necessary to routinely collect and analyze data at the hyper-local (municipal) level, which will require a higher level of coordination and cooperation among entities within Virginia. We anticipate that future *Virginia Climate Assessments* will include more comprehensive insights on sector-specific impacts (data centers, recreation, and food production), topic-specific consequences (ticks and vector-borne diseases, wildfires, blackouts), and feature areas with high social, economic, and health vulnerabilities that are often not well-represented in readily available data repositories.

Virginia is taking important steps in becoming more resilient to climate change, including the recent establishment of the Virginia State Resilience Office, and the enormous efforts led by community groups, universities, and non-profits across the Commonwealth. Together, we work to ensure all Virginians, present and future, can mutually flourish alongside the rich natural resources for generations to come.

SECTION 1

Introduction to the Virginia Climate Assessment

Virginia's climate is shaped by its unique geography spanning coastal plains, rolling piedmont plateaus, and mountainous terrain. This diversity contributes to a wide range of weather phenomena and long-term climate variability across the state. Understanding these historical trends, current conditions, and projected changes is essential for informing policy, guiding infrastructure planning, and supporting community resilience in the face of a changing climate.

The Commonwealth is home to a rapidly growing population of increasingly diverse experiences. The populations in Virginia's urban centers have grown as much as fourfold over the past half century. Likewise, Virginia's economy has undergone significant transformation—from its historical reliance on agriculture and manufacturing to a more diversified portfolio that includes technology, defense, education, tourism, and service industries. These changes have implications for many aspects of Virginians' lives that intersect with climate-related risks and opportunities.

Like the rest of the United States and the world, Virginia is experiencing a rapidly changing climate that impacts local communities, the economy, and ecosystems. Increases in flooding, extreme heat, coastal erosion and saltwater intrusion, and severe storms pose risks to transportation networks, energy systems, water resources, housing, and critical infrastructure. What we build and plan today must not only be resilient to current climate conditions but also be designed to withstand the evolving impacts of climate change over the coming decades. Integrating climate projections into infrastructure design and land-use planning is essential to ensure long-term safety, sustainability, and economic viability.

A state-level climate assessment provides essential, localized insights that support evidence-based decision-making across Virginia's diverse regions. By translating broad climate science into actionable information, it enables policymakers, community members, and businesses to prepare for region-specific impacts. Unlike national or global reports, this assessment captures Virginia's unique geographic, economic, and social vulnerabilities, informing strategies for infrastructure resilience, agricultural adaptation, public health, and economic development. Establishing a baseline of current conditions and future projections lends scientific credibility to resilience investments, regulatory planning, and coordinated adaptation efforts, which are increasingly constrained by exposure to both typical and extreme weather conditions. It also informs state leadership in addressing climate change, fostering stakeholder engagement, and guiding policies that protect both present and future generations.

About This Assessment

This *Virginia Climate Assessment* is a summary of the peer-reviewed literature compiled by subject matter experts. It is intended to provide a clear, accessible synthesis of current scientific understanding of Virginia's climate, drawing from peer-reviewed literature, government data sources, and expert analysis. It is also intended to serve as a resource for decision-makers, researchers, educators, and the public, offering insights into historical trends, current conditions, and projected changes.

Future assessments will build upon this foundation by incorporating finer-scale geographic detail, expanding coverage of climate impacts across sectors such as agriculture, public health, transportation, ecosystems, and more comprehensive review of natural disasters including wildfires and landslides, all while integrating stakeholder input to ensure relevance and applicability. By establishing a consistent and evolving framework for future climate assessments, the Commonwealth can better prepare for and respond to the challenges and opportunities presented by a changing climate.

This report provides a baseline evaluation of Virginia's current climate, recent trends, and future projections. It focuses on key climate-related risks, including:

- **Heat-related risks** associated with upward temperature trends and increased drought frequency
- **Flood risk** influenced by changing precipitation patterns
- **Flooding, erosion, and saltwater intrusion risks** in coastal areas and tidal rivers connected to the Chesapeake Bay influenced by sea level rise
- **Compound hazards**, such as concurrent heatwaves and heavy rainfall events
- **Economic exposure** of Virginia's communities to climate and weather extremes

Note that exposure is only one component of vulnerability to the above-mentioned risks; later Assessments will address the other components: sensitivity and adaptive capacity.

The *Virginia Climate Assessment* presents statewide and regional insights, organized by the six NOAA-defined Climate Divisions: Tidewater, Eastern Piedmont, Western Piedmont, Southwestern Mountain, Central Mountain, and Northern, as described below. While this report does not include fine-scale spatial analysis, future assessments will enhance geographic resolution. Familiar regional terms—such as "Valley and Ridge" and "Piedmont"—are used where appropriate to enhance clarity and relevance.

Figure 1

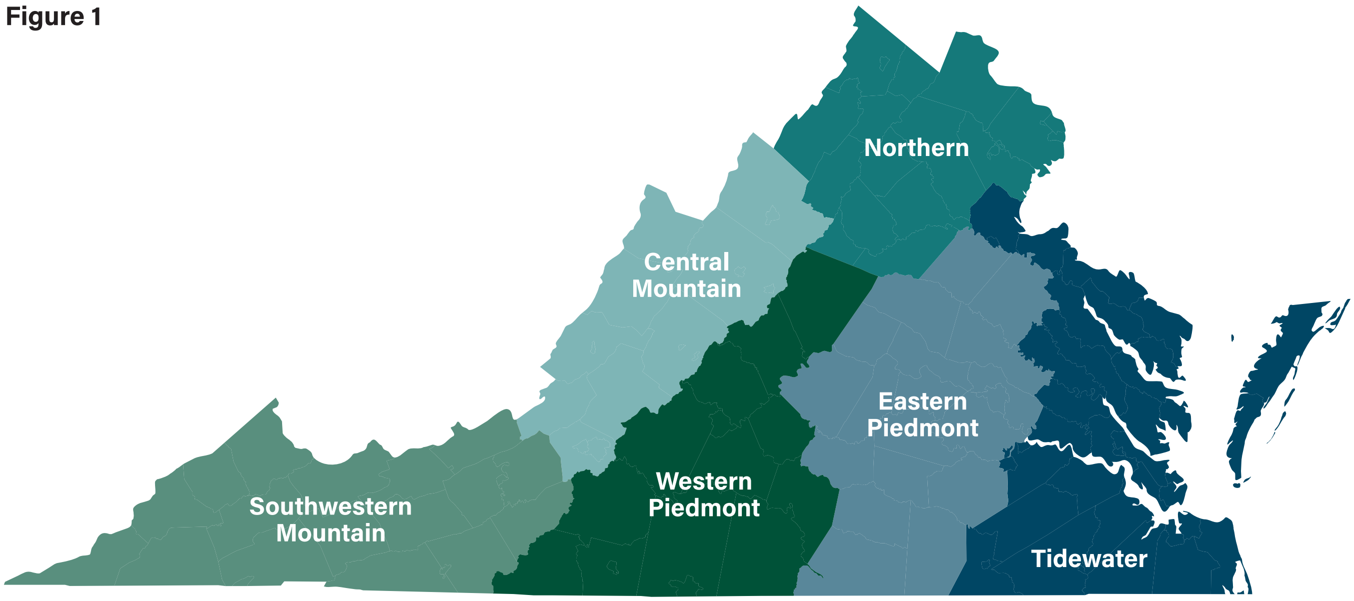


Figure 1: The Climate divisions of Virginia, as defined by the National Oceanic and Atmospheric Administration (https://www.ncei.noaa.gov/access/monitoring/dyk/us-climate-divisions).

Key Messages: Key Messages are provided in each section that distill the most critical findings of this assessment based on expert judgment and synthesis of peer-reviewed research. Each message is grounded in scientific evidence, policy-relevant but not policy-prescriptive, and focused on climate impacts and risks. Supporting text provides context, discusses implications, and offers illustrative examples to enhance understanding and accessibility.

Traceable Accounts: Each Key Message is accompanied by a Traceable Account, detailing the development of the message including supporting scientific evidence, the process and rationale for findings, expert insights addressing confidence in the Key Messages, and citations of peer-reviewed literature. The use of Traceable Accounts follows the practice used in National Climate Assessments, providing information about the state of the science, and, where applicable, identifying research gaps.

Confidence: Authors of this report have estimated their confidence in the findings based on the type, amount, quality, strength, and consistency of evidence, as well as the degree of agreement across scientific information sources. The confidence estimates follow the practice used in National Climate Assessments, with a scale of confidence gradations as follows: "*very high confidence*"; "*high confidence*"; "*medium confidence*"; "*low confidence*"; and "*very low confidence*".

Review: This Assessment was thoroughly reviewed by an independent team of experts.

How to Use this Document

The *Virginia Climate Assessment* is intended to be used to inform climate adaptation plans, resilience strategies, and policy decisions, and provide evidence for developing targeted responses to climate impacts. Key Messages can be used to identify areas of critical need for strategic planning, provide supporting evidence for budget proposals, and outline potential directions for policy development or climate action planning.

We encourage readers to further consider them for talking points, educational outreach resources, and as a starting point for identifying key issues that will impact Commonwealth residents and the economy. For users who need detailed technical information or statistics, Traceable Accounts in each chapter provide reference material to support each Key Message.

While researchers, educators, policymakers, and planners will all likely find different components of this report to be of value to their work, this report is produced for all Virginians to better understand some of the ways their home is changing.

Basics about Virginia

Geography: Virginia features a mix of forested areas, agricultural lands, urban development, wetlands, and coastal zones. Forests cover approximately 60% of the state, while agricultural land and urban areas are concentrated in the Piedmont and coastal regions. Elevations range from sea level along the Atlantic coast and lower Chesapeake Bay to over 5,700 feet in the mountains. The state can be divided into six climatically similar divisions listed above. Each climate division has relatively homogeneous climate characteristics (average temperature, average precipitation, days of sunshine, etc.) and provides a representation of the state's climate that reduces the noise of individual meteorological station data.

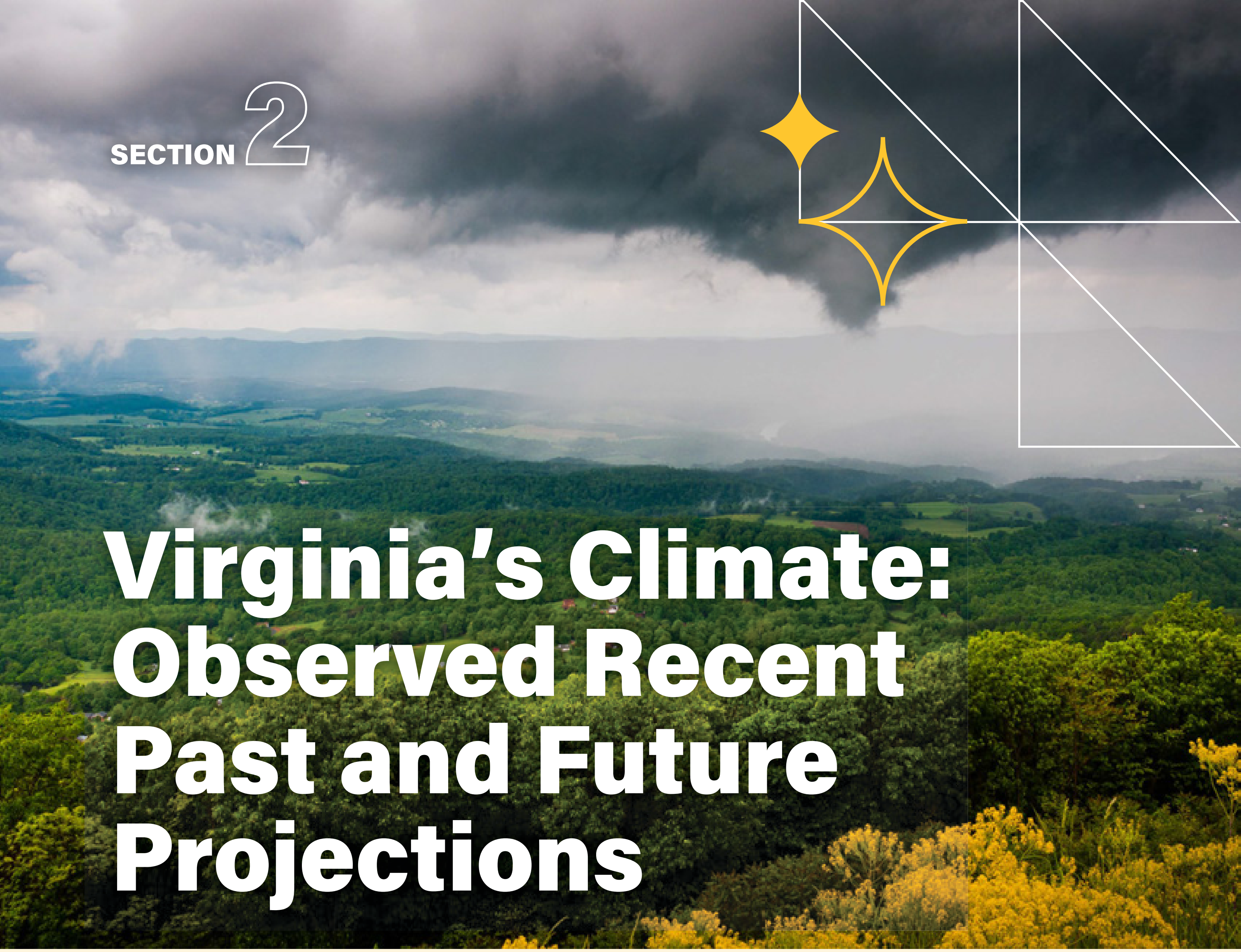
Population: Virginia has a population of over 8.7 million, with continued growth driven by urban expansion and economic diversification. The population is increasingly diverse, with significant demographic shifts influencing regional planning and climate vulnerability.

Major Cities: Key urban centers include Richmond (the capital); the Hampton Roads area including Virginia Beach, Norfolk, and Chesapeake; the urban conglomerate in northern Virginia including Arlington, Alexandria, and Fairfax; south-central cities including Danville; and Roanoke. These cities face varied climate risks, from coastal flooding to urban heat islands.

Agricultural Features: Virginia's growing seasons vary by region, with USDA hardiness zones ranging from 5b in the mountains to 8b in the southeast. The state supports diverse agricultural production, including soybeans, corn, cattle, poultry, and specialty crops, all sensitive to climate variability and extremes.

Social Vulnerability: Social vulnerability to climate change in Virginia is shaped by a combination of geographic exposure, socioeconomic disparities, and historical inequities. Coastal communities such as Norfolk and Virginia Beach face heightened risks from sea-level rise and recurrent flooding, with over 100,000 residents living in homes less than five feet above the high tide line. In Norfolk, historical practices have contributed to disproportionate climate impacts on low-income and marginalized populations, limiting access to resilient infrastructure and adaptation resources. Urban areas such as Richmond have documented uneven outcomes in exposures to hazards like heat, prompting the development of tools like the Climate Equity Index to identify and address neighborhood-level vulnerabilities. Additionally, rural counties reliant on agriculture—Virginia's largest industry—are increasingly threatened by drought, extreme heat, and invasive pests, with half of these counties facing water shortages that jeopardize $472 million in crop production. These examples underscore the need for inclusive, equity-centered climate adaptation strategies that protect the most vulnerable and enable all Virginians to thrive.

SECTION 2



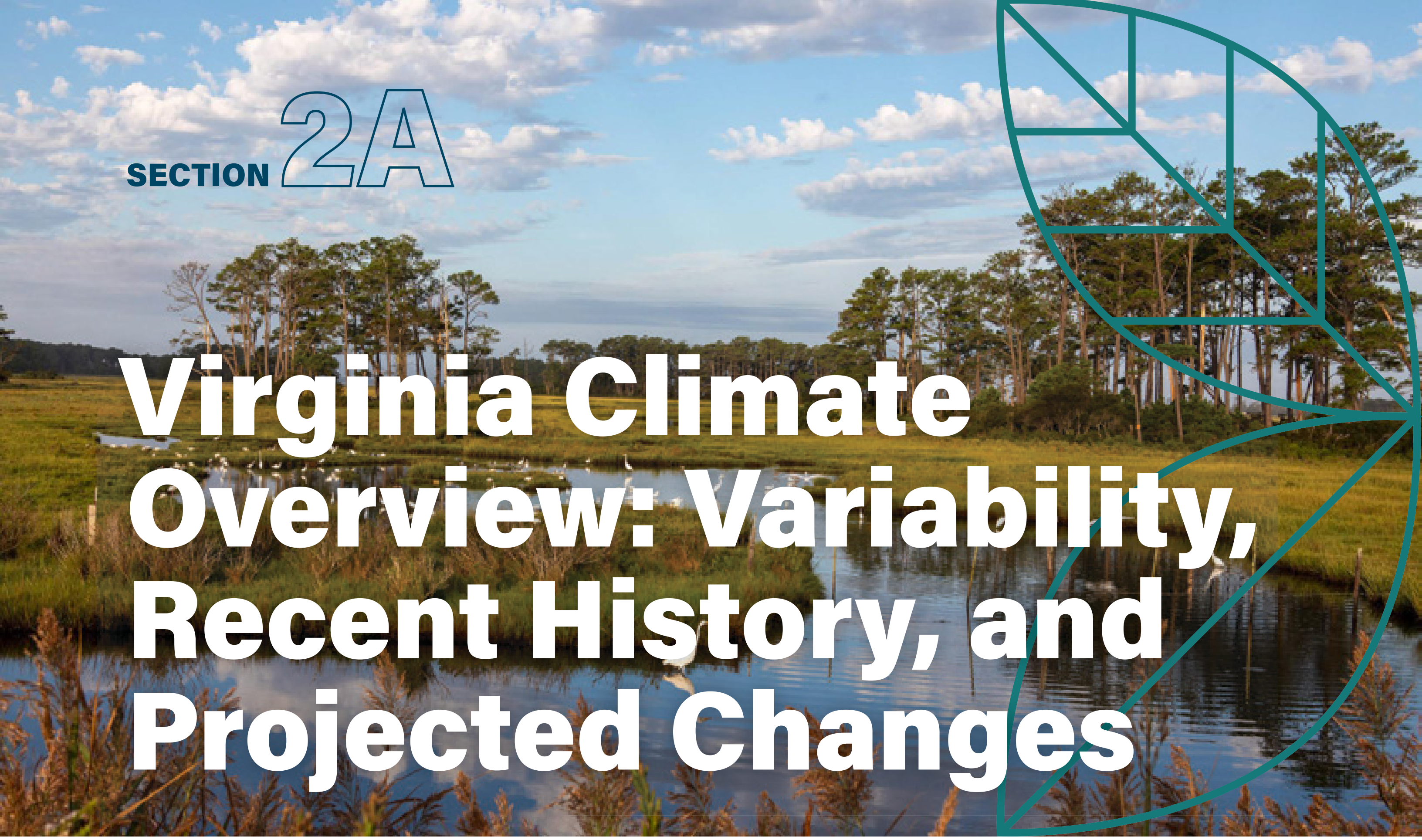
Virginia's Climate: Observed Recent Past and Future Projections

CHAPTER 2A
Virginia Climate Overview: Variability, Recent History, and Projected Changes

CHAPTER 2B
Temperature

CHAPTER 2C
Precipitation

CHAPTER 2D
Sea Level



SECTION 2A

Virginia Climate Overview: Variability, Recent History, and Projected Changes

KEY MESSAGES

1. Virginia's climate is shaped by weather patterns stemming from higher and lower latitudes, while regional variation reflects topography and coastal proximity (*high confidence*).

2. The Virginia climate has become warmer (*very high confidence*) and wetter (*medium confidence*) in recent decades, with greater precipitation extremes (*high confidence*) and more frequent tidal flooding (*very high confidence*) along the Atlantic coast.

3. Climate projections indicate continued warming (*very high confidence*) and wetting (*medium confidence*) for Virginia through the middle to late 21st century, with chronic tidal flooding along the Atlantic coast (*very high confidence*).

Key Message 1: Virginia's climate is shaped by weather patterns stemming from higher and lower latitudes, while regional variation reflects topography and coastal proximity (*high confidence*).

The humid subtropical climate of Virginia is governed by two primary seasonal drivers. The cool season climate reflects the southward migration of the polar jet stream, which relates to air temperature and the tracks of storms, including impactful coastal storms. Conversely, the warm season climate is an expression of circulation around subtropical high pressure over the Atlantic Ocean ("Bermuda High"), which transports humidity and occasional tropical weather systems into the region.

Regionally, climate across Virginia is characterized by a distinct geographical transition from cooler and drier in the mountainous west, to warmer and more humid across the eastern coastal plain (Figure 2). This pattern is modified in larger urban centers, which experience elevated temperatures due to the heat retention properties of the built environment, a phenomenon known as the urban heat island effect.

Interannual variability in Virginia's climate is associated with large-scale natural climate fluctuations. Cool season variability correlates with the El Niño-Southern Oscillation (ENSO) phenomenon, with cooler (warmer) and wetter (drier) conditions during El Niño (La Niña), as well as with the North Atlantic Oscillation (NAO), for which it is warmer (cooler) during the positive (negative) phase. Variability in Virginia's warm season climate fluctuates with the position and intensity of the Atlantic Bermuda High.

Figure 2

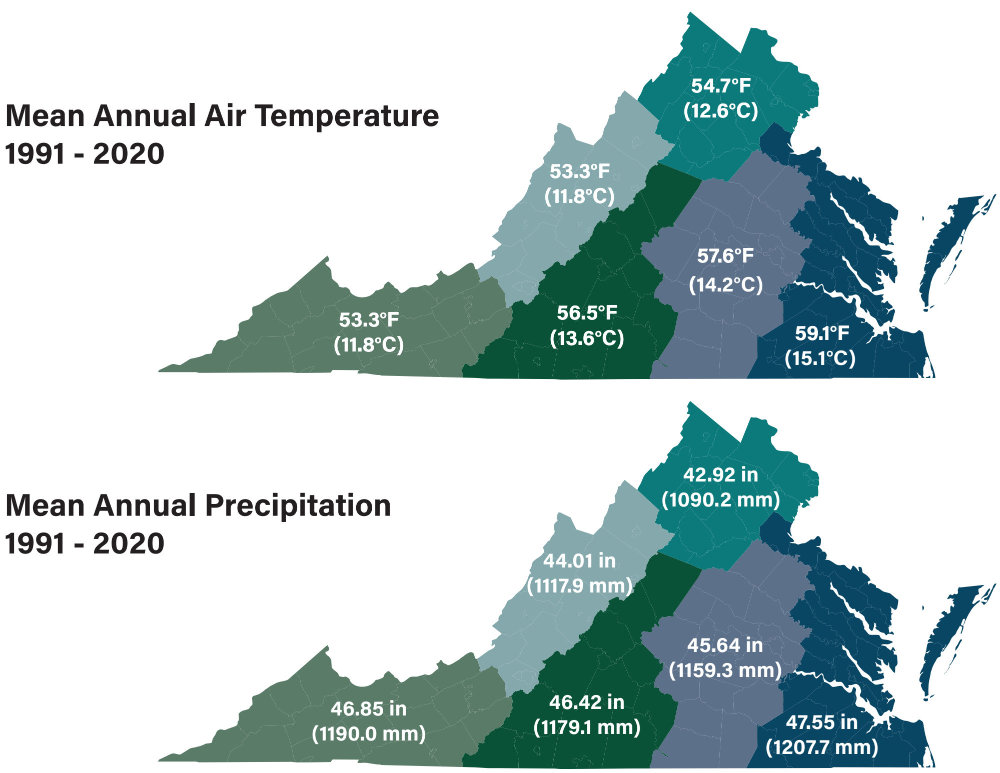


Figure 2. Climatological averages of mean annual air temperature (top) and annual precipitation (bottom) for each of the six Virginia climate divisions. Data produced using NOAA National Centers for Environmental information, Climate at a Glance: Statewide Time Series, published September 2025, retrieved on November 20, 2025 from https://www.ncei.noaa.gov/access/monitoring/climate-at-a-glance/statewide/time-series using the method described in Vose et al., 2014.

Traceable Accounts for Key Message 1

The climate of Virginia transitions from cooler and slightly drier across the mountainous western region to warmer and slightly wetter within the eastern coastal region (Hayden & Michaels 2011; Runkel et al. 2022). The rather continuous temperature pattern is interrupted locally around Virginia's larger urban centers (Norfolk, northern Virginia corridor, Richmond, Roanoke), which experience inordinate warmth due to heat retention, or the urban heat island effect (e.g., Lookingbill et al. 2025).

From a broader perspective, Virginia's humid subtropical climate is a consequence of middle latitude weather systems during the cool season and humidity delivered by northern Atlantic Ocean subtropical high-pressure ("Bermuda High") during the warm season (Hayden & Michaels 2011; Runkel et al. 2022). Cool season climate variability stems from middle latitude and subtropical jet streams that dictate temperature variability and storm tracks, including impactful coastal storms (Hayden & Michaels 2011). Interannual variability in cool season climate correlates most prominently with two natural climate fluctuations—the El Niño-Southern Oscillation (ENSO) of the equatorial Pacific Ocean (El-Askary et al. 2004; Yu et al. 2015), and the North Atlantic Oscillation (NAO) over the northern Atlantic Ocean (Chartrand & Pausata 2020). El Niño (La Niña) is generally associated with cooler (warmer) and wetter (drier) conditions, while a warmer (cooler) seasonal climate prevails during the positive (negative) phase of the NAO. Warm season variability largely reflects fluctuations in Atlantic Bermuda High position and strength, which occasionally directs tropical weather systems into the region (Hayden & Michaels 2011; Allen & Allen 2019).

Thomas Jefferson's Weather Observations

Thomas Jefferson maintained an extraordinarily detailed and systematic record of meteorological observations spanning 50 years, from July 1776 to June 1826. Beginning on July 1, 1776, while serving as a Virginia delegate to the Second Continental Congress in Philadelphia, Jefferson kept meticulous daily weather records that would eventually encompass observations from 99 locations, including his beloved Monticello, Virginia; Paris, France; Philadelphia, Pennsylvania; and Washington, D.C.

Jefferson's ambitious vision extended beyond personal record-keeping. In the 1770s, he planned to provide thermometers to dependable deputies in each Virginia county, requiring them to make twice-daily observations of temperature and wind direction as the foundation of a national weather observation network. This forward-thinking approach is a bedrock principle of weather and climate observations today.

The importance of Jefferson's Virginia climate observations cannot be overstated for modern climate assessment, despite some uncertainty, including the technological limitations of the time. His nearly unbroken observation record until 1826 serves as a benchmark for comparing contemporary climate conditions with historical norms (Figure 3), helping scientists distinguish natural climate variability from human-induced changes.

Jefferson's motivation stemmed from addressing what he perceived as practical and fundamental questions of climate and geography, making his meticulous documentation particularly valuable for understanding Virginia's historical climate patterns and informing current climate research and planning.

Figure 3

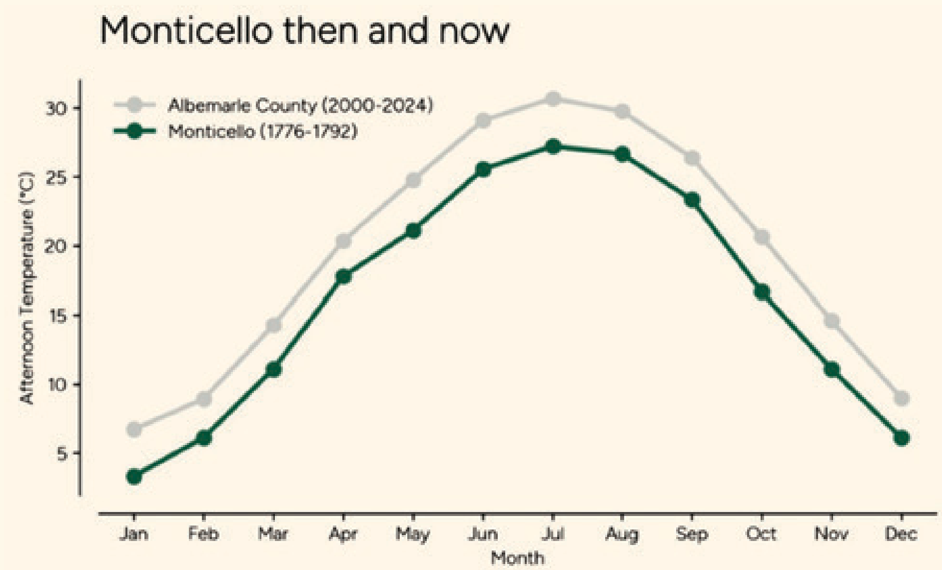


Figure 3. Monthly average temperature (°C) as recorded by Thomas Jefferson at Monticello, Virginia (green) over the period 1776 to 1792 and as computed from NCLIMGRID data averaged over Albemarle County, Virginia (gray), in which Monticello is located, for the period 2000–2024.

Key Message 2: The Virginia climate has become warmer (*very high confidence*) and wetter (*medium confidence*) in recent decades, with greater precipitation extremes (*high confidence*) and more frequent tidal flooding (*very high confidence*) along the Atlantic coast.

For the recent 30-year reference period 1991–2020, a mean annual temperature of 56.0°F (13.3°C) and total annual precipitation of 45.83 in (1164 mm) defines the contemporary regional climate of Virginia. These values represent a warmer and wetter condition than the average of the long-term instrumental record (1895–2024) (Figure 4; Section 2B).

A significant warming trend is evident within the mean temperature record, with an increase in annual statewide temperature of more than 1.5°F (0.8°C) since 1900 and an accelerated rate of warming in recent decades (Figure 4; Section 2B). While long-term statewide precipitation has been historically stable, the data record reveals a recent upward trend, albeit small, with the highest values occurring in more recent years (Figure 4; Section 2C). This is accompanied by an increase in the occurrence of extreme precipitation events, specifically a higher frequency of daily rainfall totaling 2 in (51 mm) or more.

In the coastal zones of the Atlantic Ocean and Chesapeake Bay, climate warming and wetting are concurrent with significant relative sea-level rise (Section 2D). A rise of 17 in (432 mm) along the Atlantic coast between 1927 and 2020 has directly contributed to an increase in the frequency of tidal flooding events in recent decades.

Figure 4.

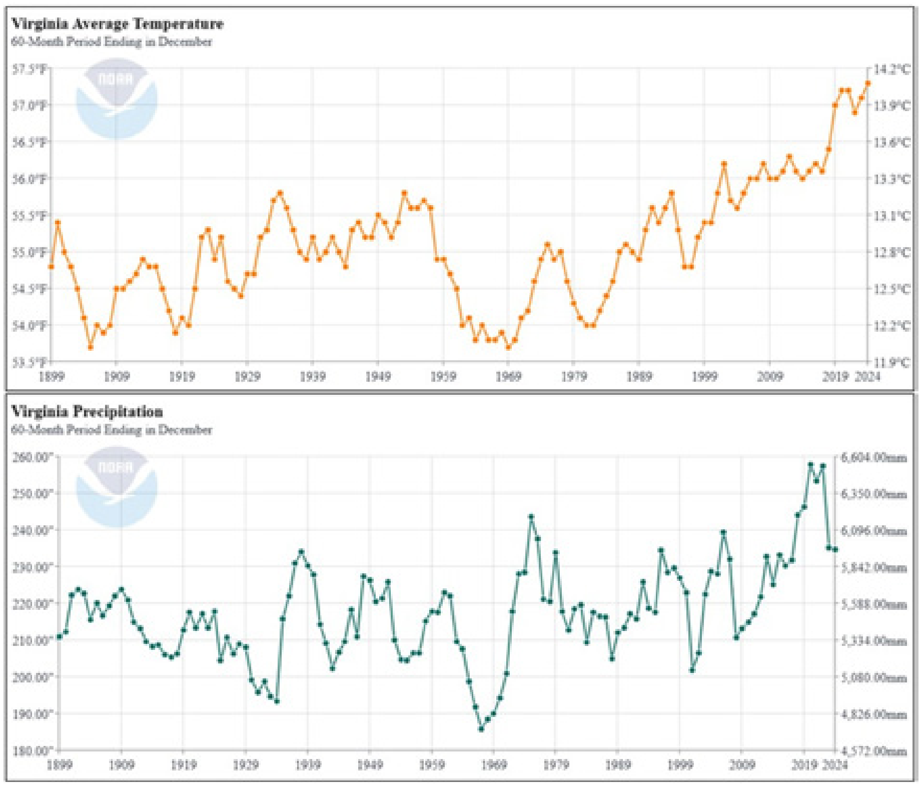


Figure 4. Five-year averages of Virginia statewide air temperature (top) and precipitation (bottom) through the instrumental record, 1895-99 through 2020-2024. Data produced using NOAA National Centers for Environmental information, Climate at a Glance: Statewide Time Series, published September 2025, retrieved on November 20, 2025 from https://www.ncei.noaa.gov/access/monitoring/climate-at-a-glance/statewide/time-series using the method described in Vose et al., 2014.

Traceable Accounts for Key Message 2

Based upon data for the most recent 30-year reference period (1991–2020), the statewide climate for Virginia is defined by a mean annual air temperature of 56.0°F (13.3°C) and total annual precipitation of 45.83 in (1164.1 mm). This is warmer and wetter than for the full instrumental record (1895–2024), which averaged 55.1°F (12.8°C) and 43.48 in (1104.4 mm). Since 1900, Virginia's mean temperature has risen by more than 1.5°F (0.8°C) (Runkle et al. 2022), with the most pronounced increase occurring across recent decades (Hoffman et al. 2019). Statewide precipitation has exhibited long-term stability through the instrumental record, but with a recent small upward trend (Allen & Allen 2019; Runkle et al. 2022), and with a tendency for the greatest values within the record to occur in more recent years. Extreme precipitation events are becoming more prevalent (Allen & Allen 2019; Marston & Ellis 2019), including the frequency of events totaling 2 in (51 mm) or more of rainfall (Runkle et al. 2022). Along the Atlantic coastline, tidal flooding has become more frequent in recent decades (Ezer & Atkinson 2015) in association with a sea level rise of 17 in (432 mm) along the Virginia coast between 1927 and 2020 (Runkle et al. 2022).

Key Message 3: Climate projections indicate continued warming (*very high confidence*) and wetting (*medium confidence*) for Virginia through the middle to late 21st century, with chronic tidal flooding along the Atlantic coast (*very high confidence*).

Projections for Virginia's climate, which align with those for the global climate, indicate continued and significant warming through the end of the 21st century. The magnitude of this warming is contingent on the global greenhouse gas emissions pathway taken. It is projected that uncontrolled higher-emissions scenarios would cause unprecedented air temperature increases for Virginia of between 7°F (3.9°C) and 13°F (7.2°C) above early-20th century levels by the year 2100 (Figure 5) (Section 2B). Very optimistic lower-emissions scenarios still yield a projected mean air temperature for Virginia that exceeds historical record temperatures by mid-century while reaching a mean temperature of between 3°F (1.7°C) and 8°F (4.4°C) above the early-20th century mean by 2100 (Figure 5). Projections of global warming yield an expectation of continued rising sea levels that are anticipated to induce problematic daily tidal flooding along the Virginia coast (Section 2D).

Along with anticipated warming, annual precipitation for Virginia is projected to modestly increase through mid-century (Section 2C), with higher-emissions pathways for greenhouse gases yielding a statistically significant 5–10% increase (2 to 4 in, or 51 to 102 mm) over the late-20th century baseline. Furthermore, climate models indicate an increase in the severity of extreme precipitation events, even under modest warming scenarios. Notwithstanding the projection of a wetter climate overall, elevated air temperatures raise concerns over an increased frequency of flash droughts—episodes of rapid-onset desiccation—posing a complex risk to the region (Section 3C).

Figure 5

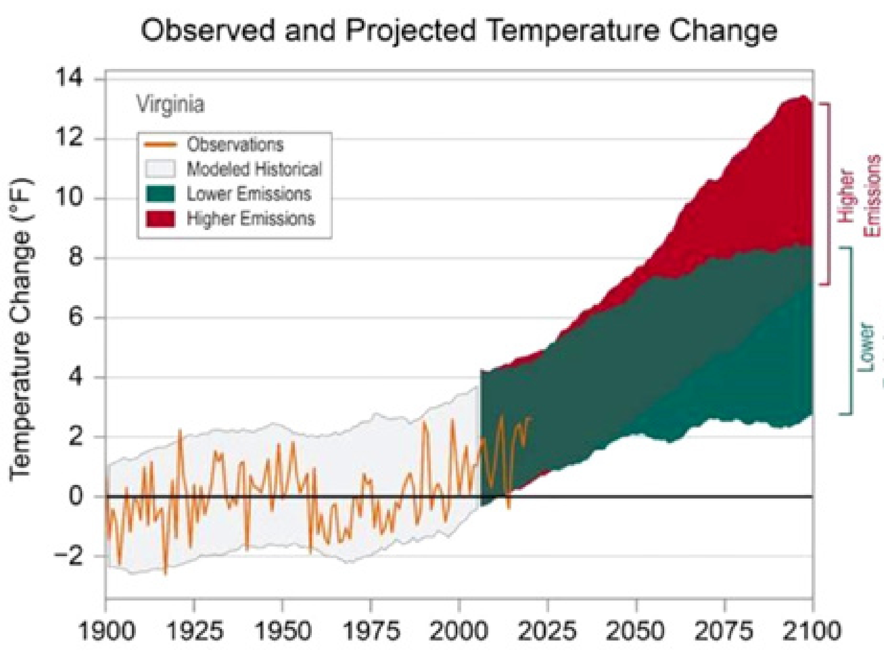


Figure 5. Changes (relative to 1901–1960 average) in observed statewide average mean annual air temperature for Virginia (1900–2020), and projected temperatures (2006–2100) under uncontrolled (higher) and optimistic (lower) global greenhouse gas emissions pathways. Shading reflects confidence around observed and projected temperatures. (Image sourced from Runkle et al. 2022)

Traceable Accounts for Key Message 3

Aligning with projections for the global climate (Crimmins et al., 2023), continued warming of the Virginia climate is projected for the remainder of this century, with unprecedented warming under higher, uncontrolled global greenhouse gas emissions pathways (+7 to 13°F), and warming beyond historical record levels by the middle of the century under optimistic lower-emissions pathways (Runkle et al. 2022). Accompanying projected global climate warming are projected global sea level rises that would yield daily tidal flooding along the Virginia coast (Mcleod et al. 2020; Runkle et al. 2022). Like global climate projections (Crimmins et al., 2023), precipitation across Virginia is projected to increase through the middle of the century. Under the highest global greenhouse gas emissions pathways, most climate models project a statistically significant increase in annual statewide precipitation of 5–10% above the late-20th century (1971–2000) average (Runkle et al. 2022), or an increase of about 2–4 in (51 to 102 mm). Under even modest scenarios of global warming, extreme precipitation events are projected to become more severe across Virginia (Sridhar et al. 2019; USGCRP 2023). Despite projections of a wetter climate, a warming climate raises concern over an increased frequency of flash droughts, or episodes of rapid drying caused by elevated air temperature (e.g., Neelin et al. 2022; Christian et al. 2023).

SECTION 2B

Temperature

KEY MESSAGES

1. In Virginia, large seasonal and daily variations imply that the most prominent temperature effects will be shifts in extremes (*high confidence*).

2. Observations indicate that while there is an overall increase in temperatures across the Commonwealth, the coldest days are warming faster than the warmest days (*high confidence*).

3. Global climate projections display a robust, statistically significant warming signal of mean and extreme temperatures in Virginia across a wide range of emissions scenarios (*high confidence*).

Key Message 1: In Virginia, large seasonal and daily variations imply that the most prominent temperature effects will be shifts in extremes (*high confidence*).

Daytime highs are about 20°F (11°C) warmer than nighttime lows, and July is about 40°F (22°C) warmer than January (Figure 6). Within each month, day-to-day changes due to weather are nearly as large as the variation of the seasonal cycle. The range of daily high temperatures is about 17°C (31°F) in July and 27°C (50°F) in January (Figure 6).

This wide temperature range and day-to-day variability means that climate change has been most visible as a shifting of extremes. The state continues to experience both hot and cold days, but the hottest days have become hotter and the coldest days have become less severe compared to earlier decades since 1960. These changes shift the seasons. For instance, warming should make the first frost arrive later, and the last frost arrive earlier.

Compared to the large swings over time, temperature differences across Virginia's geography are more modest. The spatial pattern is a gradual cooling from the warmer southeast corner near Norfolk to the cooler northwest parts of the state. This geographic temperature range is more pronounced in the winter (as shown in Figure 7a) than in the summer (Figure 7b).

Figure 6

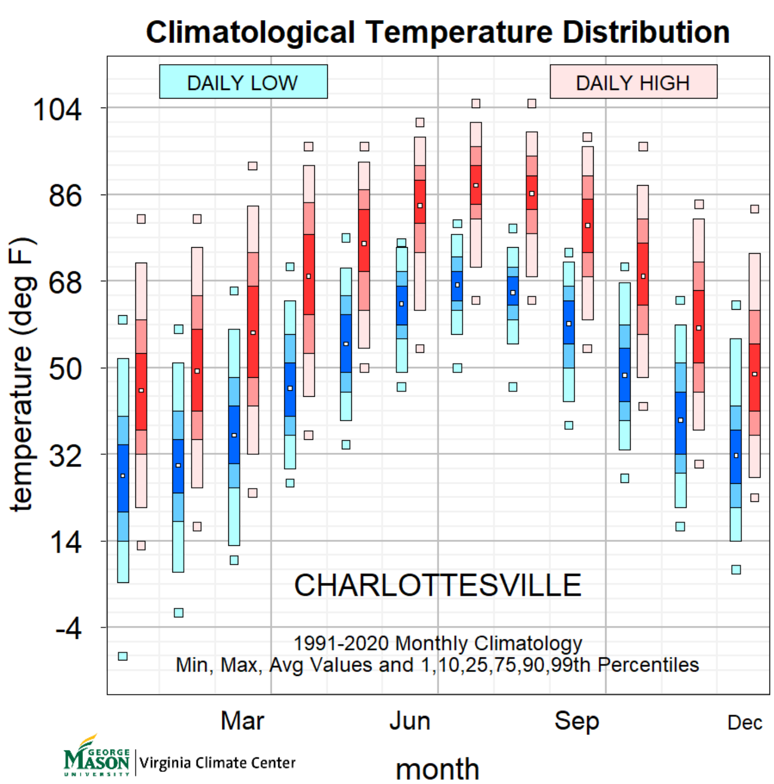


Figure 6. Statistics of daily low (blue) and high (red) temperature for each month of the year for Charlottesville, VA, 1991–2020. Bars show temperature range for 25th–75th percentile (dark shade), 10th–90th percentile (intermediate shade), and 1st to 99th percentile range (light shade). Small squares show monthly average and high and low extremes.

Figure 7

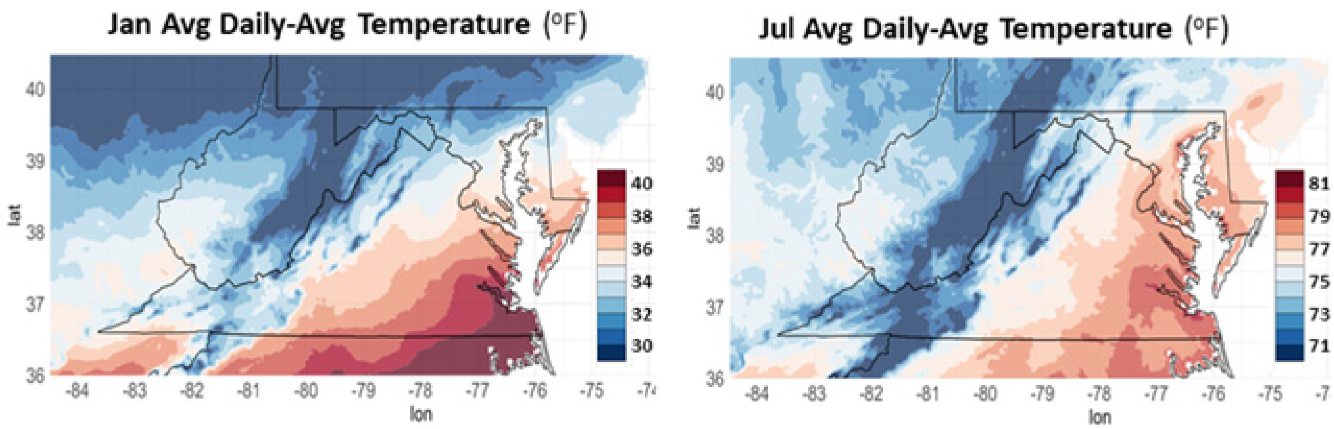


Figure 7. Spatial distribution of the multi-year mean (1991–2020) of average temperatures for January (left) and July (right).

Traceable Accounts for Key Message 1

There is not extensive recent literature on Virginia mean climate. Compilations of data were instead used to examine statistics for 1991–2020, a 30-year period typically used to characterize climatology of an area.

Time variations in Charlottesville temperature discussed in this chapter are from the United States Historical Climate Network (USHCN) station in Charlottesville (Menne et al., 2009). The USHCN is a program for taking standardized weather measurements at scattered locations throughout the United States. Data for Charlottesville and other locations throughout Virginia can also be found on the Virginia Climate Center website (Virginia Climate Center, n.d.). These show that Charlottesville has intermediate values of highs and lows among all 10 locations, all of which have fairly similar annual cycles.

Spatial variations are from NOAA's nCLIMgrid-D, which interpolates daily weather station data on to a regular array of locations with 1/24° (2.5 arc minutes, or about 3 miles) spacing between them (Durre et al., 2022).

Key Message 2: Observations indicate that while there is an overall increase in temperatures across the Commonwealth, the coldest days are warming faster than the warmest days (*high confidence*).

Global surface temperature of the entire Earth has been increasing at a rate of about 0.5°F (0.25°C) per decade since 1980 (Gulev et al., 2021, Table 2.4). Virginia (Figure 8) and the rest of the US Southeast have also been warming. Virginia shows great interannual variability, but the 1960–2024 trends for summer and winter are statistically significant (Figure 8).

Temperature trends vary with season, time, and location. Generally, summer days warmed less than winter days, and daily lows warmed more than daily highs (Hoffman et al., 2019; Durre et al., 2022; Figure 3). For daily lows, the number of extreme cold nights decreased by 1–3 days/decade and the number of extreme warm nights increased by 1–2 days/decade. However, daily highs showed more mixed results (Fall et al., 2021).

Another temperature-related quantity is Wet Bulb Globe Temperature (WBGT). This represents the temperature in the presence of heat gain and loss from radiation (such as sunlight) and cooling due to evaporative heat loss. WBGT also shows more warming in daily lows than in daily highs (Wodzicki et al., 2024).

Figure 8

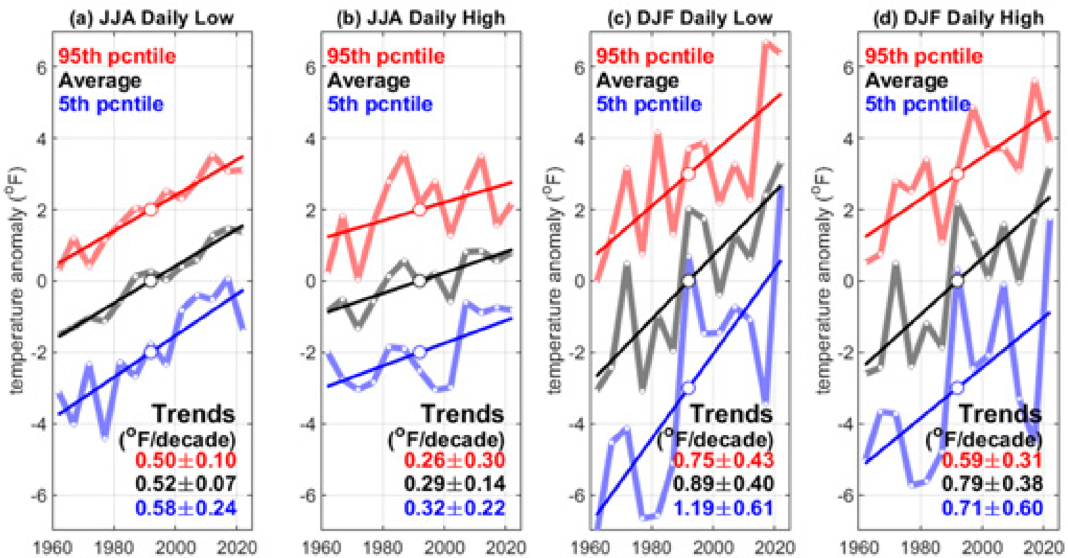


Figure 8 State-wide average of temperature metrics for 5 year periods (thick lines) and least square fits (thin lines). Metrics are based on daily lows (a,c) and daily highs (b,d) for June-July-August (a,b) and December-January-February (c,d). Temperatures are calculated for 5th percentile, average, and 95th percentile; curves are offset vertically to unclutter the figure: +2o for 95th percentile and -2o for 5th percentile. Numbers show trends and 95% confidence intervals from the least square fits.

Traceable Accounts for Key Message 2

Temperature trends are based on the NOAA nClimGrid-Daily dataset (Durre et al., 2022) for the period 1960–2024. The nCLIMGrid data is based on Global Historical Climatology Network–Daily (GHCN-Daily) (Menne et al., 2012) dataset, which interpolated station data into a regular ˜3 mi (5 km) grid using thin-plate smoothing splines and a weighting function based on distance, elevation, and proximity to a coast. The lack of land cover information and the use of GHCN-Daily data may lead to underestimation of changes related to land cover. This includes signals from urban environments and the urban heat island, leading to potential underestimation of temperatures and their historical trends for those locations. The nClimGrid-daily data has been evaluated by Durre et al (2022) against observations. This evaluation found that although the dataset reproduces observed trends in the observed record, accuracy decreases in areas with complex terrain or low density of GHCN-daily stations.

Figure 8 is constructed by taking average, 5th, and 95th percentile for a given season and for daily high or daily low over successive five-year intervals. These statistics were calculated for each gridpoint and then averaged over all gridpoints within the boundaries of the state of Virginia. Figure 8 shows a linear least squares fit for each curve, with slopes and errors (95th percentile confidence limit) printed.

The evidence is consistent with other findings. For example, reanalysis-based analysis for the Southeast US found similar differences between daily maxima and minima. (Milrad et al., 2025).

Key Message 3: Global climate projections display a robust, statistically significant warming signal of mean and extreme temperatures in Virginia across a wide range of emissions scenarios (*high confidence*).

While it is impossible to predict the exact temperature change throughout the 21st century due to uncertainties related to future emissions, climate models have demonstrated considerable skill in reconstructing climates. For emissions scenarios between middle-of-the-road and business-as-usual, climate models predict global mean surface temperature (GMST) rising by 5 to 9°F (2.8 to 4.4°C) over the 21st century. Different parts of the Earth's surface warm by different amounts, but in Virginia, warming is close to the global average (Figure 9).

Temperature extremes are also projected to increase. As with observed temperature changes, low temperatures have a larger increase than high temperatures. The annual maximum of daily high temperatures in the vicinity of Virginia is projected to increase between 100–150% of GMST warming, but annual minimum of daily low temperatures increases between 175–250% of GMST.

If global emissions are reduced, warming over the 21st century will also be reduced. Daytime high temperatures are expected to rise by over 9°F (5°C) under a high emissions scenario (Figure 9b), while a lower emissions pathway would lead to an increase of roughly 5°F (3°C), or nearly half as much warming.

Figure 9

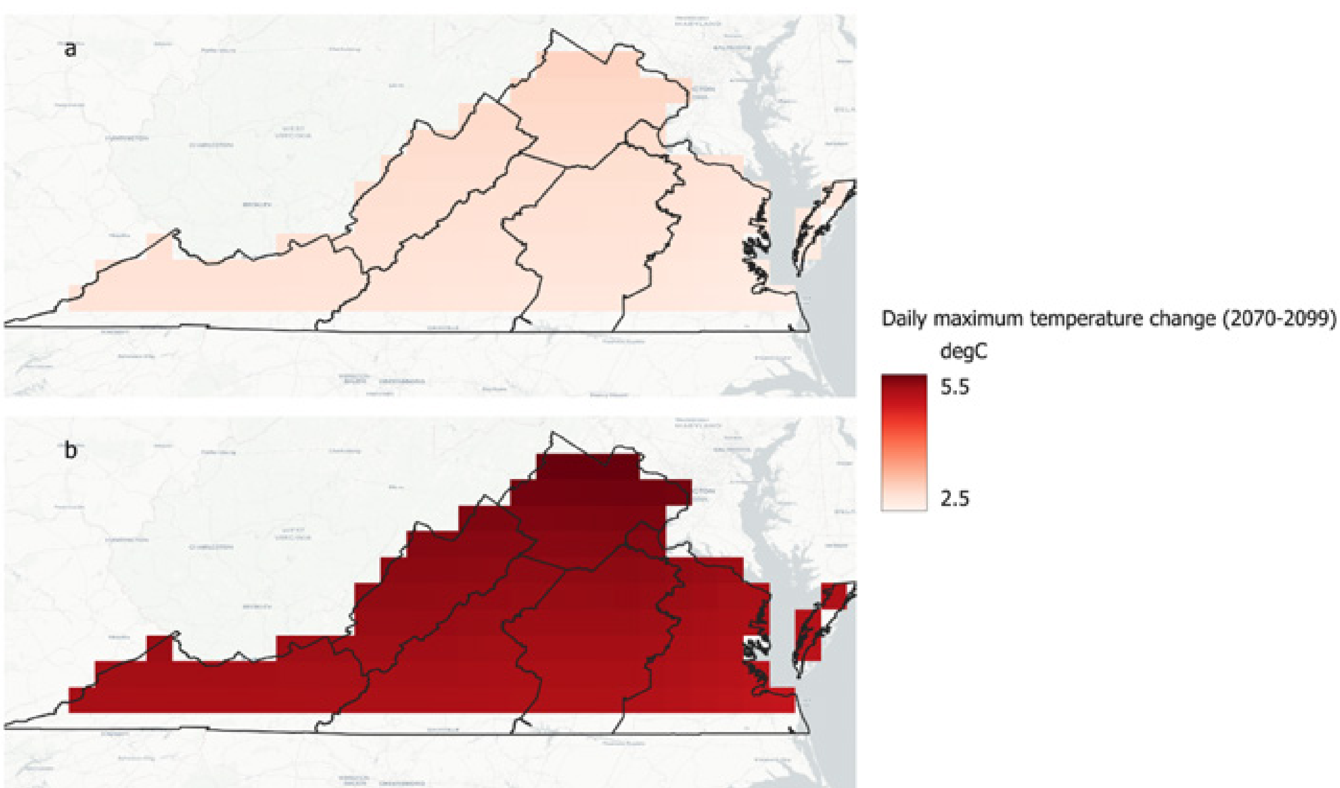
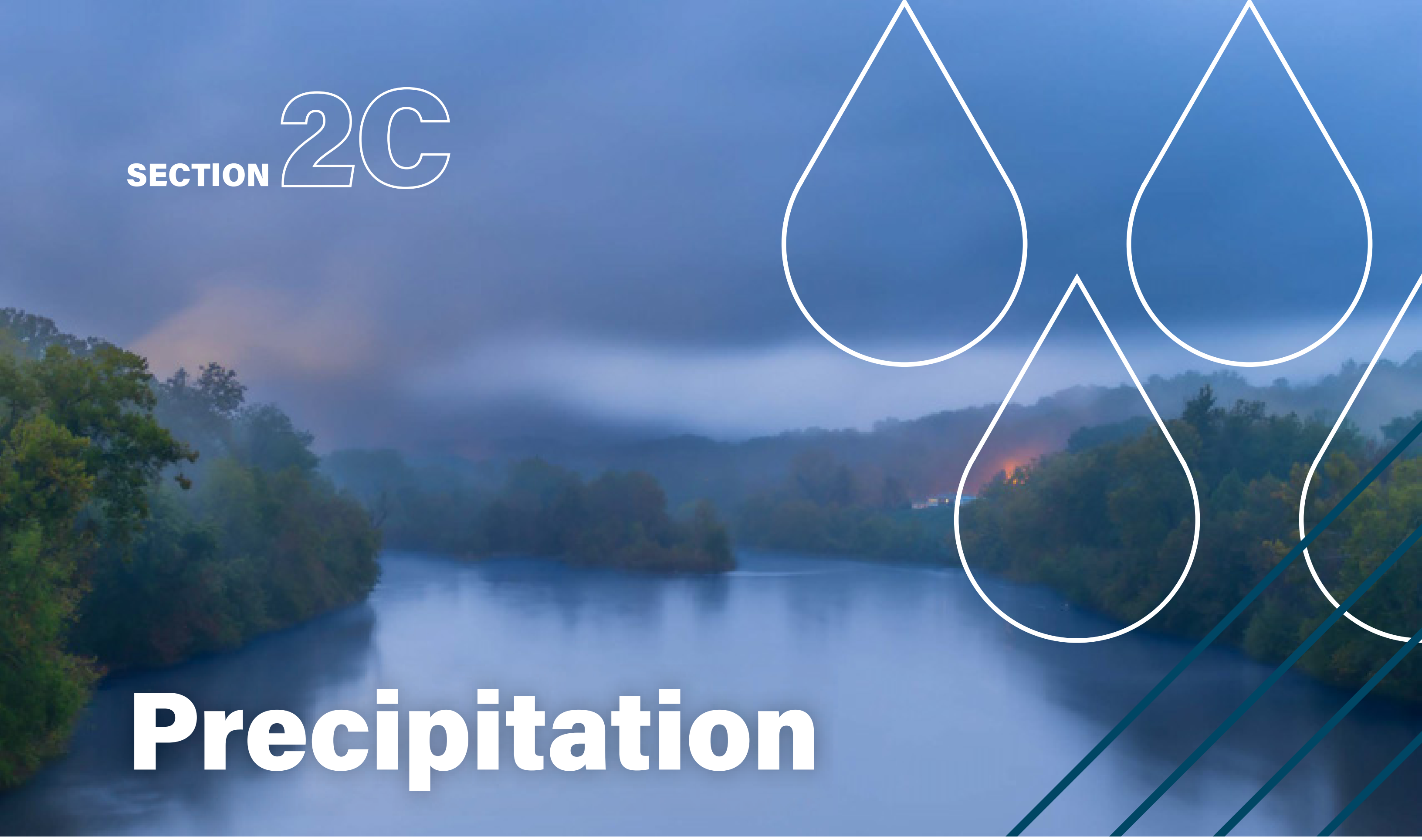


Figure 9. Daily maximum temperature change by end of century (2070–2100) for (a) SSP2-4.5 and (b) SSP5-8.5. Source: IPCC WGI Interactive Atlas (accessed September 2025).

Traceable Accounts for Key Message 3

Information for future Virginia temperatures comes from IPCC Assessment Report 6 of the IPCC Working Group I, Chapter 4, Future Global Climate: Scenario-based Projections and Near-term Information (Lee et al., 2012), and Chapter 11, Weather and Climate Extreme Events in a Changing Climate (Seneviratne et al., 2021). Projections are estimated by driving climate models by a series of scenarios with different radiative forcing (a measure of how much the Earth's radiation balance is perturbed by greenhouse gases and other factors). Here we emphasize the SSP3-7.0 scenario which has a radiative forcing of 7.0 W/m2, equivalent to almost doubling atmospheric carbon dioxide concentration.

Global mean surface temperature (GMST) warming estimated in Message 3 is based on models with the 5th to 95th percentile warming values at the year 2100 relative to the observed 1995–2014 average, as displayed in Figure 9a. The range of warming in Virginia is based on the contours displayed in Fig. 9, 2081–2100 average for SSP3-7.0, which shows the multi-model mean. Changes in extreme values are based on Fig. 11.11b,c,e,f of Seneviratne et al. (2021), which shows multi-model means for change in GMST of 3.6°F (2.0°C) and 7.2°F (4.0°C).



SECTION 2C

Precipitation

KEY MESSAGES

1. Virginia's precipitation patterns reflect a complex interplay of seasonal cycles, diverse storm mechanisms, climate pattern variability, and regional topography (*high confidence*).

2. Virginia is experiencing wetter conditions overall, with more frequent and intense precipitation events (*medium confidence*).

3. Spring and fall are getting wetter, particularly in coastal regions, while summers are becoming wetter in the eastern Chesapeake Bay watershed (*high confidence*).

Key Message 1: Virginia's precipitation patterns reflect a complex interplay of seasonal cycles, diverse storm mechanisms, climate pattern variability, and regional topography (*high confidence*).

Virginia's annual precipitation cycle peaks in late spring through summer, driven by warm-season convective thunderstorms and remnants of tropical systems. While winters are generally drier, coastal areas still receive substantial rain from nor'easters and midlatitude cyclones. On average, about 30% of days receive measurable precipitation, while the remaining 70% are dry. Most of the heavier rain events come from three main types of storms: short, intense thunderstorms; longer-lasting weather fronts; and tropical systems or combinations of these. Each of these types is governed by distinct moisture sources, uplift dynamics, and terrain effects (Figure 10). Southwest Virginia saw the heaviest rain from post-tropical Helene (2024), which made landfall as a Category 4 storm in Florida's Big Bend. Localized 10 to15 in (254 to 381 mm) totals were recorded over a larger region extending from southwestern Virginia to northwestern South Carolina, and into portions of Georgia and Florida.

Figure 10

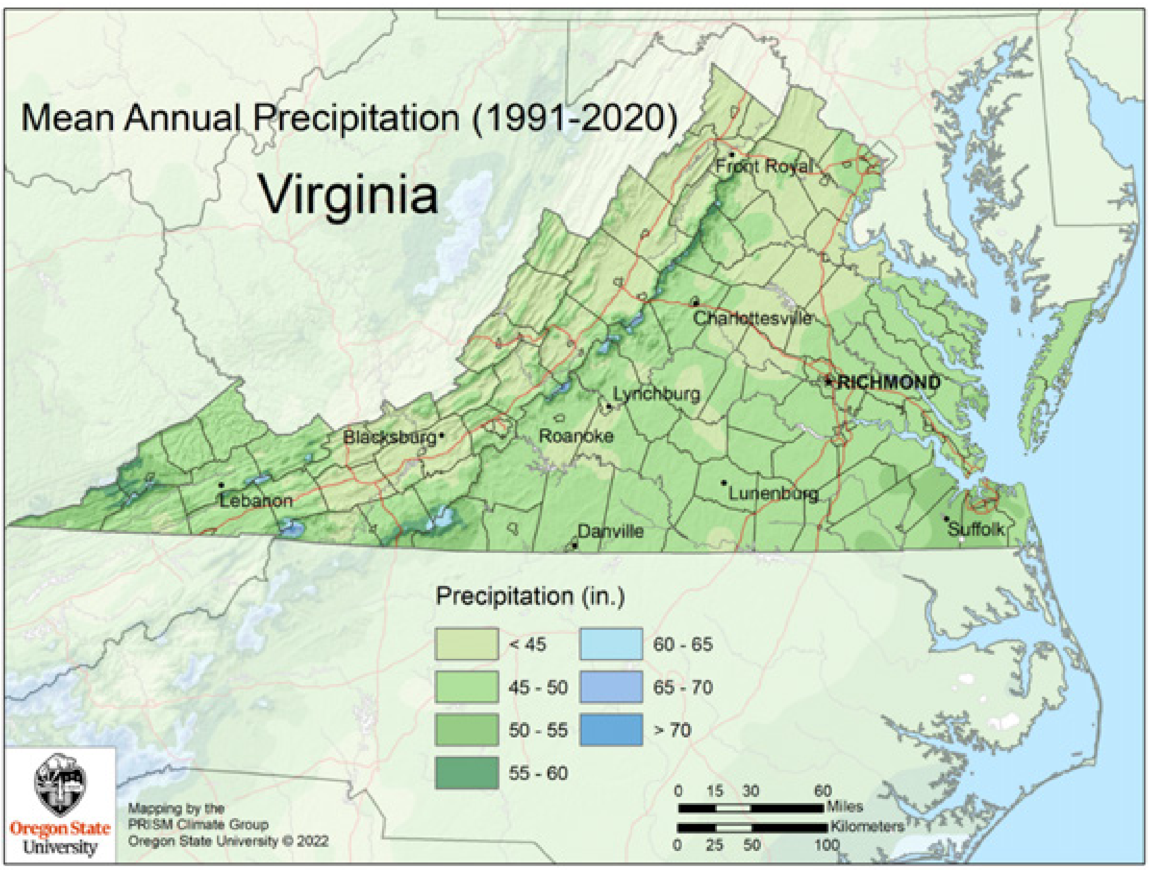


Figure 10: Statewide map of average annual precipitation (inches) from 1991–2020 (Source: Parameter-elevation Relationships on Independent Slopes Model Climate Group at Oregon State University)

Besides being affected by the fluctuating frequency and intensity of storms, interannual variability is influenced by the El Niño—Southern Oscillation (ENSO), with wetter El Niño (i.e., warming phase of the sea surface temperature) winters and drier La Niña (i.e., cooling phase of the sea surface temperature). Virginia's six climate divisions exhibit unique precipitation profiles: the coastal Tidewater region receives about 50 in (1270 mm) annually; the inland Eastern and Western Piedmont regions have humid summers and moderate winters; Northern Virginia is cooler with more snow; the Central and Southwestern Mountains see significant snowfall at elevation; and the Valley and Ridge lie in a rain shadow, yielding lower totals. Most individual rainfall events are light and brief—over 70% produce under 0.1 in (2.54 mm) and last less than two hours. The duration of dry periods varies across physiographic regions (e.g., about 16.8 days in Richmond and about 19.5 in Norfolk). Seasonal distribution, storm diversity, climate oscillations, and topography collectively shape extreme hydroclimatic risks triggered by precipitation (or lack of) across the Commonwealth

Traceable Accounts for Key Message 1

The statewide map of average annual precipitation in Virginia (1991–2020), developed by the PRISM Climate Group at Oregon State University (Daly et al., 2008), illustrates the pronounced spatial variability in rainfall across the state. Annual precipitation ranges from under 45 in (1143 mm) in parts of the northern Shenandoah Valley and Eastern Virginia to over 65 in (1651 mm) in the southwestern mountains and along sections of the Blue Ridge.

Liu et al. (2014) analyzed rain and dry period patterns from 1948 to 2010 using hourly data from eight stations representing Virginia's four major physiographic regions. Precipitation events were defined using a minimum six-hour dry interval between events, with minor events under 0.1 in (2.54 mm) excluded to emphasize hydrologically significant rainfall. Their depth-duration analysis showed that most precipitation events are brief and light: over 70% delivered less than 0.1 in (2.54 mm) and lasted under two hours. The study also evaluated storm intensity and dry spell duration. The commonly used design storm of 1 inch (25.4 mm) corresponds to a 10% exceedance probability statewide, but values varied regionally—from 0.9 in (22.9 mm) in Bristol to 1.4 in (35.6 mm) in Montebello. Dry spell analysis revealed that 70% of dry periods lasted fewer than 10 days.

A National Hurricane Center report indicates that Helene's three-day rainfall total had an annual probability of less than 0.1% in Virginia, where the highest total recorded was 10.89 in (276.6 mm) (Hagen et al., 2025).

Key Message 2: Virginia is experiencing wetter conditions overall, with more frequent and intense precipitation events (*medium confidence*).

Both the frequency and intensity of extreme precipitation events have increased significantly over the last several decades, particularly in urban and coastal areas such as Norfolk, Williamsburg, and Northern Virginia. Climate projections under moderate and highest emission scenarios, i.e., RCP 4.5 and 8.5, suggest that 24- and 48-hour rainfall intensities could double or even triple by 2099 (Figure 11). Between 1980 and 2018, Northern Virginia experienced a statistically significant increase of more than +0.25% per year in rainfall on its top 5% wettest days. When tropical cyclone days are excluded, the heaviest daily rainfall (upper 10th percentile) drops noticeably. The largest decreases were observed along the Atlantic coast, highlighting the strong contribution of tropical cyclones to extreme rainfall. Under a medium-high socio-economic scenario, the rainfall for a 24-hour duration storm with a 50-year return period at Ronald Reagan Washington National Airport is projected to be about 0.89 in/day (22.5 mm/day) higher in 2075–2100 than the one observed during 1950–2014. There is a strong confidence in the increasing trend of total annual precipitation contributed by the most extreme 5% of wet days, especially under high-emission scenarios in the Chesapeake region. Future precipitation projections in Richmond show that the 100-year storm rainfall is expected to increase by 1.2 in (30.5 mm, or 14%) under RCP4.5 and 2.4 in (61 mm, or 25.3%) under RCP8.5.

Figure 11

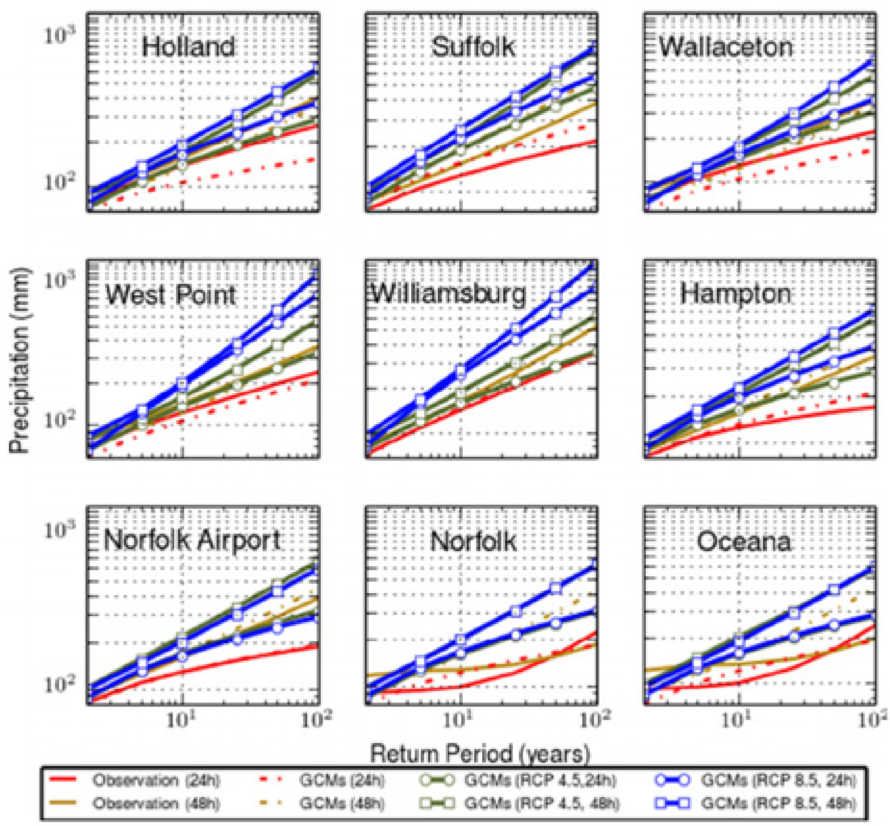


Figure 11: Intensity–duration–frequency analysis of annual extreme daily precipitation at nine ground stations in Southeastern Virginia, using both observed records and General Circulation Model (GCM)-derived historical simulations, as well as future projections under RCP 4.5 and RCP 8.5. The observed and historical GCM data cover the period 1950–2005, while the RCP 4.5 and 8.5 projections span 2016–2099. This figure is not a part of the governing OA license for this report, but has been reproduced with permission of the Licensor through PLSclear from Sridhar, V., Modi, P., Billah, M.M., Valayamkunnath, P., Goodall, J.L. (2019). Precipitation extremes and flood frequency in a changing southeastern Virginia. JAWRA, (55)(4), 780-799. https://doi-org.mutex.gmu.edu/10.1111/1752-1688.12752

Traceable Accounts for Key Message 2

A growing body of observational and modeling studies shows increasing total and extreme precipitation across Virginia, both historically and in future projections under various emission scenarios.

Allen and Allen (2019) analyzed 70 years of daily records from 43 stations (1947–2016), finding rising annual precipitation at 39 sites—averaging +0.57 in (14.5 mm) per decade—with eight trends statistically significant at the 95% confidence level. The frequency of precipitation days increased by 1.69 days per decade, with 17 stations showing significant trends. Average annual rainfall across stations was about 43 in (1090 mm), though this varied by location due to topography—e.g., Meadows of Dan and Woolwine received over 50 in (1270 mm), while Woodstock averaged just over 36 in (910 mm). Stations saw an average of 111 precipitation days per year, with Burkes Garden highest (140) and Clarksville lowest (88). Heavy precipitation days averaged 10 annually, exceeding 15 at some sites.

Sridhar et al. (2019), using Global Historical Climatology Network-Daily (GHCN-D) observations and downscaled projections from 15 GCMs, found that under RCP 4.5 and 8.5, 24- and 48-hour precipitation depths could double or triple by century's end. Between 1950 and 2010, southeastern Virginia—especially urban areas like Williamsburg, Suffolk, and Norfolk—saw significant increases in daily precipitation extremes, confirmed by statistical methods including linear regression, Theil–Sen slope estimation, and Mann–Kendall tests. These changes heighten flood risk, especially in low-lying coastal areas such as Hampton and Norfolk.

Dollan et al. (2022), using NLDAS-2 data (1980–2018), found statistically significant increases in both annual maximum precipitation and the frequency of extreme daily events across the Southern Mid-Atlantic, including Northern Virginia. Increases were particularly notable for 1-day and 5-day maxima and events above the 95th and 99th percentiles, especially along the Appalachian gradient. Likely drivers include topography, convective storms, and possibly more frequent tropical cyclones.

Knight and Davis (2009) examined TC-related rainfall trends using data from 85 stations (1972–2007) and high-resolution reanalysis (NARR, 1979–2006). They found a marked increase in the share of annual extreme rainfall attributable to tropical cyclones. In Norfolk, for instance, TC-related precipitation rose by 6.0%, 7.8%, and 9.9% per decade for the top 20th, 10th, and 5th percentiles, respectively.

Pierce et al. (2023) used a statistical downscaling method on 27 CMIP6 models (~10 ensemble members per model) across three Shared Socioeconomic Pathways (SSP2.45, SSP3.70, and SSP5.85), resulting in 329 runs. At Washington Reagan Airport, the number of days in the 99.9th percentile of wet-day precipitation is projected to increase 1.8-fold under SSP3.70 by 2075–2100.

St. Laurent et al. (2022) found robust historical and projected increases in annual precipitation driven by the most extreme 5% of wet days, particularly under RCP8.5 in the Chesapeake region. Similarly, Morsy et al. (2024) projected that Richmond's 100-year storm rainfall will rise by 1.2 in (30.5 mm, or 14%) under RCP4.5 and 2.4 in (61 mm, or 25.3%) under RCP8.5, based on downscaled CMIP5 models from CORDEX using a 1950–2005 historical baseline.

Key Message 3: Spring and fall are getting wetter, particularly in coastal regions, while summers are becoming wetter in the eastern Chesapeake Bay watershed (*high confidence*)

Virginia exhibited clear seasonal shifts in precipitation in the recent past, particularly summer precipitation in the eastern Chesapeake Bay watershed. Spring and fall have become wetter (with a statewide increase in fall of ~0.42 in (~10.7 mm)), while summers, especially in Eastern and Western Piedmont, have trended drier. Summer rainfall showed significant increases across about 30% of Virginia (notably in northern VA and west of the Potomac), with rising spring and fall extremes and non-significant changes in winter. Climate projections suggest that the Chesapeake Bay watershed will experience increased precipitation during the winter, spring, and summer months under both moderate (RCP4.5) and high (RCP8.5) emissions scenarios for the period 2066–2095, relative to the 1976–2005 baseline (Figure 12). These trends are consistent with projections through 2065, which indicate statewide increases in precipitation—most notably in winter, with changes of up to approximately 30% under RCP8.5. The highest rainfall amounts are expected in winter, particularly in the northwestern region of the Commonwealth, followed by increases in spring, summer, and fall. By late century (2061–2100), simulations from 12 CMIP6 models—selected for their skill in reproducing historical seasonal extreme precipitation—project a statistically significant increase (at the 95% confidence level) in consecutive wet days during summer across Virginia. These evolving patterns of shifting seasonal totals and more intense storms have important implications for water resource management, agriculture, and stormwater infrastructure planning across the Commonwealth.

Figure 12

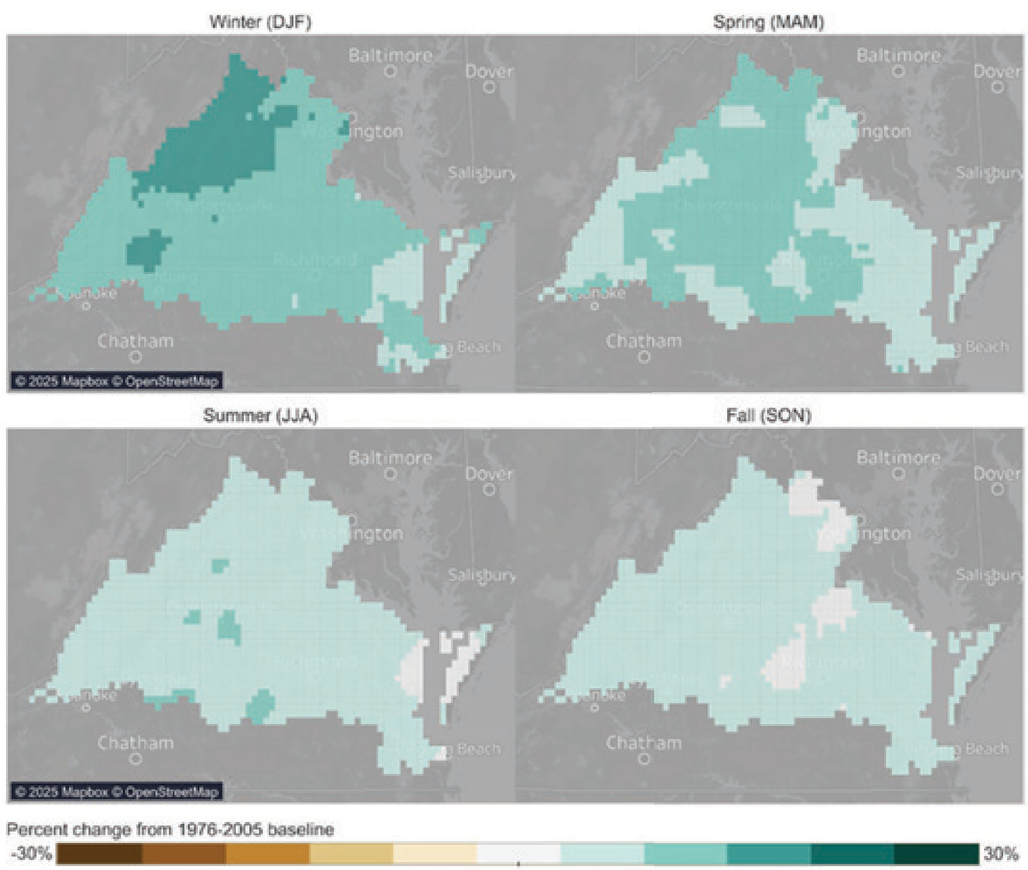


Figure 12: Changes in average seasonal total precipitation from 1976–2005 baseline to 2036–2065 under the highest emission scenario RCP8.5 (Mid-Atlantic Climate Data tools, www.midatlanticrisa.org/)

Traceable Accounts for Key Message 3

Hoffman et al. (2019) provides a comprehensive analysis of climate trends in Virginia from 1895 to 2016, with a focus on the most recent 30-year period (1986–2016). The study examines seasonal anomalies in maximum and minimum temperatures and precipitation across Virginia's six climate divisions, comparing recent conditions to long-term historical averages. Summer exhibited negative precipitation anomalies across all divisions—especially in the Piedmont—indicating a drying trend. In contrast, spring and fall showed positive anomalies, with fall showing the most pronounced increase: an average of +0.42 in (10.7 mm) statewide, including a +0.59 in (15.0 mm) increase in the Tidewater region. Winter precipitation displayed minimal change and high regional variability.

Dollan et al. (2022) identified similar seasonal trends, with the most significant increases occurring in summer precipitation—30% of the study area showed a statistically significant upward trend (95% confidence level), particularly in northern Virginia and areas west of the Potomac River. Spring and fall also showed rising trends in extreme precipitation, while winter trends remained small and statistically insignificant. Under RCP8.5, LOCA (Localized Constructed Analogs) downscaled projections at 1/16° (~3.7 mi or ~6 km) show increases in both winter and spring precipitation, raising concern for amplified spring flood risk, particularly in the Chesapeake Bay Watershed (MARISA, 2019).

Projections from 12 CMIP6 models (Akinsanola et al., 2020) indicate a statistically significant increase in consecutive wet days across Virginia during summer by the late century (2061–2100), reinforcing observed and emerging seasonal patterns.

SECTION 2D

Sea Level

KEY MESSAGES

1. Sea level has been rising in Virginia due to a combination of global sea level rise (*very high confidence*), land subsidence (*very high confidence*), and influences from oceanic and atmospheric variability (*moderate confidence*).

2. Future projections indicate that sea level rise will accelerate across Virginia coasts (*high confidence*), causing acceleration in coastal flooding (*very high confidence*).

3. The impacts of sea level rise lead to changes in Virginia's ecosystems and shorelines (*high confidence),* habitat conversion (*high confidence*), groundwater salinization (*high confidence*), and erosion (*high confidence*).

Key Message 1: Sea level has been rising in Virginia due to a combination of global sea level rise (*very high confidence*), land subsidence (*very high confidence*), and influences from oceanic and atmospheric variability (*moderate confidence*).

Sea level has been rising with accelerated rates along the Virginia coast, with rates in the lower Chesapeake Bay among the highest on the U.S. East Coast. A combination of global sea level rise and regional factors influence this rise. Warming global temperatures expand ocean waters and melt glaciers and ice sheets, raising sea level. Regionally, land is also sinking as the earth's surface recovers from the weight of ice sheets (glacial isostatic adjustment) and from groundwater withdrawal, especially in the lower Chesapeake Bay and the Tidewater region of southeastern Virginia. Changes in oceanic and atmospheric circulation also affect sea level variability. Long-term weakening of the Atlantic Meridional Overturning Circulation (AMOC) and short-term variations in the Gulf Stream can elevate sea levels along the U.S. Atlantic coast. Changes in atmospheric pressure patterns and prevailing winds contribute to sea level variability. Monthly and seasonal-scale climate patterns, like the Madden-Julian Oscillation (MJO) and the El Niño Southern Oscillation (ENSO), can alter winds and temporarily increase sea levels. As a result of sea level rise, there is increased flood risks to coastal Virginia areas due to higher tides and larger storm surges (see Figure 13 and section 3B. Flood Risk, for details).

Figure 13 (a)

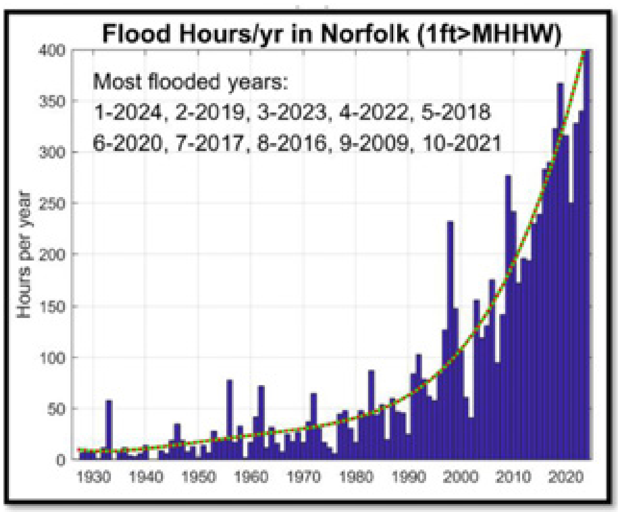


Figure 13 (b)

Figure 13. (a) The accelerated minor flooding (1foot above the mean high tide) in Norfolk, VA, showing the number of flood hours per year; note that 2024 was the most flooded year on record. (b) A typical "sunny day flood" in the streets of Norfolk when high tide is combined with strong winds or an offshore storm (picture taken by T. Ezer).

Traceable Accounts for Key Message 1

Global sea level rise due to thermal expansion and melting of glaciers and ice sheets are well documented (Kopp et al., 2014; IPCC, 2023; Ripple et al., 2024), but spatial variations in local sea level rise are more complex as they are affected by multiple different factors. Local land subsidence is especially large in southeastern Virginia and the Hampton Roads region (Boon et al., 2010; Boon, 2012; Ezer and Corlett, 2012;

Bekaert et al., 2017; Buzzanga et al., 2020), with typical sinking rates of ~2-6 mm/yr (~0.8-2.4 inches/decade)—since these rates are of the same order as global sea level rise, local sea level rise can be twice as large as global sea level rise. Therefore, local sea level rise since 1975 (Ezer, 2023) can range from ~4.5-4.8 mm/yr (~1.8-1.9 inches/decade) in the upper Chesapeake Bay (e.g., Baltimore or Annapolis) to 5.8-6.2 mm/yr (~2.3-2.4 inches/decade) in the middle to lower Chesapeake Bay (e.g., Lewisetta or Norfolk). On the eastern shore of Virginia (e.g., Kiptopeke) local sea level rise is somewhat less than that in the Hampton Roads area, ~4.7 mm/yr (~1.85 inches/decade), probably due to impact on sediment compact from the Chesapeake Bay meteor crater of ~35 million years ago (Eggleston and Pope, 2013; Bekaert et al., 2017).

The remote impact of ocean and atmospheric dynamics on sea level is also very complex and not fully explored yet (Ezer et al., 2013; Goddard et al., 2015; Volkov et al., 2019; Dangendorf et al., 2021; Ezer, 2025). Potential climate related weakening of the Atlantic Meridional Overturning Circulation (AMOC; Smeed et al., 2014; Orbe et al., 2023) and slowdown or shifting Gulf Stream can contribute to elevating sea levels along the U.S. Atlantic coast by changing the slope of sea surface height across the Gulf Stream (Ezer et al., 2013). Changing patterns of atmospheric pressure and wind can also affect coastal sea level (Piecuch et al., 2016). There is a strong statistical correlation between Gulf Stream weakening and accelerated sea level rise along the U.S. mid-Atlantic coast on decadal time scales (Ezer et al., 2013) and on short time scales (Ezer, 2016). This mechanism works because the Gulf Stream keeps coastal sea level about 1–1.5m (3–5 feet) lower than the offshore ocean southeast of the Gulf Stream. Therefore, when the Gulf Stream slows down, sea level increases on the coast and decreases offshore. The area north of Cape Hatteras, North Carolina, is known as a sea level rise "hotspot" (Sallenger et al., 2012), and sea level reconstructions support that this "hotspot" recurs throughout history based on North Atlantic Oscillation (NAO) phase and Arctic ice melt (Gehrels et al., 2020).

Both sub-seasonal and seasonal factors can amplify or suppress changes in sea level expected from larger scale circulations like ENSO and long term trends. At the Sewell's Point tide gauge sea levels tend to be higher related to the El Nino phase of ENSO and MJO activity, with stronger easterlies contributing to the November 2009 high water event (Arcodia et al., 2024). Changes in AMOC and shifting wind patterns associated with the NAO can cause differences in sea level within the Chesapeake Bay (Ezer and Updyke, 2024). Hurricanes and tropical storms can have multiple impacts on sea level along the Virginia coast—direct storm surge and floods due to precipitation, as well as indirect effects of disruption to the First Virginia Climate Assessment: Draft for External Review Gulf Stream flow that can cause a post-storm sea level rise for weeks after the storm disappeared (Ezer, 2020; Park et al., 2024).

The impact of the rising seas in coastal Virginia (both along the Atlantic coast and the Chesapeake Bay) is seen in the accelerated flood frequency and severity (Ezer and Atkinson, 2014; Sweet and Park, 2014; Bao et al., 2016; Burgos et al., 2018; Boesch et al., 2023; Ezer, 2022, 2023; Han et al., 2024; Tran and Lakshmi, 2024), as thresholds have been exceeded with increasing regularity—with rising seas and sinking land, even moderate storms or high tides that in the past posed no risk, now can flood streets and coasts (see also Section 3B. Flood Risk).

Key Message 2: Future projections indicate that sea level rise will accelerate across Virginia coasts (*high confidence*), causing acceleration in coastal flooding (*very high confidence*).

Future projections indicate that both global and local sea level rise will accelerate throughout the 21st century across coastal Virginia. Climate models predict that thermal expansion and land ice melting will become increasingly dominant factors in global sea level rise, with the highest acceleration in rates with greater levels of warming toward 2100. However, local factors like sinking land, changes in atmospheric and ocean circulation, and changes in the frequency and intensity of storms will remain important. Therefore, future local projections vary at locations across Virginia (Figure 14). Low elevation coastal lands are highly vulnerable to small changes in water levels, and these changes are difficult to predict. Sea level rise is projected to significantly increase the frequency and severity of coastal flooding events, including recurrent high tide flooding that historically caused minimal impact. Sea level rise due to compound events—storm surge, heavy rainfall, high tides and potential remote influence from the AMOC, the North Atlantic Oscillation (NAO), and the Gulf Stream are especially difficult to predict. These compound flood events are anticipated to become more frequent under climate change, posing escalating threats to infrastructure, ecosystems, and coastal communities in Virginia (see section 3B. Flood Risk).

Figure 14 (a) **Figure 14 (b)**

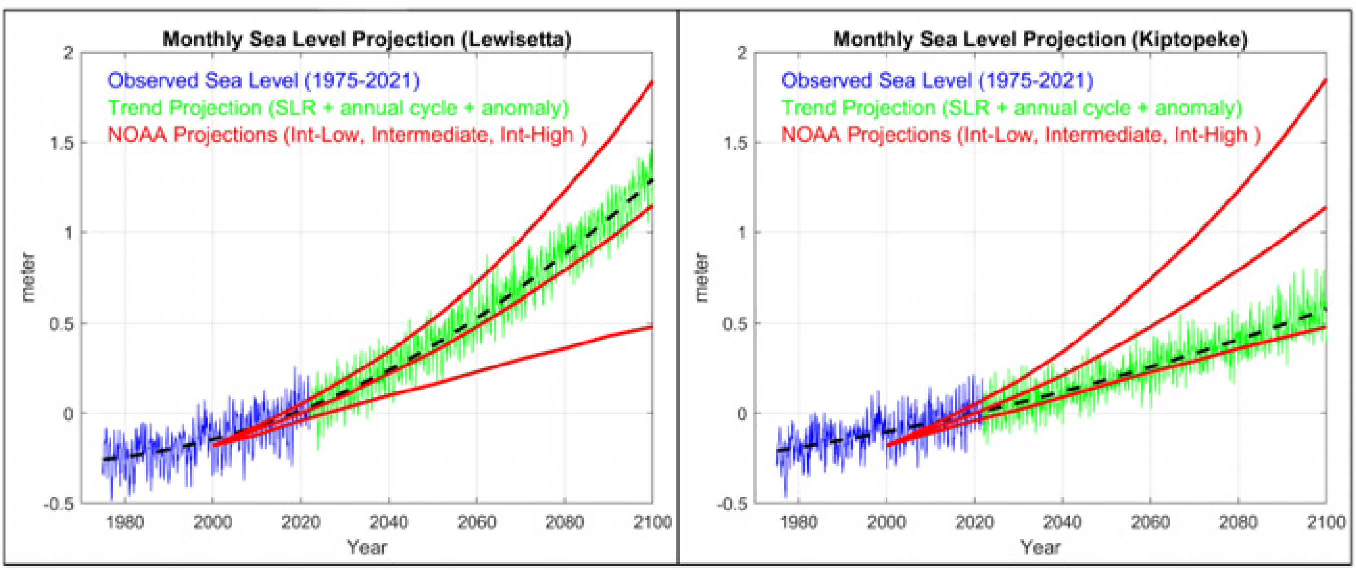


Figure 14. A comparison between NOAA's local sea level projection scenarios (red lines) and projections based on statistics of local tide gauge observations (green lines) at (a) Lewisetta, and (b) Kiptopeke, VA. (a) and (b) are located on the western and eastern shores of the Chesapeake Bay, respectively, demonstrating potential differences in future sea level due to local dynamics and spatial variations in land subsidence. This figure is not part of the governing OA license for this report, but has been reproduced with permission of SNCSC from Ezer, T. (2023). Sea level acceleration and variability in the Chesapeake Bay. Ocean Dynamics, (73)(1), 23-24. https://doi.org/10.1007/s10236-022-01536-6

Traceable Accounts for Key Message 2

Acceleration of future sea level rise in the area can be derived from statistical models of past data or from climate models (Boon and Mitchell, 2015; Ezer and Corlett, 2012; Ezer, 2022, 2023; Sweet et al., 2022); all these models predict the increase in sea level rates, though the uncertainty of future sea level increases significantly with time. Compound events—storm surge, heavy rainfall, and high tides when coincide are difficult to predict (Wahl et al., 2015). Local models demonstrate for example that sea level like today's highest normal tide will occur in Norfolk 100% of the time by 2080 under low to moderate sea level rise projections, and by 2100, storm surges may reach nearly twice the height of anything seen in the past 90 years (Ezer, 2022). Observational studies show that flooding thresholds are now exceeded with increasing regularity, even during moderate storms or high tides and predictions show that this trend will continue and accelerate in the future. Ezer and Atkinson (2014) documented that the duration of minor tidal flooding has accelerated in recent years for most coastal locations from the Gulf of Maine to Florida. For example, the average duration of annual minor flooding increased by approximately 20 hours from before 1970 to 1971–1990, but increased by approximately 50 more hours between 1971–1990 to 1991–2013. Sweet and Park (2014) demonstrated that as sea levels rise, the reduced gap between mean sea level and flood elevation thresholds means that smaller storm surges or sea level anomalies increasingly exceed flood level thresholds, transforming what were once rare extreme events into regular nuisance flooding occurrences. Residents along the shores of the Chesapeake Bay are particularly vulnerable to the consequences of sea-level rise, including chronic flooding events, and communities are potentially at risk of chronic inundation from sea-level rise and storm surges by the end of the century (Boesch et al. (2023). Sea level rise can exacerbate minor tidal flooding that causes "nuisance flooding," where even moderate weather fronts passing during high tide can lead to water levels reaching 2 feet above mean higher high water, flooding more streets and overwhelming storm drainage systems. Future flood prediction in the Chesapeake Bay (Ezer, 2022, 2023) show the future acceleration in frequency and severity of flooding everywhere but also indicate large spatial variations along the Virginia coasts, so there is a need for high-resolution downscaling of sea level rise from global and regional climate models into local cities and streets.

Key Message 3: The impacts of sea level rise lead to changes in Virginia's ecosystems and shorelines (*high confidence*), habitat conversion (*high confidence*), groundwater salinization (*high confidence*), and erosion (*high confidence*).

Sea level rise is transforming Virginia's coastal ecosystems and shorelines. Under projected sea level rise, models suggest tidal inundation and salinity will increase, particularly in drought years when there is less freshwater river flow. Local tidal ranges are being affected by increased water depths and volumes that interact with changing estuary characteristics. Tidal amplitudes have slightly increased in the upper Bay and decreased in the lower Bay over the past century. Modeled future tidal range responses vary throughout the Bay and are dependent on management decisions. For example, when sea level rise inundates low-lying land, modeled tidal range is reduced in most areas of Virginia except for some increase in tidal range in upper portions of the Chesapeake Bay estuary. Conversely, hardening shorelines amplifies tidal range everywhere except in the lower Bay. Evidence of the impact of salinity changes can be seen for example in the York River, Virginia (Figure 15), where tidal influence in creek systems migrated towards the headwaters over the past 40 years as water levels rose. Models suggest that continued sea level rise will result in increased average salinity, salt intrusion length, and stratification. These changes propagate through the ecosystem, changing habitat types and associated communities, nutrient storage and cycling, and resulting in saltwater intrusion into coastal systems.

Figure 15

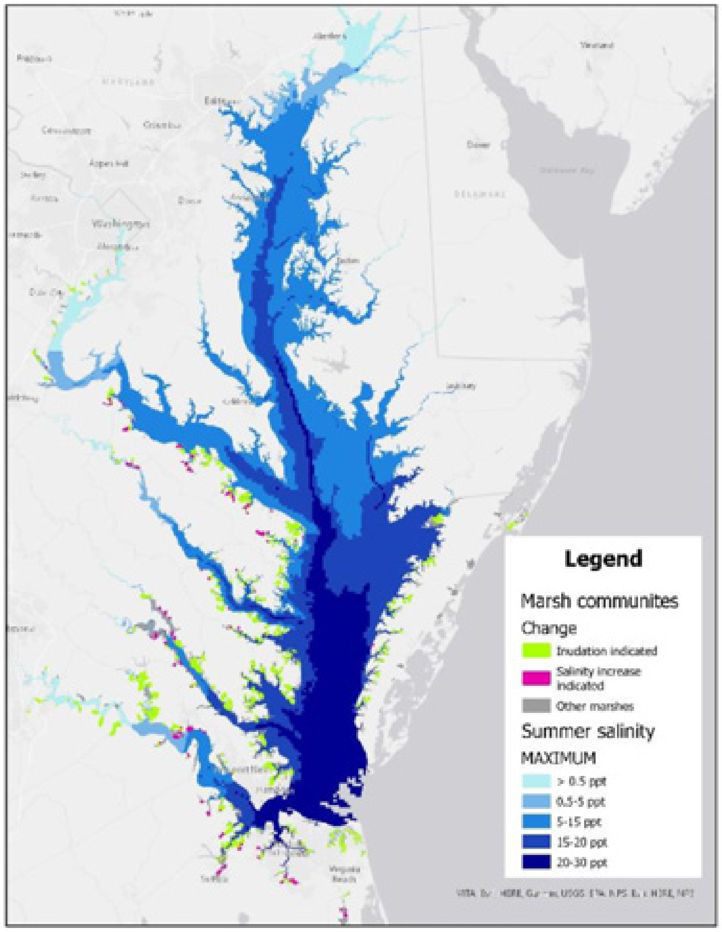


Figure 15. Increasing salinity upriver and rising water levels are shifting marsh plant community locations in Virginia. Areas in blue indicate summer salinity maximum, areas in green indicate inundation regions, and areas in red indicate where salinity increased. Permissions granted to use this image originally published in Mitchell, M., (2018). Impacts of Sea level rise on tidal wetland extent and distribution. (Publication No. 0261D_10041). [Doctoral dissertation, The College of William and Mary]. http://doi.org/10.25773/v5-5s6z-v827

Traceable Accounts for Key Message 3

The impact of sea level rise on salinity and ecosystems in estuaries like the Chesapeake Bay is well documented (Hong and Shen, 2012; Rice et al., 2011). Sea level rise also can change the tidal amplitudes (Hall et al., 2013; Lee et al. 2017). For example, tidal ranges have slightly increased in the upper Chesapeake Bay and decreased in the lower Chesapeake Bay over the past century (Ross et al., 2017). Salinity changes have been monitored in the mainstem of the Bay between 1949 and 2006 (Hilton et al., 2008). In some creek systems vegetative indicators of tidal influence have migrated towards the headwaters over the past 40 years as water levels rose (Mitchell et al., 2017). Modeling suggests that continued sea level rise will result in increased average salinity, salt intrusion length, and stratification (Hong and Shen, 2012) along the mainstem of the Bay and in the tributaries. These changes propagate through the ecosystem, changing habitat types and associated communities (e.g., Mitchell, 2018), nutrient storage and cycling (Weston et al., 2011, Neubauer, 2013), and resulting in saltwater intrusion into coastal systems. Sea level rise-induced saltwater intrusion fundamentally alters coastal ecosystem functions by shifting plant communities from freshwater-adapted to salt-tolerant species, reducing biodiversity and changing nutrient cycling patterns. This salinization process disrupts established food webs, degrades freshwater wetland habitats that serve as critical nurseries for many species, and can lead to the formation of “ghost forests” where salt-intolerant trees die off, ultimately transforming productive coastal ecosystems into less diverse salt marshes or open water areas (Kirwan and Gedan, 2019). Groundwater is becoming more saline contaminating freshwater aquifers and altering soil chemistry—a process that has been documented in abandoned coastal agricultural fields where flooding events dramatically elevate both water table levels and salinity concentrations (Rubin et al., 2024). Simultaneously, accelerated coastal erosion is reshaping Virginia’s shorelines, with the combined forces of higher baseline water levels and more frequent storm surge events removing protective barriers and exposing previously stable inland areas to direct marine influence (Strange et al., 2008). These physical changes are driving substantial carbon and habitat loss throughout the US mid-Atlantic coastal zone, with Virginia experiencing some of the most severe impacts as its low-lying geography makes it particularly vulnerable to the cascading effects of sea level rise (Warnell et al., 2022).

SECTION 3

Impacts and Implications for Virginia

CHAPTER 3A
Heat Risk

CHAPTER 3B
Flood Risk

CHAPTER 3C
Drought Risk

CHAPTER 3D
Cascading Effects and Compound Risks

SECTION 3A

Heat Risk

KEY MESSAGES

1. Heat risk is on the rise in Virginia (*high confidence*), leading to significant health impacts and healthcare costs (*high confidence*).

2. Heat stresses infrastructure and built environments critical to Virginian's daily lives (*high confidence*).

3. Extreme heat impacts ecosystems important to the life, livelihoods, and wellbeing of Virginians (*medium confidence*).

Key Message 1: Heat risk is on the rise in Virginia (*high confidence*), leading to significant health impacts and healthcare costs (*high confidence*).

Extreme heat affects humans through a range of physiological mechanisms that can lead to mortality and hospitalization. In Virginia, where extreme temperatures are often accompanied by high humidity, these impacts may be intensified as humans struggle to dissipate heat. Records show that extreme heat has increased throughout the 21st century in Virginia. Trends in one such indicator, the wet bulb globe temperature (described in Table 1), are as high as 0.29°F (0.16°C) per decade across nearly the entire Commonwealth since 1950. Although there is no one definition of a heat wave, historical trends show a small increase in the number of heat wave days for at least some definitions. Future projections indicate, however, increases between 10–50 days above 95°F (35°C) by the end of the century.

Not all populations are affected equally. Populations with high susceptibility to thermal stress (e.g. young, elderly) as well as those with high heat exposure or low access to cooling (e.g., outdoor workers, unhoused people, transit riders, athletes, and prisoners) are particularly high risk. Heat risk is inequitably distributed, and evidence shows vulnerable populations with both higher temperatures and historical disinvestment due to urban planning policies like redlining and urban renewal, as well as lack of accessibility to cooling capacity in rural areas.

Improving resilience to extreme heat is cost-effective and improves public health. As extreme heat is associated with greater increases in all-cause hospitalizations (217% increase) and emergency room visits (179% increase), adaptation strategies can greatly reduce healthcare costs borne by residents and healthcare systems in the Commonwealth.

Table 1. Common indicators used to measure human heat risk in the U.S.

Dry bulb temperature	Also known as air temperature or even ambient air temperature, this is the most common measure of how hot it feels, and the one most people are used to seeing. Dry bulb temperature is what common thermometers tell us. Historical and current temperatures are often reported from NOAA instruments, which are highly standardized so that their measurements are comparable and not subject to common errors. Air temperatures can stress our bodies, as humans must maintain a core temperature of around 98°F (36.7°C) and a skin temperature of around 95°F (35°C). If ambient conditions are much warmer, our bodies will have to shed excess heat through sweating and other mechanisms.

Wet bulb Temperature	The wet bulb temperature is the temperature that a parcel of air would cool to at 100% relative humidity (saturation). Hence, the value of the wet bulb temperature is always less than or equal to the air temperature. The value of the wet bulb temperature can be calculated (given air temperature, humidity, and atmospheric pressure) or measured directly using a wet-bulb thermometer which is simply a thermometer covered by a wet piece of cloth with air flowing over it to allow for evaporation. The evaporation of water from the soaked cloth on the wet bulb thermometer is analogous to the evaporation of sweat from a person's skin surface, the main mechanism by which humans thermoregulate. This is why wet bulb temperature has routinely been used as the indicator of the environmental limit to human tolerance of extreme heat.
Heat Index	The US National Weather Service (NWS) uses the heat index to provide a "feels like" temperature, which more accurately describes how hot it feels to the human body by combining air temperature with relative humidity. The heat index is calculated for shady, light-wind conditions and may not be applicable to those in direct sunlight, where the heat index value can be up to 15°F higher. The NWS Baltimore/Washington Office issues an Extreme Heat Warning when the heat index reaches 110°F (43.3°C)
Wet Bulb Globe Temperature (WBGT)	WBGT was developed in the 1950s by the United States military as a way to measure heat stress in recruits undergoing basic training due to many falling ill due to heat exhaustion and other heat-related complications. The WBGT incorporates the entirety of the ambient environment's influence on human thermal balance by including direct measurements of radiation (and indirect impacts of wind) into its derivation in addition to air temperature and humidity. Because of the incorporation of radiation into its derivation, it is better equipped to predict outdoor heat stress when compared to other indices such as the Heat Index.
NWS HeatRisk	NWS HeatRisk is a forecasting tool that assesses the potential for heat-related health impacts over a seven-day period by generating a daily risk level. It operates by comparing official NWS temperature forecasts to dynamic, location-specific thresholds. The index evaluates how unusually warm the temperatures are for a location and date, considers the duration of the heat, and assesses whether overnight lows provide relief or add to cumulative stress. It also adjusts for acclimatization, recognizing that early-season heat can be more impactful. Because direct long-term humidity data is scarce, the system infers its effects by analyzing temperature patterns, such as unusually warm nights and small day-to-night temperature swings. These risk levels are ultimately grounded in peer-reviewed science and CDC data on temperatures known to cause health complications, resulting in a comprehensive, 24-hour risk value tailored to specific locations and conditions throughout the year.

Traceable Accounts for Key Message 1

There is a large body of evidence based on the physiological mechanisms that lead to increased mortality and morbidity when humans are exposed to extreme heat (Crandall & González-Alonso, 2010; Kenney et al., 2014; Khatana et al., 2022; Koroxenidis et al., 1961; Vecellio et al., 2022) (*high confidence*).

Climate reanalysis data shows that in Virginia, summer wet bulb globe temperature, a measure of heat stress that accounts for air temperature, radiation, and humidity, has increased since the 1950s (Milrad et al., 2025) (*high confidence*). There is a very high likelihood that these positive trends will continue across emissions scenarios throughout the 21st century (Iturbide, 2022). Historical trends in the number of heat wave days in Virginia across a range of definitions show a small positive trend (*low confidence*) in the 1979–2011 (Smith et al., 2013). Future projections of days with maximum temperatures reaching 95°F (35°C) from the CMIP6 ensemble (Gutiérrez et al., 2021) show increases between ˜10 days (SSP1-2.6) to > 50 days (SSP5-8.5) by end of century (*high confidence*).

In Virginia, observations-based studies have demonstrated links between social vulnerability and urban heat risk (*high confidence*). The evidence has been reported for various regions within the Commonwealth, with an analysis based on citizen-science based data across 10 cities in Virginia showing disproportionately high temperatures in historically redlined neighborhoods and those with high percentages of people of color (M. Allen et al., 2022; M. J. Allen et al., 2025; Hoffman et al., 2020). Intra-urban temperature differences as high as 9.2°F (5.1°C) were observed in neighborhoods with large socially vulnerable populations. A study on heat risk in Richmond, VA found heightened heat emergency rates amongst people experiencing homelessness, alcohol abuse, and mental health issues in Richmond, VA (Braun et al., 2024). Although there is not a large body of evidence specifically for Virginia on the high heat risk in these populations, national scale studies support the Braun et al. findings (Nori-Sarma et al., 2022; Stall et al., 2025). At least one other study found that although there was no difference in mortality rates, patients who were self-identified as drug users experienced longer hospital stays due to heat-related illness. Unhoused and rough sleeping populations also experienced more exposure to heat, in combination with other stressors like air pollution at night, leading to elevated risks (Leggat et al., 2024). An analysis of NOAA-funded urban heat island mapping campaign data showed significant disparities in heat exposure in redlined neighborhoods and those with large black populations across 10 cities in Virginia (Lookingbill et al., 2025). Evidence from all-payer data in Virginia shows large increases in hospitalizations and emergency calls for all causes during periods of extreme heat, leading to increased healthcare costs (Woolf et al., 2023).

Key Message 2 Heat stresses infrastructure and built environments critical to Virginian's daily lives (*high confidence*).

Extreme heat impacts energy and transportation systems, leading to increased costs for users and local authorities. High temperatures increase electric power demand for cooling while decreasing capacity of supply and transmission networks. Cooling degree-days, an indicator of cooling energy demand, has increased in all Virginia Climate Divisions by 19.8 to 45°F-days (11 to 25°C-days) per decade since 1951. The largest increases are in the warmest regions, Tidewater and Northern (Figure 16). Evidence from modeling studies indicates increases in energy demand between 3–5.8% in the Southeast US by 2050. Nearly half of all blackouts occur during the warm season, leaving affected populations exposed to co-occurring extreme heat and its health impacts. Meanwhile, heat index extremes are the most common weather type during outages in counties in the Northern Climate Division. The recent surge in energy intensive data centers, particularly in the Northern division, could impact the sensitivity of the electric system to warming climates as demand for cooling increases as its share of the local grid demand increases.

Extreme heat can disrupt transportation systems through thermal expansion-based deformation of infrastructure and accelerated degradation of materials. Analysis of no-adaptation scenarios in the US highlight extreme heat as the leading driver of road-related costs, and these are highest in the Southeast U.S. Increase in heat-related rail buckling is a driver of projected costs and can lead to loss of passenger rail connectivity in Virginia. Studies show that Virginia could offset over 2 times the cost of future electrical grid impacts by adopting a proactive approach to adaptation as opposed to a reactive approach.

Figure 16

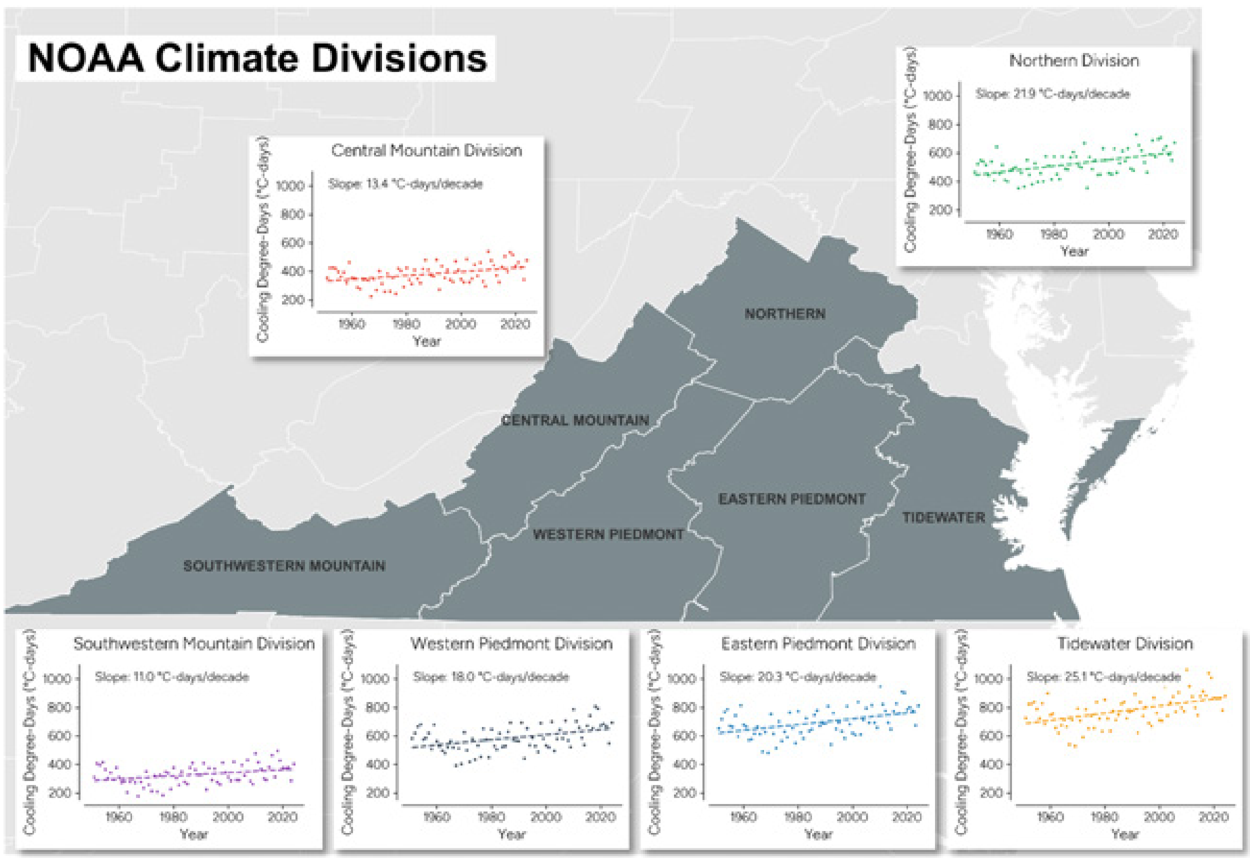


Figure 16. Trends in cooling degree-days by Climate Division in Virginia. All trends are statistically significant (p < 0.001): NOAA nClimGrid-daily.

Traceable Accounts for Key Message 2

The impacts of high temperatures on energy infrastructure are well understood and impact generation, transmission (Bartos et al., 2016), and demand for energy (*very high confidence*). The costs associated with these impacts can be significant, with estimated increases in cooling degree days over 20% by 2050 in the US Southeast and 5.8% projected increase in electric demand (McFarland et al., 2015) (*low confidence, high likelihood*). Electrical grid systems can fail during extreme heat events due to high demand, leading to blackouts that can then threaten the lives of individuals relying on indoor cooling systems (Stone et al., 2021; Stone et al., 2023). Data centers are half of all commercial volume (22% of total) reported by the largest electric utility in Virginia, Dominion Energy (Dominion Energy, 2023), and may increase the sensitivity of energy demand to extreme heat, particularly in the Northern Division (*medium confidence*). There is evidence in recent years that the most common weather type during blackouts in the Northern Climate Division counties is elevated mean and maximum heat index (Saki et al., 2025). However, blackouts in the rest of the state do not appear related to weather events. Although there is no direct evidence that extreme heat has led to data center-related outages, recent reports attribute extended high temperature events with sending data centers offline due to insufficient cooling (Bergen, 2022; Lyngaas, 2022). Recent reports estimate that by 2028, data center electricity consumption will reach between 6.7–12% of the total US use (Shehabi et al., 2024). Cooling degree-day calculations use the nClimGrid-daily dataset aggregated to the NOAA climate divisions (Durre et al., 2022).

The extreme heat impacts on transportation infrastructure are well understood (*high confidence*). Uneven thermal expansion of materials in contact can lead to deformation of joints, rail, and road segments, which can in turn lead to derailments and slowdowns (Croll, 2005; Yang & Bradford, 2018). Rail systems can warp and buckle due to extreme heat, and studies show that in Virginia these impacts can affect passenger rail due to combinations of high ridership and exposure to heat. Counties in Virginia and adjacent Washington, D.C. are particularly vulnerable (*medium confidence*) due to a combination of network connectivity and high heat exposure (Janatabadi et al., 2025). Economic estimates of the impact of climate change are highest in the Southeast US, where temperature-driven failures like buckling for rail and rutting for roads are the lead driver of losses in no-adaptation scenarios (Neumann et al., 2021).

Investments in adaptation strategies today offset significant future costs (*medium confidence*). Virginia could offset over 2 times the cost of future electrical grid impacts by adopting a proactive approach to adaptation (Hoffman et al., 2023). Proactive adaptation strategies for road and rail include temperature sensors for railroad tracks and working to reduce disruption times for roads undergoing repairs, while for electrical grid infrastructure this could include building additional capacity to reduce the load on each transformer, in each case using climate-relevant data to project future risks and responding proactively (Fant et al., 2020; Neumann et al., 2021; Hoffman et al., 2023).

Key Message 3: Extreme heat impacts ecosystems important to the life, livelihoods, and wellbeing of Virginians (*medium confidence*).

Natural systems that provide habitat for important fauna and flora as well as support Virginia's agricultural sector can be sensitive to extreme heat events, impacting Virginians' livelihoods and wellbeing. Increasing growing season length (Figure 17) strains soil and irrigation systems, compounding other climate impacts such as water availability. Urban forests, a common nature-based solution to heat extremes in cities, are projected to experience stress due to elevated temperatures if mean annual temperatures continue to rise.

Native species can struggle with rising temperatures, and new species such as the stone crab or shrimp may thrive in the new environmental conditions. Warmer waterways reduce oxygen levels, increasing stress for fish like brook trout, an iconic Appalachian species. In the Chesapeake Bay, warm water can harm underwater grasses and reduce fish and crab habitat. These impacts are often negative; harmful invasive species and disease vectors may thrive under warmer conditions, while native populations may not be well adapted to extreme heat events. Warmer summers enhance the development of harmful algae blooms (HABs) which impact both marine and human health. There is some evidence that inland wetlands are shrinking or drying out due to heat and drought. Such landscapes provide essential habitats for birding and hunting, capture carbon dioxide, and serve as a buffer during extreme weather events such as nor'easters.

Meanwhile, extreme heat may decrease the attractiveness of natural and historical tourist attractions, negatively impacting local economies. Hotter summers and more frequent heatwaves make outdoor travel less appealing or even dangerous—especially for hiking, beachgoing, and festivals. Peak seasons for fall foliage, spring blooms, and wildlife watching are shifting, creating confusion and lower visitor satisfaction. Reduced snowfall and fewer cold days have also negatively impacted the availability of winter sports like skiing in the region.

Figure 17

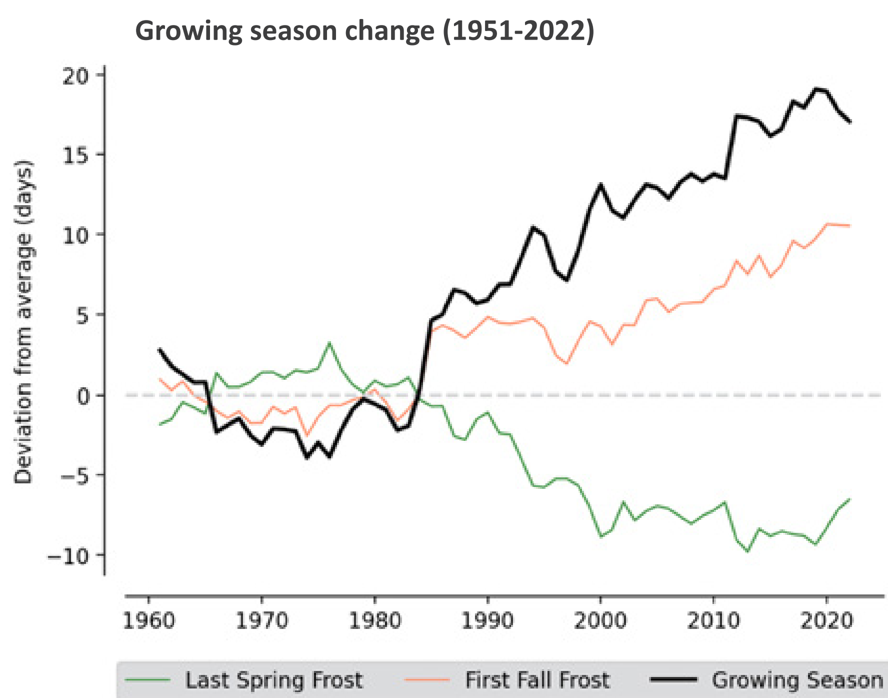


Figure 17. Deviation from 1961–1990 average in date of last Spring frost, first fall frost, and length of growing season. Source: NOAA nClimGrid-daily

Traceable Accounts for Key Message 3

Temperature records, with *very high confidence*, indicate that crop growing seasons in Virginia have become longer as annual temperatures rise (Durre et al., 2022; Mueller et al., 2015). Although this may provide an opportunity for growers to increase production, increasing temperatures may affect yields (*medium confidence*). Recent work has found that a large proportion of urban forest tree and shrub species may be particularly at risk from temperatures exceeding their habitability thresholds due to combined climate and urban heat island effects. In Virginia, the proportion of plants at risk is over 70% (Esperon-Rodriguez et al., 2022).

As annual temperatures change, there is a *high likelihood* native species may become stressed and no longer be adapted to their environment, and some evidence of this happening has been reported for the Southeast US (Ingram et al., 2013; Rogers et al., 2017). Invasive species may also gain traction in new environments as air temperatures rise, and evidence shows that this is the case in the entire Eastern US (J. M. Allen & Bradley, 2016; Bradley et al., 2010). Vector-borne disease spread could rise due to warming temperatures (*low confidence*) as habitability of vectors and breeding seasons lengthen (Cleveland et al., 2023; Deichstetter, 2017; Reiter, 2001). There is some evidence that habitability of land mammals has been impacted, although there are no comprehensive studies on the subject (Pagels & Moncrief, 2015). There is some evidence of new species occupying waters in Virginia's Chesapeake region, as the documented cases of stone crabs show (Hafner, 2025).

Warmer waters have already eased the introduction of invasive species that compete with native species in the Chesapeake (Grosholz, 2023). Moreover, warmer summers have also been crucial in the proliferation of harmful algal blooms, which lower oxygen levels in water habitats and lead to mortality of native species (Byl et al., 2025). Other habitats, like wetlands, have also been impacted by extreme heat (Ballut-Dajud et al., 2022; Salimi et al., 2021), with reconstructed losses since 1700 estimated at close to 50% of total land area in many regions of the Southeast US (Fluet-Chouinard et al., 2023), although attribution of loss of specific wetlands to heat may be difficult in the context of rising sea-level and salt intrusion in the Tidewater region. Other recreationally important regions are projected to be impacted by warming climates (*high likelihood*). As winters warm, Appalachian ski regions will lose between 13.8% (SSP1-2.6) to up to 37% (SSP5-8.5) of snow cover days (*medium confidence*) (Mitterwallner et al., 2024).

SECTION 3B

Flood Risk

KEY MESSAGES

1. Coastal flooding is worsening due to storm surges, sea level rise, and land subsidence (*high confidence*).

2. Pluvial and riverine flooding are causing widespread damage due to intense and frequent rainfall, land use changes, and aging stormwater infrastructure (*medium confidence*).

3. Communities are experiencing flooding due to the compounding effects of coastal, riverine, and pluvial hazards (*high confidence*).

Key Message 1: Coastal flooding is worsening due to storm surges, sea level rise, and land subsidence (*high confidence*).

The Tidewater and Northern climate divisions are increasingly exposed to flooding driven by storm surge, rising seas (see Chapter 2D. Sea Level Rise), and high tides, with land subsidence exacerbating these issues (see Fig. 18). Major events like Hurricane Isabel in 2003 and Hurricane Irene in 2011 caused widespread damage, with stormwater infrastructure design standards being outpaced by current climate conditions. Virginia coastal areas also experience frequent lower magnitude nuisance flooding, disrupting daily life in many ways including infrastructure impacts to commuter roadways, economic hardship of property damage, agricultural losses, saltwater intrusion, and public health concerns with failing septic systems and wastewater overflow. These impacts are felt in various parts of Virginia, where local conditions influence how communities experience and respond to coastal flooding. Looking ahead, future climate projections indicate not only increased intensity of flood events, but also shifts in flood timings, durations, and extents that will reshape how risks are distributed across the commonwealth. In response, local governments are fostering flood awareness and implementing adaptation strategies, including nature-based solutions such as living shorelines, stormwater parks projects, and transportation upgrades. The Virginia Coastal Resilience Master Plan is also providing a statewide framework to guide these efforts.

Traceable Accounts for Key Message 1

There is strong agreement across peer-reviewed studies and state-wide assessments that sea level rise, land subsidence, and coastal storms are very likely increasing flood risk in Virginia's coastal regions (Goodall et al. 2021; Eggleston et al., 2013; Strauss et al., 2014; Ezer, 2018; Ruckert et al., 2019). Tide gauge records and modeling studies confirm that storm surge and tidal flooding are already exceeding historical expectations (Burgos et al., 2018; Mitchel et al. 2023; Jeong et al., 2024; Lashley et al., 2025). Socioeconomic exposure analyses project that areas like Norfolk and Hampton Roads will experience significantly more frequent and severe flooding, with population vulnerability amplifying the social and economic impacts (Crawford et al., 2023; Eghdami et al., 2023). Research also highlights cascading impacts such as infrastructure disruption, public health risks, and potential displacement (Nourali et al., 2024; Mitchell et al., 2023). Road closures are another potential disruption with impacts to different socioeconomic groups across the commonwealth, particularly in the Tidewater and Northern climate divisions (Ruess et al., 2025b), also highlighted in transportation vulnerability assessments (Tahvildari et al., 2021). The duration of flooding is also receiving increased attention as a factor that magnifies infrastructure vulnerabilities (Pezza et al., 2021). Economic loss modeling (McNab et al., 2024; Lorie et al., 2020) and the role of natural and nature-based features (NNBF) in flood mitigation (Glass et al., 2018; Hendricks et al., 2023; Humphreys et al., 2021; Robson et al., 2024; Morris et al., 2019) are also well documented. Household-level adaptation and community-scale resilience are also emerging as key strategies (Yusuf et al., 2025; Ismael et al., 2024). Beyond scientific assessments, coordinated policy and planning efforts are also shaping how Virginia responds to coastal flood risk. The Virginia Coastal Resilience Master Plan provides a statewide framework to support these efforts for the commonwealth (DCR, 2021), with additional tools such as the Virginia Institute for Marine Science Tidewatch Map identifying short-term future coastal flood risk. Coastal municipalities across the commonwealth are additionally making efforts to understand and inform their constituents about coastal flood risks, including places in the Northern climate division (Fairfax County, 2025) and Tidewater climate division (FEMA, 2016; HRPDC, 2019; Norfolk City, 2025).

Figure 18

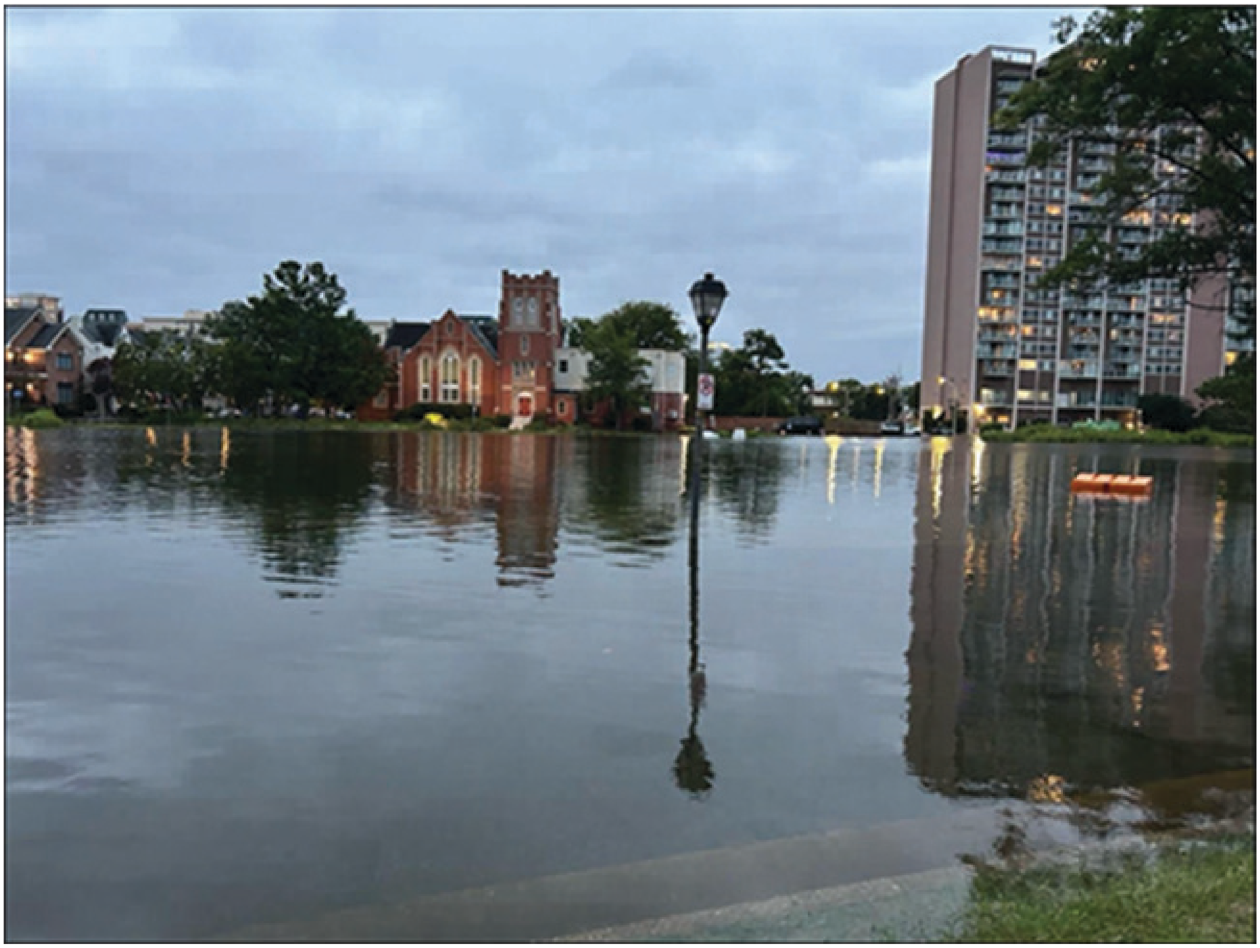


Figure 18. Street flooding from wind associated with the passage of Hurricane Erin off the East Coast in Norfolk. Photo taken and provided by Tal Ezer (Old Dominion University).

Key Message 2: Pluvial and riverine flooding are causing widespread damage due to intense and frequent rainfall, land use changes, and aging stormwater infrastructure (*medium confidence*).

All Virginia climate divisions are experiencing flash flooding and stream overflows, especially during intense, short-duration storms (see Fig. 19A and 19B). Events like the 2022 Buchanan County flood and Hurricane Helene in 2024 caused significant damage to homes, roads, and utilities in the Southwestern Mountain and Western Piedmont climate divisions, including upwards of $159 million in agricultural damages. Tropical Storm Ophelia in 2023 similarly impacted the Tidewater climate division. Urban development combined with aging stormwater infrastructure has exacerbated this risk by significantly increasing impervious landcover. Extreme precipitation will further increase the frequency and severity of pluvial flooding (see Fig. 19C and Chapter 2C. Precipitation). In response, communities are adopting innovative tools and strategies to enhance flood preparedness and resilience, including piloting a flash flood warning system in the Central Mountain region, and developing forward-looking precipitation design standards in the Northern Virginia and Tidewater regions. These local initiatives are complemented by efforts from local governments and watershed managers working to integrate future climate conditions into floodplain planning and stormwater design. Across the commonwealth, the upcoming Virginia Flood Protection Master Plan and the Virginia Department of Emergency Management's Flood Intel Unit are examples of statewide initiatives to support these efforts. Sustained investment in forecasting, data-sharing, and community engagement will be essential to managing risk and building resilience across Virginia.

Traceable Accounts for Key Message 2

There is consistent evidence that heavy rainfall and changes in land use are likely contributing to more frequent riverine flooding in upland Virginia (Dollan et al., 2022; Sridhar et al., 2019; Chilton et al., 2024). Observational and modeling studies show that intense, short-duration storms are overwhelming drainage systems and triggering flash floods, particularly in the Blue Ridge, Appalachian Plateau, and Northern Piedmont (Coelho et al., 2025; Whitehurst et al., 2022; Brendel et al., 2020b). The 2022 Buchanan County flood is a recent example of the severe impacts on rural infrastructure and communities, while Hurricane Helene in 2024 had significant monetary impacts on Southwestern parts of the commonwealth (NOAA, 2025), including upwards of $159 million in agricultural damages (Barlow, 2024). Hydrologic behavior is increasingly variable due to land use change, as shown in case studies across upland watersheds (Ibrahim and Salim, 2023; Pradhan and Loney, 2018). Emerging technologies such as probabilistic flash flood warning tools (Brendel et al., 2020a) and cloud-based alert systems (Sobral et al., 2023) are being piloted to improve preparedness. Local planning efforts are also evolving to incorporate future climate expectations (Grant et al., 2023), while the upcoming Virginia Flood Protection Master Plan (DCR, n.d.a), VDEM's Flood Intel Unit information, and flooding resources like HRPDC's "Virginia Flooding Events and NFIP Insurance Claims" (HRGEO, n.d.) provide statewide information for addressing these risks. An example of flash flooding in Northern Virginia occurred on July 8, 2019 ,when 4.5 in (114 mm) of rain fell in one hour (the equivalent of one month's worth of rainfall), causing nearby Four Mile Run to rise more than 11 feet (3.4 meters); this event caused nearly $10 million in residential damages and over $950,000 in losses to commercial property (Crisis Track, 2019).

Figure 19 (a)

Figure 19 (b)

Figure 19 (c)

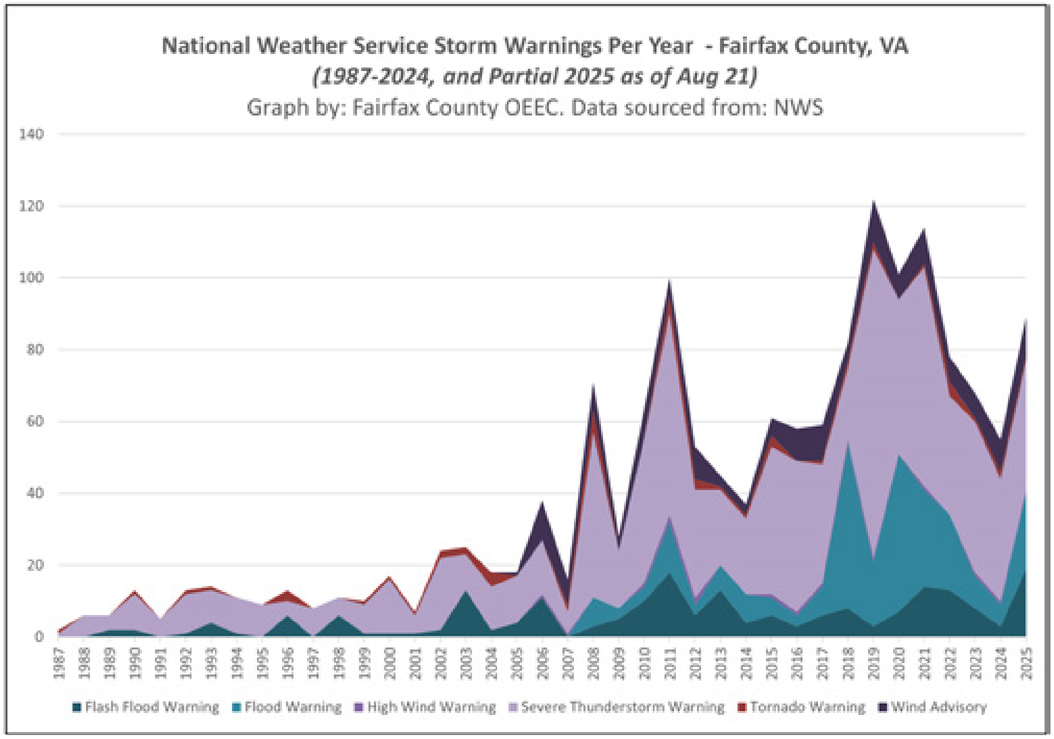


Figure 19. Examples of flooding in Fairfax County, VA, showing A). a swift-water rescue, B). transportation infrastructure failure due to flooding, and C). the increasing trends of flash flooding, thunderstorms, tornadoes, and other related weather events over the past nearly four decades. All figures provided by Allison Homer (Fairfax County).

Key Message 3: Communities are experiencing flooding due to the compounding effects of coastal, riverine, and pluvial hazards (*high confidence*).

Virginia recorded almost $900 million in flood-related damages between 1950–2021. These damages are largely a result of compound flooding, which results from the interaction of multiple hazards, including precipitation, tides, storm surge, and riverine overflows (see Fig. 20). Combined, these flood drivers exceed urban drainage system capacities and amplify impacts to both rural and urban populations in the Tidewater and Northern climate divisions, including areas like the Potomac River corridor, the James River Basin, and the Eastern Shore. Alongside undersized and outdated drainage systems, this causes disruptions to transportation, agriculture, commerce, utilities, emergency services and impacts to public health. Stormwater aging infrastructure in low areas is particularly vulnerable, as higher tides reduce the ability of water to flow downstream, and more intense precipitation events limits drainage capacity and increase inland flood duration. Compound events are often underestimated by outdated flood models, leading to gaps in preparedness and insurance coverage. Looking ahead, climate change is expected to increase the frequency and intensity of these events, especially in densely developed areas (See Chapters 2C. Precipitation and 2D. Sea Level Rise). Communities are beginning to respond with innovative systems, such as green infrastructure, stormwater retrofits, and updated flood models. Stakeholder engagement programs designing customized local solutions have become increasingly important, with $67 million announced through the Community Flood Preparedness Fund in July 2025.

Figure 20

Figure 20. Compound nuisance flooding overwhelming stormwater infrastructure in the City of Alexandria during high-tides and precipitation event. Photo taken by Celso Ferreira (George Mason University).

Traceable Accounts for Key Message 3

There is strong and growing evidence that compound flooding is very likely already affecting both Virginia's urban and rural areas across Tidewater and Northern climate divisions. Compound flooding, caused by the interaction of precipitation, storm surge, tides, and riverine overflow, has been documented in the Tidewater and Northern Virginia regions, and the James River Basin, Eastern Shore, and the Potomac River corridor (Goodall et al. 2021; Tran and Lakshmi, 2024 Chilton et al., 2024; Shen et al., 2022). These events often overwhelm stormwater systems and disrupt transportation, utilities, and emergency services (Tahvildari et al., 2022). In low-gradient coastal regions, aging infrastructure is particularly vulnerable, as reduced gravity head during high tide events limits drainage capacity and increases inland flood duration (Han and Tahvildari, 2024). Outdated flood models used to create flood risk maps often underestimate the risk of compound events, leading to gaps in preparedness and highlighting challenges for preparedness and risk management in the Southeast Atlantic (Nederhoff et al., 2024). Insurance data from the Mid-Atlantic region shows that co-occurring rainfall and high tides significantly increase the likelihood of damage claims (Chen et al., 2023).

Communities are beginning to respond with green infrastructure, stormwater retrofits, and updated modeling. The Virginia Coastal Resilience Master Plan (DCR, 2021) and the upcoming Virginia Flood Protection Master Plan (DCR, n.d.a) both support efforts to address compound flood risks, including significant state-level coordination by the Virginia Department of Conservation and Recreation as well as participation by the Flood Resilience Advisory Committee. Assessments of flood risk for the commonwealth have additionally provided clearer insights for working towards more flood safe futures (SNHR, 2023). The Annual Virginia Flood Preparedness Coordination Meeting brings government agencies and other key stakeholders together to advance and coordinate efforts and expenditures to increase flood resilience and preparedness for the commonwealth. Stakeholders are additionally being engaged through the development of the Community Outreach and Engagement Plan (DCR, 2024). Furthermore, the Virginia Flood Risk Information System (DCR, n.d.b) serves as a valuable resource for accessing Federal Emergency Management Agency flood insurance rate maps (FEMA, n.d.). The Virginia Community Flood Preparedness Fund (Virginia Code § 10.1-603.25) additionally provides significant support to stakeholder-driven flood planning, with $67 million announced in funding in July 2025 (Governor of Virginia, 2025). These efforts are increasingly important as Virginia recorded almost $900 million in flood-related damages between 1950–2021, anticipating upwards of $13 million in annual flood damages in future years (Banbury, 2025).

SECTION 3C

Drought Risk

KEY MESSAGES

1. Drought is an increasing concern in Virginia (*high confidence*), with a shift towards more frequent shorter-term droughts in the past 25 years (*medium confidence*).

2. Flash droughts are particularly dangerous and difficult to respond to due to their rapid development and limited predictability (*high confidence*).

3. Drought heavily impacts agriculture (*very high confidence*), forestry (*high confidence*), water resources (*very high confidence*), and the data center industry (*medium confidence*), with the Western and Northern parts of the Commonwealth being most affected (*high confidence*).

Key Message 1: Drought is an increasing concern in Virginia (*high confidence*), with a shift towards more frequent shorter-term droughts in the past 25 years (*medium confidence*).

Virginia is now and has historically been vulnerable to drought. Recent decades have seen many record-breaking multi-year droughts, including in 1999–2002, 2007–2008, and 2010–2012, as well as more recent shorter-duration droughts in 2023, 2024, and 2025. Drought is the second most expensive disaster in Virginia, behind only hurricanes and tropical storms, costing the Commonwealth 2 to 5 billion dollars from 1980–2024. Drought frequency and intensity are also increasing due to increased water loss caused by elevated heat (see 2B. Temperature) alongside more inconsistent and localized rainfall (see 2C. Precipitation). Changing soil moisture and groundwater losses can also contribute to drought impacts, amplifying risk. As a result, drought costs will likely continue to increase.

Given their complex dependance on multiple overlapping climate factors, drought impacts can develop rapidly and vary sharply across the Commonwealth (see Fig. 21 for a recent example). The Tidewater, Eastern Piedmont, and Western Piedmont climate divisions have similar drought records, with long-term droughts in 2002 and 2008 transitioning to short-term droughts in recent years. The Northern and Central Mountain climate divisions instead had fewer droughts in the early 2000s, but slightly worse conditions in recent years. The Southwestern Mountain climate division has had some of the worst long-term droughts historically, with milder recent years.

Figure 21

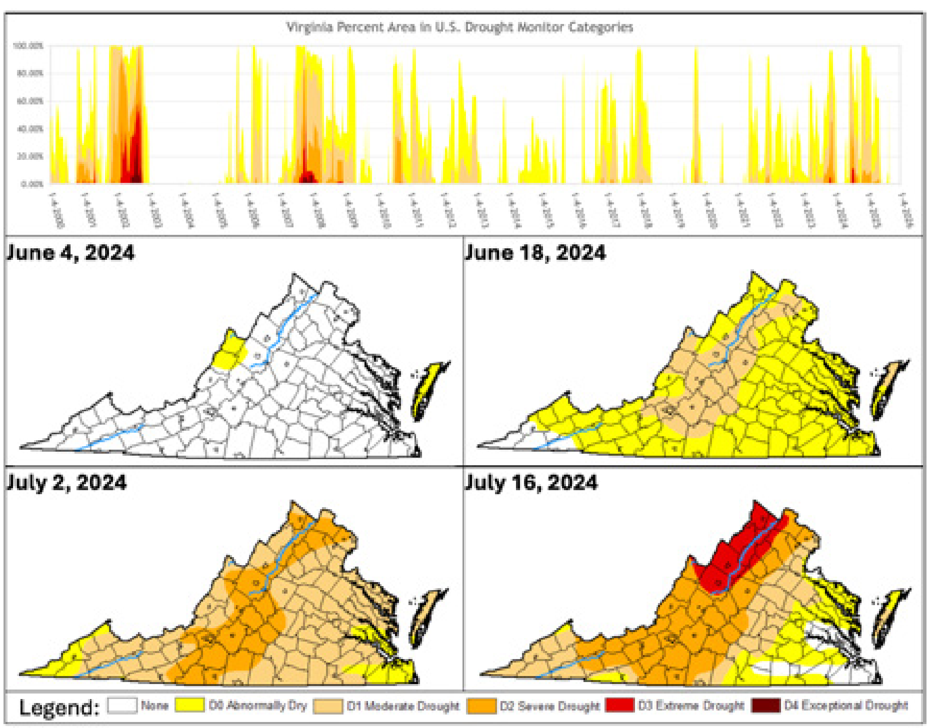


Figure 21. Plot shows Virginia percent area in U.S. Drought Monitor categories, weekly from 2000-present (top). Maps show four specific days representing snapshots every 2 weeks over a 6-week period during the 2024 drought: June 4, June 18, July 2, and July 16. All figures created September 5, 2025 using droughtmonitor.unl.edu

Drought monitoring in Virginia has progressively increased since 2003

Virginia experienced a particularly severe and extended drought from 1999–2002, causing water shortages and service interruptions across the Commonwealth. Given how unprepared the Commonwealth was for a drought of this magnitude and duration, in 2002 Executive Order #39 "The Virginia Water Supply Initiative" was issued, requiring the development of a formal drought assessment and response plan and eventually leading to the development of the Virginia Drought Assessment and Response Plan. This plan, published in 2003, established a robust drought monitoring structure across the Commonwealth. This effort included creating a Drought Monitoring Task Force led by the Virginia Department of Environmental Quality (VDEQ), delineating 13 drought evaluation regions, and defining four drought indicators (precipitation deficit, streamflow, groundwater level, and reservoir storage) along with defined drought level thresholds for triggering additional monitoring actions. This monitoring continues to the present day with regular reports published by the VDEQ summarizing drought risk across the Commonwealth, including a map visualization of drought indicator status (see Fig. 22) as well as regular Task Force meetings to assess regional drought risks.

Figure 22

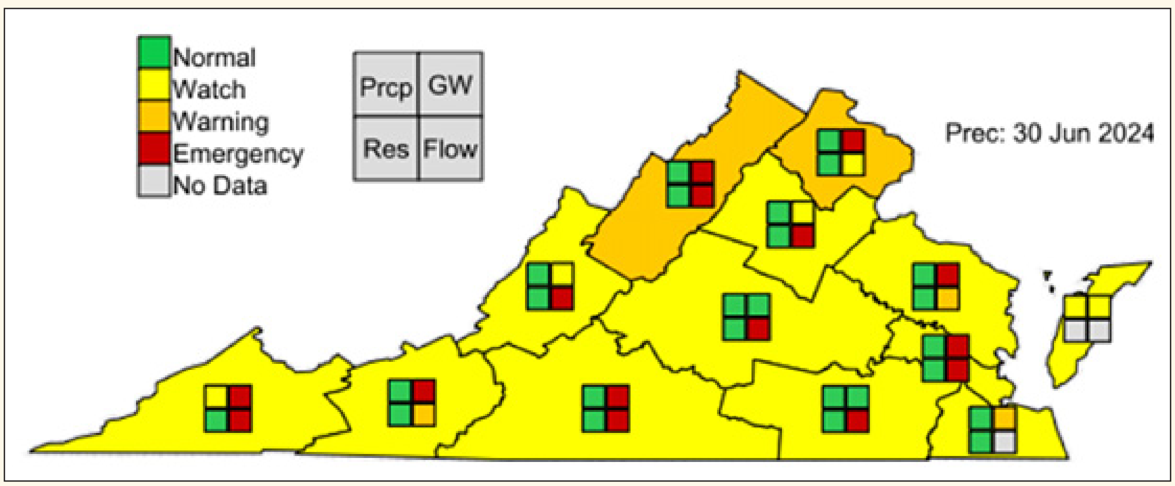


Figure 22. Drought Indicator Status on July 30, 2024, showing drought conditions during the flash droughts occurring at the time as well as highlighting conditions of precipitation, groundwater levels, reservoir, and streamflow levels ("Prcp", "GW", "Res", and "Flow", respectfully). For example, the "Northern Virginia" Drought Evaluation Region (Northeastern-most orange region) was in "Warning" condition at the time, denoting that "The onset of a significant drought event is imminent" (VDEQ, 2025a) with "Normal" precipitation and reservoir levels but streamflow levels in "Watch" state and groundwater levels in "Emergency" state. This map is representative of routinely updated drought monitoring led by the Virginia Department of Environmental Quality, who also serve as the lead member of the Virginia Drought Monitoring Trask Force. Historical image of 2024 drought provided by Virginia Department of Environmental Quality on September 10, 2025.

Traceable Accounts for Key Message 1

Drought frequency and intensity are increasing because of climatic changes due to drought's deep relationship with precipitation, temperature, and evapotranspiration (Trenberth, 2011; Teuling et al., 2013; Valipour, 2015; Runkel et al., 2022; Zhao et al., 2022; Li et al., 2024). The Southeastern US in particular is experiencing an increase in drought frequency and drought risk (Ficklin et al., 2015; Apurv & Cai, 2021; Lackstrom, 2022). Virginia specifically is susceptible to droughts (MWCOG, 2000; VDRTAC, 2003; MWCOG, 2024), with some recent long-term droughts occurring from 1999–2002, 2007–2008, and 2010–2012, with more flash-type droughts in recent years including 2023, 2024, and 2025 (NIDIS, 2025a; USDM, 2025a). Drought is additionally the second most expensive disaster (nearly 20% of total) after tropical cyclones, costing the Commonwealth approximately 2–5 billion dollars from 1980–2024 (NOAA, 2024). Soil moisture is a particularly important variable in Virginia when assessing drought risk (Zaitchik et al., 2013; Xu et al., 2018).

Key Message 2: Flash droughts are particularly dangerous and difficult to respond to due to their rapid development and limited predictability (*high confidence*)

The Southeastern US is especially susceptible to rapid onset "flash" droughts (see Fig. 23), with Virginia seeing recent increases of more than two U.S. Drought Monitor categories (of four total categories) in fewer than six weeks (see Fig. 20). Flash droughts have similar impacts to longer droughts but are challenging to detect and predict due to their rapid development, often resulting in significant economic and ecological damage due to insufficient preparation time. When accompanied by extreme heat (see 3A. Heat Risk), flash droughts typically exhibit higher severity and longer recovery times, making assessments of drought-related cascading effects highly important (see 3D. Cascading Effects).

While historical trends are valuable, the Drought Monitor relies heavily on the Palmer Drought Severity Index, a method known to be slow in detecting flash droughts. The Virginia State Water Resources Plan additionally notes that shorter-term droughts typically have higher errors in hydrologic model runs, emphasizing the need for monitoring improvements. While the 2003 Virginia Drought Assessment and Response Plan does not define soil moisture as a drought indicator (see Call-Out Box above), the Drought Monitoring Task Force has begun considering soil moisture in risk reporting.

Figure 23

Figure 23. A pond near Sandy Hook Road in Strasburg, VA showing dry conditions in October 2019. Photo credit: Richard Cooley, The Northern Virginia Daily. Permissions granted to use this image from Thornberry, M. (2019, October 3). Virginia's drought watch has ranging e«ects for the region. The Northern Virginia Daily. Retrieved November 12, 2025, from https://www.nvdaily.com/nvdaily/virginias-drought-watch-has-ranging-effects-for-region/article_3c09e45b-ce45-5edf-861e-f28914b7f8ac.html

Traceable Accounts for Key Message 2

Shorter-term "flash" droughts are becoming particularly concerning (NIDIS, 2025b) in the Southeastern US and Virginia, which experience a higher frequency of flash droughts compared to the rest of the country (Otkin et al., 2018; Long, 2021; Otkin et al., 2021; Seneviratne et al., 2021; Leeper et al., 2022; Schwartz et al., 2023; Christian et al., 2024; Deepa & Vijayan, 2025; Goswami & Gallant, 2025). While flash droughts do not necessarily have worse impacts than slower droughts (Ho et al., 2023), flash drought impacts can often be very significant due to inadequate preparation due to limited monitoring, predictability challenges, and lack of awareness (Alencar et al., 2024). Hydrologic modeling of short-term droughts is particularly challenging, with drought flow errors in excess of 50% in some parts of Virginia (SWRP, 2020, section B.2.4). Furthermore, when accompanied by extreme heat, flash droughts often become severely exacerbated, with global surveys indicating a range of 6.7–90.8% higher severity and 8.3-114.3% longer recovery times (Gu et al., 2025).

The US Drought Monitor is often considered the "standard" drought measure nationally (USDM, 2025a); however, many drought measures and indices are often not sufficiently nuanced to capture the Southeastern US and Virginia (Lloyd-Hughes, 2014; Bachmair et al., 2016; Li et al., 2024). This is in part due to the Southeastern US needing regionally catered indicators because of wetter conditions than the Western US (Gamelin et al., 2022). More specifically, national-level drought assessments prioritize using Palmer indices (NOAA, 2025; USDM, 2025a) which are known to be slow in detecting quick-onset flash droughts (USDM, 2025b). Alternative drought indices, such as the Standardized Soil Moisture Index, may be more appropriate for short-term drought monitoring across larger areas (Xu et al., 2018).

Drought continues to be monitored in Virginia, with the Virginia Department of Environmental Quality (VDEQ) publishing regular Drought Advisory Updates based on established drought monitoring practices for the Commonwealth (VDRTAC, 2003; VDEQ, 2025). National assessments of drought tend to focus on whole states or climate divisions (USDM, 2025a), while VDEQ's assessments for Virginia use 13 unique regions (VDEQ, 2025), complicating comparisons across these datasets.

Key Message 3: Drought heavily impacts agriculture (*very high confidence*), forestry (*high confidence*), water resources (*very high confidence*), and the data center industry (*medium confidence*), with the Western and Northern parts of the Commonwealth being most affected (*high confidence*).

Drought has significant impacts in Virginia, most notably on agriculture, forestry, water resources, and the data center industry. During drought conditions, agriculture (Virginia's largest private industry, contributing over $80 billion and 380,000 jobs annually) experiences significantly decreased crop yields and livestock production, with some farmers experiencing 90% decreased crop sale revenue during the 2024 drought. With livestock making up most of Virginia's agricultural cash receipts, the Central Mountain climate division is especially vulnerable, as are the Tidewater, Southwestern Mountain, and Western Piedmont (see Fig. 24). Beyond agriculture, data centers in the Northern climate division are also potentially impacted, where more than 300 operational data centers demanded nearly 2 billion gallons of water for cooling in 2023 (up 63% since 2019). Baseflow depletion will increase tidal inundation and saltwater intrusion in coastal regions (see 2D. Sea Level Rise), exacerbated by increased groundwater demands. Longer droughts harm private groundwater wells, influencing rural communities especially. Wildfire risk is also higher during drought (see 3D. Cascading Effects). Decreased soil moisture and vegetation loss further set the stage for increased flash flood risk (see 3B. Flood Risk). Drought-related health risks also include decreased food nutrition, poor air quality, sanitation concerns, and increased likelihood of vector-borne disease.

Figure 24

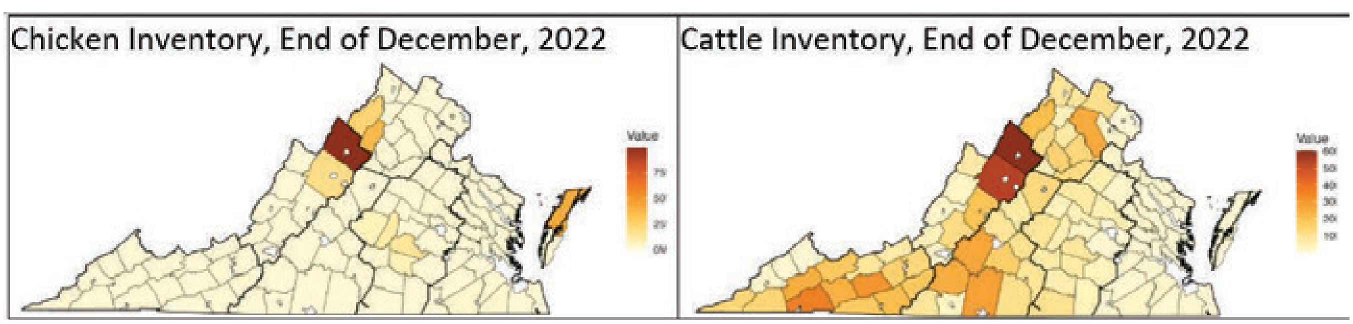


Figure 24. Inventory of Chicken (left, including broilers and roosters, legend in millions) and Cattle (right, including cows and other cattle, legend in thousands) in Virginia for the end of December, 2022. Maps created using data from USDA NASS Quick Stats tool.

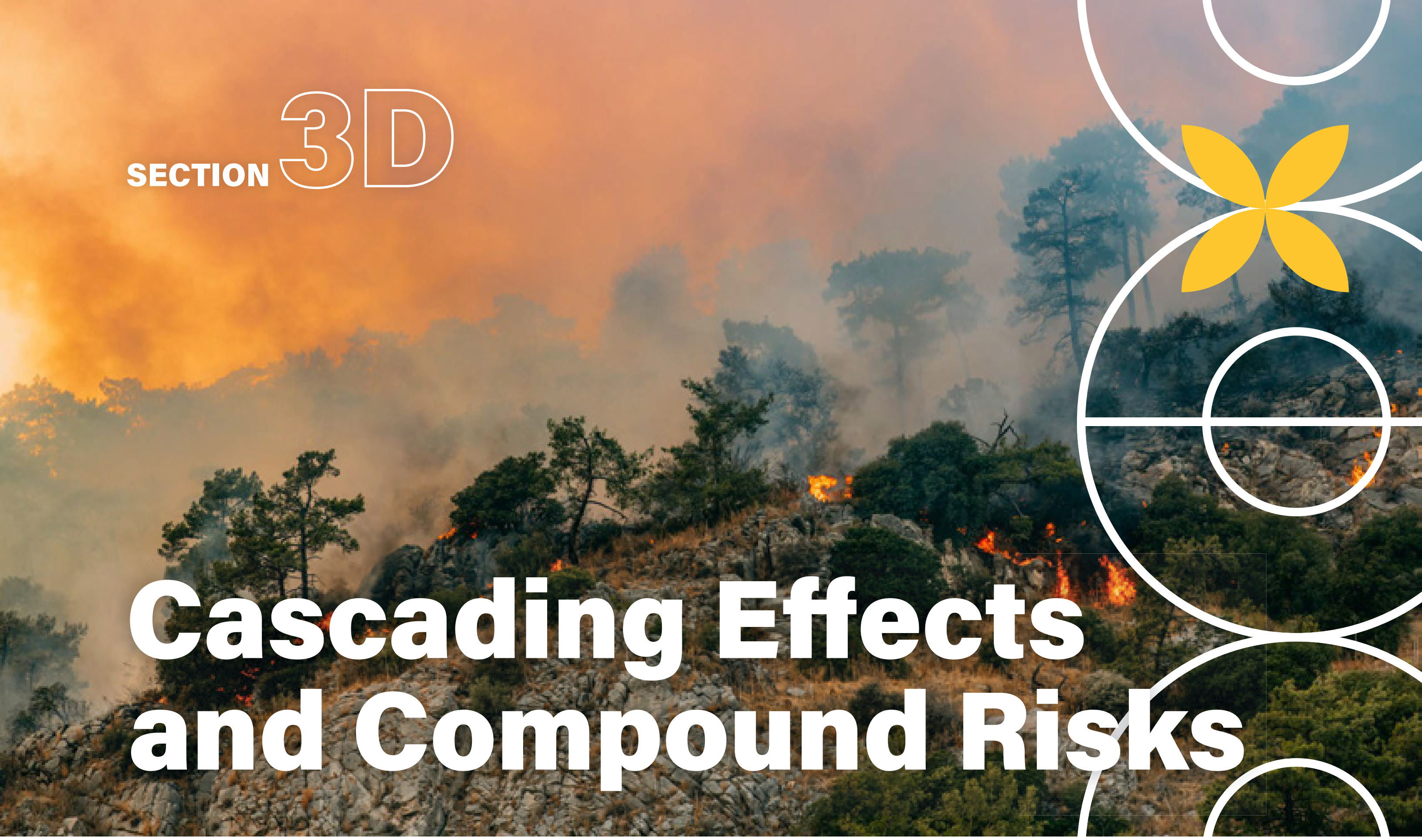
Traceable Accounts for Key Message 3

Drought has impacts on many sectors, perhaps most famously on water supply (NIDIS, 2025c) and agriculture (Mysiak, 2013; Ward, 2014; Kuwayama et al., 2019; Gumidyala et al., 2020; NOAA, 2021; Leeper et al., 2022; Ruess et al., 2025a; USDA, 2025a), though other sectors are also significantly impacted including energy (Siddik et al., 2021) and general health (CDC, 2024). In Virginia, drought has notable impacts on agriculture (Kang & Sridhar, 2017), forestry (Klos et al., 2009; Peters et al., 2015; Hu et al., 2017) and water resources (VDEQ, 2022), historically leading to a variety of impacts including fire danger, water restrictions, hay scarcity, cattle sales, and decreased lake levels (USDM, 2025c). Additionally, 16% of Virginia's combined utility and non-utility generating energy capacity is hydroelectric (Virginia Tech, n.d.), which is known to be vulnerable to drought due to decreased streamflows.

Drought significantly impacts agriculture, which is Virginia's largest private industry with an economic impact of over $80 billion annually and more than 380,000 jobs provided in Virginia (VDACS, 2025a; VFB, 2025a). Farmland additionally makes up approximately 30% of Virginia's total land area (USDA, 2025b) and over 60% of Virginia's food trade stayed in the Commonwealth rather than being exported (Lin et al., 2019; ORNL, 2025). As a result, reductions in Virginia food production have immediate local effects. Impacts can be particularly extreme, with corn production down 40% and some farmers reporting up to a 90% decrease in crop sale revenue during the recent 2024 drought (Staley, 2024; VFB, 2025b). Virginia's top agricultural commodities are broilers by a wide margin, followed by cattle and calves, then miscellaneous crops (USDA NASS, 2024; VDACS, 2025b). Livestock subsequently presents some of the biggest monetary risk when considering disaster impacts, and these impacts would spread to all parts of the Commonwealth (USDA NASS, 2025). Flash droughts are exacerbating impacts on farmers in recent years (Paullin, 2024; Wallace, 2024).

Water resources are also severely impacted by drought, as potential streamflow reductions that are 20% more severe than in previously experienced Virginia droughts are expected in the future (VDEQ, 2022). While groundwater is often considered a valuable alternative water source during times of scarcity (Shortridge et al., 2023), drought can impact local wells and ultimately necessitate changes to water management strategies (Swistock & Sharpe, 2005; VDH, 2015; MPS, 2021). Drought conditions additionally increase the risk of flash flooding due to soil compaction and vegetation loss, resulting in decreased infiltration capacity and subsequent increased runoff during extreme storms (Barendrecht et al., 2024). Drought has also been shown to increase transmission of certain vector-borne pathogens, including West Nile Virus (e.g., Paull et al., 2017)

In Northern Virginia, drought-induced disruptions to water availability in the Potomac River could reduce economic output by more than $4.5 billion in just one month (Thornton & Clower, 2023). Data centers in Northern Virginia are particularly vulnerable to reductions in water availability, where more than 300 operational data centers demanded nearly 2 billion gallons of water in 2023 (up 63% since 2019) (Yañez-Barnuevo, 2025).



SECTION 3D

Cascading Effects and Compound Risks

KEY MESSAGES

1. Compound climate and weather extremes are increasingly cascading into power outages in Virginia (*medium to high confidence*).

2. Rising temperatures are compounding with local and distant pollution sources to degrade Virginia's air quality (*medium to high confidence*).

3. Compound flooding and cascading storm-driven outages threaten to overwhelm Virginia's infrastructure and emergency systems (*medium to high confidence*).

What Are Compound and Cascading Climate Hazards?

Compound and cascading hazards occur when climate-driven events do not act in isolation but instead overlap or trigger chains of impacts that magnify risk. Compound hazards arise when multiple drivers converge at the same time or in close sequence. In Virginia, examples include the interaction of heavy rainfall with tidal flooding in Hampton Roads, or heatwaves coinciding with peak energy demand driving up air pollution. Cascading hazards occur when one disruption propagates through interdependent systems. A storm that causes widespread power outages can quickly cascade into failures of water treatment, telecommunications, transportation, and healthcare. These dynamics are not hypothetical. Since 2000, more than 94% of Virginia's major power outages have been caused by hurricanes, ice storms, and other weather hazards. The 2012 derecho shut down 911 services in Northern Virginia, demonstrating how a storm can disable multiple critical systems at once. In 2023, smoke from Canadian wildfires blanketed Virginia with hazardous air, reducing visibility and prompting public health advisories. In Hampton Roads, sea level rise combined with heavy rainfall has increasingly overwhelmed stormwater systems, closing roads and isolating neighborhoods. Evidence shows that vulnerable populations bear the greatest burdens of these compounding and cascading hazards. Communities with high energy insecurity, limited access to healthcare, or homes in flood-prone areas face longer and more frequent disruptions and higher health risks. Unequal resilience investments across regions deepens these disparities. Conventional risk assessments that consider one hazard at a time underestimate the real threats to Virginia's communities, infrastructure, and economy. Planning for compound and cascading hazards requires integrated approaches that link energy, health, water, transportation, and emergency systems into a cohesive resilience strategy.

Key Message 1: Compound climate and weather extremes are increasingly cascading into power outages in Virginia (*medium to high confidence*).

Extreme weather hazards are the dominant driver of power outages in Virginia. Events such as hurricanes, ice storms, and derechos have disrupted the grid repeatedly in recent decades, leaving millions without electricity. These outages occur more often as the climate warms, and severe weather intensifies. Virginia's electric grid, which depends heavily on overhead distribution lines and includes substations in low-lying and flood-prone areas, was not designed for today's weather extremes. The result is a system increasingly vulnerable to cascading failures when hazards strike.

Outages do not stop at the grid but ripple through every sector of society. When electricity is lost, hospitals, water systems, transportation networks, and communications fail to function as intended. Traffic signals go dark, and emergency services are delayed. Water treatment systems lose capacity and put public health at risk. Telecommunications and access to fuel or medical care are interrupted. These disruptions multiply the impact of the initial hazard, creating a chain of cascading effects across essential services.

The consequences of these outages fall unevenly across communities. Populations with high levels of energy insecurity, chronic illness, or limited mobility experience the harshest outcomes. When outages overlap with periods of extreme heat or cold, vulnerable households are forced to endure conditions that heighten health risks. Northern Virginia's data center corridor introduces a new layer of sensitivity, as concentrated electricity demand during extreme conditions raises the chance of failure across a much larger service area. Uneven resilience investments across regions mean that the communities most in need often remain the least protected.

As power outages become more frequent, their cascading impacts extend beyond service interruptions to affect Virginia's broader stability. Energy disruptions have economic and operational consequences for key sectors—from manufacturing and logistics to the state's expanding data center corridor—while prolonged outages under extreme heat or cold elevate health risks and emergency response demands. These interconnected stresses reveal how climate-driven grid vulnerabilities can undermine regional economies, strain public resources, and slow recovery across the Commonwealth.

Traceable Accounts for Key Message 1

There is very strong evidence that climate and weather hazards are the primary cause of outages in Virginia. Data from the Department of Energy and NOAA show that more than 94% of Virginia's major outages since 2000 have been associated with hurricanes, ice storms, and severe storms (DOE, 2021; Axios Richmond, 2024) (*very high confidence*).

Historical examples highlight the scale of these events. Hurricane Isabel in 2003 left approximately 1.8 million customers without electricity. The 2012 derecho caused more than 1 million outages across the Mid-Atlantic, including Northern Virginia, and interrupted 911 emergency services. A severe ice storm in 2022 left hundreds of thousands without power. Dominion Energy's 2024 Integrated Resource Plan recognizes that much of Virginia's grid remains vulnerable, particularly overhead distribution lines and substations exposed to flooding and wind (Dominion Energy, 2024) (*high confidence*).

The health impacts of outages during extreme temperature events are well documented. Studies show sharp increases in mortality and hospitalization when blackouts coincide with heatwaves or cold spells—for example, a National Review synthesizing 50 studies (Casey et al., 2020) and a multi-city analysis finding that concurrent heatwave–blackout events more than double heat-related mortality (Stone et al., 2023). (Casey et al., 2020; Stone et al., 2023). Although Virginia-specific data on outage-related health outcomes are limited, similar patterns have been observed in empirical evaluations following major U.S. outages, including Hurricane Irma (Skarha et al., 2021) and the 2003 Northeast blackout (Anderson et al., 2012). Taken together, these national studies provide strong evidence of these risks (*high confidence*).

Cascading impacts across interdependent systems are consistently reported. Power loss can disrupt water treatment and wastewater facilities, limit telecommunications capacity, and hinder transportation and fuel access (Union of Concerned Scientists, 2015; DOE CESER, 2024). The 2012 derecho in Virginia demonstrated these failures, with outages cutting power to traffic signals and delaying emergency response (*high confidence*).

Socially vulnerable populations are disproportionately affected. Research shows that disadvantaged groups often face longer outages and greater exposure to associated health risks (Dugan et al., 2023; Klinger et al., 2014). In Virginia, energy insecurity and inequitable access to resources increase exposure to cascading outage impacts. While direct Virginia-specific studies of outage equity remain limited, national findings and local vulnerability data suggest similar patterns (*medium confidence*).

Northern Virginia's data center concentration represents an emerging risk. Dominion Energy reports that data centers now account for approximately 22 percent of its commercial electricity load (Dominion Energy, 2024). Comparable failures during heatwaves in California and the UK, where data centers overheated and shut down, highlight the cascading risks of concentrated demand (Lyngaas, 2022; Bergen, 2022). While Virginia has not yet experienced a data center-driven blackout, the convergence of climate hazards and concentrated load represents a credible and growing concern (*medium confidence*).

Key Message 2:Rising temperatures are compounding with local and distant pollution sources to degrade Virginia's air quality (*medium to high confidence*).

Virginia's air quality is increasingly shaped by climate-driven interactions. Higher temperatures accelerate ozone formation, increase energy demand and emissions, and intensify wildfire activity across North America. These processes converge in Virginia, where local combustion, transported smoke, and unfavorable weather patterns combine to produce degraded air quality. Recent events, including the Canadian wildfires of 2023, demonstrated how distant fires can blanket Virginia with hazardous smoke, while record summer heat continues to drive ozone exceedances across the Commonwealth.

The impacts of degraded air quality cascade through health, infrastructure, and the economy. Short-term pollution episodes raise emergency room visits, exacerbate chronic conditions, and increase premature mortality. Schools close playgrounds, workers face reduced safety on job sites, and residents curtail outdoor activity. Visibility declines disrupt aviation and highway safety, while labor productivity falls in outdoor industries. These ripple effects extend the reach of poor air quality well beyond the atmosphere, touching critical services and daily life across Virginia.

The burdens of degraded air quality fall unevenly across communities. Children, older adults, outdoor workers, and residents with respiratory or cardiovascular illness experience the greatest health risks. Low-income households and communities of color are more likely to live in areas with higher baseline pollution and often lack the means to purchase air filtration or relocate during smoke events. In addition, these populations are more likely to work outdoors and/or commute via public transit, thereby increasing their exposure to ambient air pollution beyond their own residential address. Unequal access to healthcare and protective resources compounds these disparities, leaving the most vulnerable Virginians exposed to the harshest consequences.

Traceable Accounts for Key Message 2

There is strong evidence linking climate change to worsening air quality (Fiore et al., 2015). Combustion processes produce both greenhouse gases and air pollutants harmful to health, while particulate matter can either warm or cool the atmosphere depending on its composition (IPCC, 2021). Particulate matter interacts with clouds and radiation, altering precipitation, circulation, and albedo. Climate change also influences short-term episodes by increasing stagnation events, which are associated with poor air quality days in Virginia. Climate projections indicate an “ozone climate penalty” of several parts per billion due to more frequent unfavorable meteorological conditions, a notable concern given the 70 ppb health-based standard (Jacob & Winner, 2009; Fiore et al., 2015). In the northeastern U.S., future reductions in nitrogen oxide emissions beyond the substantial reductions that have been achieved in the last few decades may mitigate this penalty (Fiore et al., 2015) (*high confidence*).

Observations confirm that wildfire smoke is now a major contributor to degraded air quality in Virginia. Burke et al. (2023) found that wildfire smoke has contributed to stagnating annual average PM2.5 trends since 2016, reversing decades of improvement. During June 2023, smoke from Canadian wildfires produced some of the highest short-term PM2.5 concentrations on record in Virginia, forcing public health advisories and widespread outdoor activity restrictions (CDC, 2023; Crimmins et al., 2023). This provides strong evidence that compounding drivers (rising temperatures and wildfire activity) are directly affecting Virginia residents (*high confidence*).

Cascading effects of poor air quality are well established. Research shows associations between pollution episodes and increased hospitalizations for respiratory and cardiovascular disease (Pothirat et al., 2019). Poor air quality disrupts schools, outdoor work, and transportation systems, with broader economic consequences from lost productivity and reduced tourism (Finlay et al., 2012; U.S. EPA, 2022). The 2020 Virginia Clean Economy Act is projected to yield substantial health improvements and avoided costs by reducing fossil fuel use in electricity generation, highlighting the potential to break these cascading risk chains (Ortiz et al., 2023) (*high confidence*).

Vulnerable populations are consistently shown to bear disproportionate pollution burdens (Henneman et al., 2025). Children, the elderly, and people with asthma or heart disease are most sensitive to degraded air quality. Outdoor workers, particularly in agriculture and construction, are exposed for longer durations during episodes of smoke or ozone exceedances. Low-income households and historically marginalized communities have fewer resources to mitigate exposure and often live in areas with higher baseline pollution (Hoffman et al., 2020). While detailed Virginia-specific studies remain limited, evidence from regional and national analyses strongly supports this conclusion (*medium confidence*).

Key Message 3: Compound flooding and cascading storm-driven outages threaten to overwhelm Virginia’s infrastructure and emergency systems (*medium to high confidence*).

Virginia faces increasing risks from hazards that interact to disrupt critical infrastructure. In Hampton Roads, sea level rise, heavy rainfall, and storm surge combine to produce compound flooding that overwhelms drainage networks and inundates roads. In Northern Virginia, severe storms trigger widespread power outages that cascade into transportation failures and impair emergency services. Both regions illustrate how climate hazards interact with vulnerable infrastructure to magnify risks across systems essential for safety and recovery.

These disruptions cascade across multiple sectors. Flooded roadways isolate neighborhoods, delay emergency response, and disrupt access to hospitals and military installations. Storm-induced power outages disable traffic signals, interrupt 911 services, and stall fuel distribution. In Hampton Roads, floodwaters can mobilize contaminants from industrial and wastewater facilities, creating Natech disasters (natural hazard-triggered technological accidents) that add further stress to public health and the environment. In Northern Virginia, the combination of outages and heat extremes increases the risk of cascading health emergencies during storms.

The consequences of these hazards fall most heavily on communities with limited adaptive capacity. Residents in flood-prone neighborhoods face repeated losses, higher insurance costs, and reduced recovery capacity. Vulnerable populations without vehicles may be unable to evacuate when roads are submerged. Households dependent on electricity for medical devices are at particular risk during extended outages. Without integrated planning that addresses interconnected infrastructure systems, Virginia's most at-risk regions will continue to experience compounding and cascading impacts that strain emergency response and undermine resilience.

Traceable Accounts for Key Message 3

There is strong evidence that Hampton Roads is among the nation's most vulnerable regions to compound flooding. Sea level at Sewells Point has risen 17 inches since 1927, one of the fastest rates on the East Coast (Runkle et al., 2022). Han and Tahvildari (2024) demonstrate how storm surge and rainfall interact to produce compound flooding in Norfolk and Virginia Beach. These conditions regularly overwhelm stormwater systems and close major roads, disrupting emergency access and daily mobility (*high confidence*).

Evidence also shows that cascading storm-driven outages have already strained Northern Virginia's emergency systems. The 2012 derecho caused more than 1 million outages across the Mid-Atlantic, including Northern Virginia, and interrupted 911 services (Runkle et al., 2022). Dominion Energy reports that overhead distribution lines and limited redundancies make the grid particularly sensitive to severe storms (Dominion Energy, 2024). DOE CESER (2024) highlights the cascading risks of storm-induced blackouts for transportation and emergency response (*high confidence*).

Cascading impacts across systems are well documented. Floodwaters in Hampton Roads threaten to inundate Superfund and Toxic Release Inventory sites, creating Natech disasters that release hazardous materials into communities (Crawford et al., 2023). Flood-driven contamination events have also been observed in California (Cushing et al., 2023), suggesting similar risks in Virginia. In Northern Virginia, power outages disable traffic signals and delay emergency response, increasing the likelihood of secondary emergencies (DOE CESER, 2024). These multi-sector cascades are supported by both local and national evidence (*high confidence*).

Socially vulnerable populations bear disproportionate impacts. Communities with high social vulnerability scores in Hampton Roads are more likely to live in flood-prone areas, face higher costs of recovery, and lack access to transportation (Crawford et al., 2023). In Northern Virginia, medically dependent populations and households with limited financial resources are most exposed to outage-related risks. While Virginia-specific empirical studies remain limited, patterns of exposure and vulnerability documented nationally strongly support these conclusions (*medium confidence*).

SECTION 4

Exposure to Climate Risks and Hazards

KEY MESSAGES

1. All of Virginia's economic sectors and natural systems are sensitive to climate change and face increased exposure to risks that affect many activities, places, and populations (*medium to high confidence*).

2. One of the most important effects of climate change in Virginia is its impact on key economic and employment activities and populations in each region (*medium to high confidence*).

3. One of the most important effects of climate change on Virginia's economic sectors is its impact on critical infrastructure which underpins a functioning economy (*medium to high confidence*).

Key Message 1: All of Virginia's economic sectors and natural systems are sensitive to climate change and face increased exposure to risks that affect many activities, places, and populations (*medium to high confidence*).

Nearly all sectors of the Virginia economy face some degree of exposure to climate hazards, and more than 3 million residents already live in high multi-hazard risk counties. Table 2 below organizes Virginia's major sectors (rows) against four cross-cutting areas of exposure (columns); labor and human health, infrastructure and utilities, supply chains and production, and ecosystems; demonstrating the impacts climate hazards have on every sector, across multiple dimensions.

Five separate billion-dollar flood disasters have impacted Virginia since 1980, and over 1.4 million socially vulnerable residents live in areas where such events trigger cascading impacts across housing, health, and infrastructure systems. Housing flood exposure is expanding. Flood insurance premiums in Virginia are projected to rise by ~45%, and more than 340,000 Virginia homes, nearly 10% of the state's housing stock, are already at substantial flood risk.

In the agriculture sector, Virginia's farmland is predominantly rain-fed, with limited irrigation and encompassing significant low-lying coastal areas, leaving the sector exposed to drought and flooding risks. Virginia's natural resource-based recreation economy is valued at ~$9 billion. Natural systems like forests in the Central and Southwestern Mountains face landslide risks from extreme rainfall, while in the Tidewater marshes and islands are eroding and submerging, reducing habitat that supports fisheries and tourism livelihoods. Heatwaves are having worsening impacts statewide, including at least 13 documented worker fatalities and 620 injuries (gross undercounts) from "environmental heat" between 2011 and 2018.

Even economic sectors considered low risk, like finance, depend on exposed systems (power grids, road networks, and cooling infrastructure) that are vulnerable to storms, flooding, and extreme heat. As Virginia's climate hazards intensify, exposure is not just localized, it is systemic and interconnected, creating conditions for cascading impacts that can ripple across geographies and sectors.

Traceable Accounts for Key Message 1

Statewide exposure was assessed using the FEMA National Risk Index (NRI) at the county level, classifying whether Virginia counties were in the top third nationally by overall risk score, and summing resident populations of those counties, adding up to more than half of Virginia population (FEMA, 2023) (*high confidence*). Population vulnerability was assessed using the CDC Social Vulnerability Index (SVI), which ranks census tracts nationally by socioeconomic, demographic, and housing factors. In Virginia, more than 1.4 million residents live in tracts classified among the top 10% most socially vulnerable nationwide (CDC, 2022). Hazard exposure was assessed using FEMA NRI, which provides county-level multi-hazard ratings based on expected annual loss, social vulnerability, and community resilience. More than 3 million Virginians live in counties with a "Relatively High" or greater multi-hazard risk score (FEMA, 2023). Communities where these designations overlap represent populations that are simultaneously highly vulnerable and highly exposed (EPA, 2021b).

Historical flood-related loss exposure is characterized by counting Virginia-implicating billion-dollar flood disasters (inflation-adjusted ≥ $1B) in the NOAA NCEI database, five events since 1980 (NCEI, 2024a) (*high confidence*). Flood insurance exposure was assessed using Policygenius flood premium projections, which estimate that average NFIP premiums in Virginia will increase by ~45% following implementation of FEMA's Risk Rating 2.0 methodology, from $743 to approximately $1,077 annually (Policygenius, 2023). Housing exposure was quantified using the First Street Foundation's national flood risk model, which finds that 344,400 Virginia homes (~9%) are currently at substantial flood risk, projecting a significantly higher exposure footprint than existing FEMA flood maps indicate (First Street Foundation, 2020; U.S. Census, 2024) (*medium confidence*).

Agricultural exposure in Virginia is shaped by limited irrigation, widespread rain-fed acreage, and vulnerability of coastal farmland (*high confidence*). The 2022 Census of Agriculture reports only 61,216 irrigated acres statewide, about 0.84% of land in farms and 5.5% of farms, demonstrating limited irrigation capacity (USDA NASS, 2022). Nearly 1 million acres of non-alfalfa hay were harvested in 2022, a predominantly rain-fed crop that is sensitive to precipitation deficits (USDA NASS, 2023). In coastal regions, spatial analysis has documented saltwater intrusion on farmland: about 2,200 acres in Virginia have already been visibly impacted, and adjacent cropland faces yield declines that together are projected to cause $39–70 million in annual agricultural revenue losses (University of Maryland et al., 2023; VIMS, 2020). Forests in Virginia mountain regions are at risk from degraded ecosystems and loss of biodiversity, which puts at risk Virginia's natural resource-based recreation economy, valued at over $9 billion annually (Aylor, 2023) (*high confidence*).

Virginia's mountainous regions are highly landslide-prone not only during episodes of extreme rainfall but also in the aftermath of drought. Dry periods kill or weaken vegetation, increasing wildfire risk; once slopes are burned, they are highly susceptible to landslides from even modest rainstorms (U.S. Geological Survey, n.d.; Araújo Santos et al., 2020). Commonwealth geological assessments, based on USGS mapping, show that more than half of western Virginia counties fall within high-risk zones, with historic storms like Hurricane Camille (1969) triggering thousands of debris flows (Virginia DOE, n.d.). Climate Central's Virginia and the Surging Sea assessment projects that sea level rise and coastal flooding could permanently inundate thousands of acres of low-lying marshes and barrier islands, placing critical habitats, fisheries, and coastal tourism assets at risk across the Chesapeake Bay and Tidewater regions (Strauss et al., 2014). The Bureau of Labor Statistics reported that from 2011 to 2018 in Virginia, at least 13 workers died due to excessive heat, and another 620 missed work because of heat-related illnesses and injuries. It is acknowledged that these figures are gross undercounts, as Bureau of Labor Statistics (BLS) estimates of heat-related illness, injury, and death are extremely conservative, and because many heat-related illnesses and deaths are blamed on natural causes (VCCA, 2020) (*medium confidence*).

Federal assessments document dependencies that extend risk exposure to sectors like telecommunications and finance. DOE's analysis shows power generation and cooling systems are vulnerable to storms, flooding, and heat (DOE, 2016a, DOE, 2016b) (*high confidence*). The FCC's Resilient Networks NPRM indicates that communications infrastructure depends on uninterrupted power, accessible transportation routes for maintenance, and temperature control for equipment, all of which can fail during extreme climate events (FCC, 2021) (*high confidence*).

Table 2: Sector-Level Risks and Hazards by Area of Exposure Applicable to Virginia

This table summarizes how each major Virginia economic sector is exposed to climate hazards across four cross-cutting areas: people and labor; buildings, infrastructure, and utilities; supply chains and production; and natural systems. Each row can be read as a sector profile, showing the types of climate-driven risks that affect that sector across multiple parts of its operations. The columns show the different pathways through which hazards disrupt sector performance, demonstrating the systemic nature of exposure across Virginia's economy.

Economic Sector/ Activity	Key Areas of Risk Exposure and Hazard			
	Labor, Employment, Human Populations	**Buildings, Infrastructure, Equipment, Utilities**	**Supply Chain, Production, Distribution**	**Plants, Animals, Ecosystems**
Commerce, Industry	Heat stress, injury risk, degraded air quality (ozone, wildfire), and lost workdays for outdoor retail/logistics workers from extreme heat and storm-related closures	Damage or disruption to facilities (stores, warehouses, ports, manufacturing and industrial areas) from flooding, wind; HVAC strain during heatwaves; closures from telecom outages	Closure of sites or disruption of services due to damage to facilities or interruption in energy and telecom; disruption of shipping, affecting distribution of inputs and finished products	Negative impacts on commerce around nature-based tourism and recreation spending (see more under Recreation)
Education	Heat stress in schools without adequate AC; absent students and impacts on teachers and staff from extreme event disruptions; reduced student learning and cognitive performance during high-temperature periods	Damage to schools and education buildings due to flooding or extreme weather.	Closure due to extreme events causing power outages; disruption in transportation, school food distribution in rural areas; telecom outage impacts to learning	Negative impacts and reduced access to natural resource demonstration areas, biological and environmental research and education due to damages to natural areas (see more under Forest and Natural Lands, Wildlife)
Energy, Telecommunications	Heat stress and degraded air quality affecting outdoor powerlines, plant, and telecom workers; elevated risk of accidents during extreme weather conditions	Flood/wind damage to power plants, transmission lines, substations, telecom networks; grid stress and outages from heat wave demand spikes; cooling water shortages during droughts	Disruption to energy production and distribution due to infrastructure damage, causing downstream service interruptions	Spills from flooding damage to fuel pipelines causing cascading impacts; wildfire damage to distribution infrastructure from drought/heat waves, especially when combined with extreme wind events

Economic Sector/ Activity	Key Areas of Risk Exposure and Hazard			
	Labor, Employment, Human Populations	**Buildings, Infrastructure, Equipment, Utilities**	**Supply Chain, Production, Distribution**	**Plants, Animals, Ecosystems**
Forest and Natural Lands, Wildlife	Heat stress and degraded air quality effects on forest and wildlife workers; safety risk from wildfires	Road and trail washouts, erosion damage from flood and drought extreme oscillations; wildfire damage to infrastructure	Timber transport delays from road washouts or wildfire closures	Heat stress on natural vegetation and wildlife, damage to vegetation from wind and flooding, insect-borne disease and flood-related diseases in livestock and wildlife, landslides and erosion damage to forests and other natural lands, saltwater intrusion in coastal lands
Government Services, Public Safety	Heat stress and degraded air quality exposure for emergency responders; high workload during extreme events	Extreme event damage to public buildings, equipment, emergency operations centers; impacts from power or telecom outages	Disruption of services due to disruption of transportation routes, telecommunications, power	
Housing	Heat stress and degraded air quality (ozone, particulate matter) exposure for construction workers; extreme heat, cold, and flood exposure risks to unhoused populations; increased demand for emergency shelters during and after disasters.	Flooding, wind, hail damage to housing; loss of habitable units and displacement increase demand on temporary housing and emergency shelter systems following extreme events	Disruption of supply chain for construction materials; local shortages or construction price spikes due to clustering of damage and resulting construction demand	Construction debris and runoff impacts on local water and habitats due to flooding and wind

Economic Sector/ Activity	Key Areas of Risk Exposure and Hazard			
	Labor, Employment, Human Populations	**Buildings, Infrastructure, Equipment, Utilities**	**Supply Chain, Production, Distribution**	**Plants, Animals, Ecosystems**
Medical	Heat-related illness; insect-borne disease and flood-related diseases; injury risk from extreme events response	Damage to hospitals, clinics, elder care facilities, equipment (generators, vehicles, etc.), power lines, telecommunication lines, pipelines, roads due to flooding, wind, and other extreme weather; extreme heat increasing demand putting stress on electrical grids and cooling systems; flooding impacts on water treatment and water quality.	Disruption of medical and emergency services or closure of sites, limited access, damage to facilities, or interruption in energy and telecommunications; shortages of medicines, equipment, or supplies during extreme events	Public health degradation from ecological degradation (water quality, pests) creating high potential for vector-borne and other infectious diseases
Military	Heat stress on outdoor personnel	Damage to buildings, equipment (generators, water treatment, construction equipment, farm equipment etc.), power lines, telecommunication lines, pipelines, roads due to flooding, wind, and other extreme weather; extreme heat increasing demand putting stress on electrical grids and cooling systems	Disruption of supply chain for supplies, fuel, and parts deliveries	

Economic Sector/ Activity	Key Areas of Risk Exposure and Hazard			
	Labor, Employment, Human Populations	**Buildings, Infrastructure, Equipment, Utilities**	**Supply Chain, Production, Distribution**	**Plants, Animals, Ecosystems**
Recreation	Heat stress and degraded air quality (smoke, ozone) affecting park/ recreation workers and visitors to outdoor recreation sites; safety risk to visitors during extreme weather	Flood/wind damage to beaches, trails, campgrounds, facilities, lodging; reduction in outdoor tourist activity due to extreme heat; damage to coastal lodging	Disruption of tourist amenities due to access issues; closure of sites due to flooding or damage from extreme weather	Coastal beach land loss from sea level rise; trail washouts due to flooding; forest ecosystem damage due to wind, flooding, landslides; wildfire damage due to drought and extreme heat; ecosystem losses due to baseline climate changes
Transportation	Heat stress and degraded air quality (ozone, smoke) affecting road, rail, port, and construction workers	Damage to roads, bridges, ports, buildings, equipment, power lines, telecommunication lines, pipelines due to flooding, wind, and other extreme weather; extreme heat increasing electricity demand putting stress on electrical grids and cooling systems	Disruption of freight transportation routes due to flooding or damage from extreme weather; disruption of access in rural communities	Ecosystem damage from fuel spills or debris from ports and coastline areas after hurricanes and storm surge
Water	Heat stress and degraded air quality (ozone, smoke) affecting outdoor workers	Flood/wind damage to water treatment plants, pumping stations; drought limiting water supply	Disruption of water treatment and delivery of service due to extreme weather; sewer and stormwater overflow due to precipitation rates surpassing system capacity; irrigation water delivery disruptions from drought	Disruption of water for irrigation or natural water resources for ecosystems and wildlife; saltwater intrusion from sea level rise; damage to aquatic habitats from extreme storm events

Source: Center for Climate Strategies

Key Message 2: One of the most important effects of climate change in Virginia is its impact on key economic and employment activities and populations in each region (*medium to high confidence*).

Many of Virginia's top leading regional economic and employment producers are exposed to climate risks and hazards. In Tidewater, leading employers, health care, military support services, tourism, and transportation, are impacted by sea level rise, tidal flooding, and hurricanes. By 2050, tidal flooding alone around Chesapeake Bay could jeopardize ~263,500 jobs and $11 billion in wages, and by 2045, $2.1 billion in coastal homes are at risk of chronic inundation.

In the *Eastern and Western Piedmont*, agriculture, logistics, and manufacturing face high direct exposure to climate-driven hazards like heavy rainfall, drought, and extreme heat. In 2019, repeated flash flooding events inundated roads and commercial areas in Petersburg and Richmond. Heatwaves increasingly threaten labor productivity and worker safety in agriculture and construction, with up to 1.8 million labor hours lost annually by 2050.

Northern Virginia's economic output, based in government and data infrastructure, depends on continuous access to high-functioning transportation and facility operations. Flash floods in 2019 and 2021 overwhelmed parts of Fairfax County, shutting down arterial roadways and temporarily closing government buildings, demonstrating an instance where a localized event threatened government functions.

In the *Central and Southwestern Mountain* regions, the economies driven by manufacturing, health care, forestry, energy production, and tourism are exposed to erratic rainfall, heat-driven drought, and landslides. Extreme precipitation has damaged roads and cut off rural communities, while drought in more than 60 Virginia counties in 2023–2024 resulted in degraded forage quality, undercutting livestock viability in counties already burdened by economic hardship. These conditions have triggered USDA drought disaster declarations and required significant aid spending. Deeper overviews of expected losses to key regional economies are shown below in Table 3.

Traceable Accounts for Key Message 2

Census County Business Patterns (CBP) data were used to identify leading employers and sector composition in the Tidewater (ports, military support services, tourism, and transportation). Job and wage exposure figures (~263,500 jobs; ~$11.1B by 2050) are taken from a Chesapeake Bay analysis that links projected tidal flooding with employment and payroll distributions (Liao, Pesek, Walls, & Ferreira, 2023) (*medium confidence*). Property exposure figures (~9,030 Virginia homes; ~$2.1B in value at risk by 2045) are drawn from the Union of Concerned Scientists' coastal inundation risk analysis (UCS, 2018). These losses have direct implications for the estimated $23,094,209 local tax base from coastal properties, as well as Tidewater's tourism- and recreation-driven economic activity.

In the Eastern/Western Piedmont, economic effects (freight delays, flooded commercial corridors, facility downtime) from the 2019 flash-flood events in Petersburg/Richmond are drawn from NWS storm reports and local accounts documenting inundated roads and commercial areas (NWS Wakefield, 2019; Vasicek, 2022; Vogelsong, 2021). The precipitation chapter documents an increase in heavy precipitation events across Virginia, raising the likelihood of freight delays and facility downtime in agriculture, logistics, and manufacturing. The National Climate Assessment notes that heavy rainfall and flooding frequently block or damage critical infrastructure such as roads, bridges, railways, energy networks, and supply chains, leading to operational disruptions across sectors (Reidmiller, et al, 2017) (*high confidence*). These findings are consistent with regional analyses showing statistically significant increases in extreme daily rainfall across the Mid-Atlantic (Dollan, Maggioni, & Johnston, 2022).

Projected heat-related labor losses were quantified using exposure–response functions applied to future heat metrics, with EPA estimating that by 2050, up to ~1.8 million labor hours per year may be lost in Virginia's outdoor and heat-exposed jobs (*medium confidence*). These projections align with evidence of worker exposure, inequities, and infrastructure strain discussed in the Heat Risk chapter; while adaptation measures (e.g., work-shift changes, cooling access) can reduce realized losses, baseline risk increases with continued warming (EPA, 2021a).

In Northern Virginia, flash floods in 2019 and 2021 led to major road closures and temporary shutdowns of public buildings, as documented in NCEI storm event records. These localized disruptions demonstrate the sensitivity of government operations and data infrastructure to pluvial flooding, where even short-lived access failures can have significant economic consequences (NCEI, 2024b; Sharif, Maggioni, & Dollan, 2025) (*high confidence*).

In the Central and Southwestern Mountains, extreme precipitation has damaged rural roads and bridges, isolating communities, and disrupting business operations (NCEI, 2024b) (*high confidence*). At the same time, USDA drought disaster declarations have been issued in more than 60 Virginia counties across consecutive years, reflecting widespread grazing and forage stress that reduces livestock viability in regions already experiencing economic hardship (VDACS, 2023) (*medium confidence*). These conditions have prompted significant federal aid spending through USDA disaster assistance programs supporting livestock and forage producers (USDA 2024; USDA, 2025c).

Table 3: Key Hazards and Exposure of Virginia Economic Sectors by Climate Division

This table shows how leading economic sectors in each NOAA climate division of Virginia are exposed to specific climate hazards, using FEMA Expected Annual Loss categories as indicators of regional risk. Read down each column to see which hazards cause the greatest expected losses in each region; read across each row to understand how key sectors in that region are sensitive to those hazards. The far right column provides brief notes on the most important sector-level vulnerabilities in each region. The key to the right explains the loss categories and indicates the dollar ranges associated with FEMA's Expected Annual Loss estimates.

NOAA Climate Division	Top Economic Sectors[1]	FEMA Expected Annual Losses by Hazard, Loss categories with values over $3 million [2]										Notable Sector Level Exposure and Sensitivity to Climate Hazards
		Hurricane	Coastal Flooding	Riverine Flooding	Tornado	Strong Wind	Drought	Hail	Ice Storm	Heat wave	Wildfire	
Tidewater	Health care and social services; Retail trade; Professional, scientific and technical services; Manufacturing; Accommodation and food service	Building value ($50-$310 million); Population equivalence ($10-$50 million); Agriculture value ($3-$10 million)	Building value ($50-$310 million); Population equivalence ($3-$10 million)	Building value ($10-$50 million); Population equivalence ($10-$50 million)	Building value ($10-$50 million); Population equivalence ($10-$50 million)	Population equivalence ($3-$10 million)	Agriculture value ($10-$50 million)		Building value ($3-$10 million)	Population equivalence ($3-$10 million)		• Health care – emergency access; hospital resilience • Military support services – naval base recurrent flooding • Tourism – coastal land loss, storm surge, and access disruptions to beachfront economies • Transportation and freight – major ports and shipping • Agriculture – hurricane and drought
Western Piedmont	Health care and social services; Manufacturing; Professional, scientific and technical services; Retail trade	Building value ($10-$50 million)		Building value ($3-$10 million)	Building value ($3-$10 million)	Population equivalence ($3-$10 million)						• Health care – flooding and power loss affect access • Manufacturing & Industry – 100+ extreme heat days/year • Other Sectors – floods inundating buildings, transportation, and telecommunication infrastructure
Northern	Professional, scientific, and technical services; Health care and social services; Information; Federal civilian workforce, Retail trade	Building value ($50-$310 million); Population equivalence ($3-$10 million)		Building value ($3-$10 million); Population equivalence ($3-$10 million)	Building value ($3-$10 million); Population equivalence ($3-$10 million)	Building value ($3-$10 million); Population equivalence ($10-$50 million)		Building value ($3-$10 million)		Population equivalence ($3-$10 million)		• Secure data infrastructure – damage to data center infrastructure, electricity supply • Federal agencies and government contractors – disruption of mobility, telecommunication • Urban Heat & Health – vulnerability especially in lower income neighborhoods • Housing – flooding/storm damage in low lying areas
Central Mountain	Health care and social services; Manufacturing; Retail trade	Building value ($3-$10 million)		Building value ($3-$10 million); Population equivalence ($3-$10 million)		Population equivalence ($3-$10 million)						• Health care access – floods disrupt road, power, and communication access to health services • Manufacturing – extreme heat, supply chains • Forestry – e.g. spring 2024 wildfires • Energy generation disruption • Tourism and Retail – flooding impacts on access
Eastern Piedmont	Finance and Insurance; Health care and social services; Professional, scientific and technical services; Retail trade; Accommodation and food services	Building value ($50-$310 million)			Building value ($3-$10 million); Population equivalence ($3-$10 million)	Population equivalence ($3-$10 million)	Agriculture value ($3-$10 million)			Population equivalence ($3-$10 million)		• Agriculture – high drought vulnerability, low irrigation rates • Logistics & Freight – storm and flooding impacts on freight corridors • Other Sectors – floods inundating buildings, transportation, and telecom. infrastructure • Tourism and Retail – flooding impacts on access
South-western Mountain	Manufacturing; Health care and social services; Retail trade			Building value ($3-$10 million); Population equivalence ($3-$10 million)							Building value ($3-$10 million)	• Manufacturing - extreme heat, supply chains Health care access – flooding causes mobility and access issues • Forestry – 2024 wildfires and invasive species • Energy production – concerns for flooding related spills • Tourism and Retail- mobility, flooding, storms • Food & Nutrition – high regional food insecurity, fragile supply chains and access

Source: Center for Climate Strategies

1. *Sectors in the top three in terms of either payroll or employment. Based on County Business Patterns (CBP, 2022), Census of Agriculture (USDA, 2022), and Federal Employees by Congressional District (ACS, 2023)*
2. *Based on FEMA expected annual losses. Only shows the areas of risk where expected annual losses for the region are above $3 million.*

FEMA Expected Losses Key

Building value	$3-$10 million
Population equivalence	$10-$50 million
Agriculture value	$50-$310 million

Key Message 3: One of the most important effects of climate change on Virginia's economic sectors is its impact on critical infrastructure which underpins a functioning economy (*medium to high confidence*).

Virginia's economy depends on reliable infrastructure like data centers, ports, highways, military, water treatment, and the electric grid, all of which face mounting climate risks. Disruptions to infrastructure threaten job access, supply chains, and essential services. For example, Hampton Roads handles $73B in annual trade through its port facilities, supporting over 436,000 jobs statewide; storm surge and sea level rise threaten key terminals and access routes.

Northern Virginia, home to the world's largest concentration of data centers, with 13% of global data center capacity, has seen outages and is increasingly exposed to flash floods, extreme heat, and grid strain. Tidal flooding and storm surge at Naval Station Norfolk, the world's largest naval base, threatens military readiness and necessitates multi-billion-dollar resilience projects.

Statewide, 94% of major power outages stem from weather-related events. Hurricane Isabel alone caused $128 million in grid damage and left 1.8 million residents and businesses without power. As heatwaves intensify, the Department of Energy warns that storm damage and peak demand prices will drive utility cost increases.

Flooding especially is straining Virginia's transportation and stormwater systems, primarily in coastal and mountainous regions where road washouts, culvert failures, and drainage overflows are increasingly common.

Infrastructure faces increased exposure to climate risk and cascading effects of related hazards and loss and damage across sectors and communities, particularly where infrastructure is aging, under-resourced, or operating near capacity. A picture of the many precipitous impacts from just one severe event is shown below in Figure 25.

Traceable Accounts for Key Message 3

Virginia's economic reliance on infrastructure systems is documented in Commonwealth planning and sector studies. VDOT resilience plans highlight elevated flood and storm risks to roads, bridges, and drainage networks (VDOT, 2021; VDOT, 2023). Virginia's Coastal Resilience Master Plan identifies climate threats to ports and military facilities (Commonwealth of Virginia, 2022), while VIMS analyses confirm the vulnerability of Tidewater coastal infrastructure to sea level rise (VIMS, 2020). NVTC emphasizes that Northern Virginia's concentration of data centers depends on reliable power and cooling systems (NVTC, 2024).

The economic scale of the Port of Virginia is documented by ITA, which attributes ~$73 billion in annual trade and more than 436,000 Virginia jobs to port-related activity along supply chains (ITA, 2019). NOAA sea level rise assessments identify Hampton Roads as one of the most vulnerable U.S. port regions, with storm surge and tidal flooding threatening terminals and critical access routes (Runkle et al., 2022) (*high confidence*).

Northern Virginia hosts the largest global concentration of data centers, with industry reports estimating that the region contains 13% of global data center capacity (JLARC, 2024). Dominion Energy identifies flash flooding, grid reliability, and rising cooling demand under extreme heat as growing risks to facility operations

(Dominion Energy, 2022). Data center–grid interactions have already created operational challenges for U.S. grid operators (McLaughlin, 2025), and storm-related outages have disrupted major cloud services, including the AWS us-east-1 outage during the 2012 derecho (Miller, 2012) (*high confidence*).

Naval Station Norfolk, the world's largest naval base, faces recurrent tidal flooding and storm-surge exposure that directly affects military readiness (*medium confidence*). NOAA coastal risk assessments identify Hampton Roads as one of the nation's most vulnerable regions for sea level rise and nuisance flooding (NOAA, 2022) (*high confidence*). Federal oversight further documents that resilience at Norfolk and other Hampton Roads installations will require large-scale, multi-billion-dollar investments to sustain base operations and surrounding economic activity (GAO, 2019). These findings align with the Sea Level Rise chapter's documentation of high relative sea level rise in Tidewater.

An analysis by Climate Central confirms that 94% of major power outages in Virginia over the past two decades were caused by weather-related events—a figure that aligns with national trends showing severe weather as the dominant driver of grid disruption (Climate Central, 2024). A prominent example is Hurricane Isabel (2003), which caused an estimated $128 million in grid damage and left ˜1.8 million customers without power, (NOAA, 2024; VSCC, 2004) (*high confidence*). DOE assessments warn that heatwaves and storms increase utility costs by driving peak demand prices, causing storm-related damage to transmission and distribution systems, and accelerating wear on grid equipment (DOE, 2022) (*medium confidence*). These projected pressures are consistent with the Virginia Heat Risk chapter's findings of rising heat metrics relevant to energy demand and cooling.

VDOT asset resilience plans and VIMS analyses document that heavier rainfall increasingly causes road washouts, culvert failures, and drainage overflows, particularly in coastal and mountain terrain (VDOT, 2021; VIMS, 2020). The precipitation chapter further reports intensification of heavy-rainfall statistics that increase these failures.

The ASCE 2021 Infrastructure Report Card identifies Virginia's roads, bridges, water, and energy systems as aging, under-resourced, and often operating near capacity, conditions that heighten vulnerability to climate hazards and cascading failures (ASCE, 2021). EPA's adaptation assessments also emphasize that aging water, wastewater, and stormwater systems face amplified risks under extreme rainfall and heat, increasing the potential for cross-sector disruptions (EPA, 2024) (*high confidence*).

Figure 25. Example of Cascading Impacts of a Single Extreme Weather Event (i.e., extreme precipitation)

This is an example of how one climate driven event (extreme rainfall) can start multiple chains of impact and feedback loops resulting in numerous risks, hazards, and economic and social impacts to populations, natural systems, economic sectors, and activities.

Source: Center for Climate Strategies

Color key:

- blue = climate risk impact driver
- green = hazard exposure on natural and human-built infrastructure
- yellow = hazard impacts on activities and services
- orange = climate loss and damage

Figure notes:

- *Bubbles are sized to fit text and are not indicative of impact magnitude.*
- *Solid lines indicate direct impacts between impact levels (e.g. driver -> hazard exposure or hazard impact -> loss and damage), while dotted lines indicate linkages within impact level (e.g. telecom -> emergency services).*

SECTION 5

Glossary

Adaptive capacity – The ability of people, communities, institutions, or ecosystems to adjust to climate change, moderate potential damages, and cope with consequences

Atlantic Bermuda High – A semi-permanent, subtropical area of high pressure in the North Atlantic Ocean off the East Coast of North America that migrates east and west with varying central pressure

Atlantic Meridional Overturning Circulation (AMOC) – A system of ocean currents that circulates water within the Atlantic Ocean, transporting warm and cold water and nutrients

Coastal flooding – Inundation of land areas along the coast due to storm surge, high tides, or sea-level rise

Compound flooding – Occurrence of multiple flood drivers (e.g., storm surge and rainfall) that combine to worsen impacts

Cooling degree day – A measure of how much and how long the temperature requires air conditioning, typically when daily average temperatures are above 65°F

Debris flow – A fast-moving landslide composed of water, soil, rock, and organic matter, often triggered by intense rain on burned or saturated slopes

Derecho – A widespread, long-lived, straight-line windstorm

El Niño-Southern Oscillation (ENSO) – A periodic fluctuation in sea surface temperature (El Niño) and the air pressure of the overlying atmosphere (Southern Oscillation) across the equatorial Pacific Ocean that influences seasonal weather variations worldwide

Environmental heat – A Bureau of Labor Statistics classification for occupational injuries, illnesses, and fatalities related to high ambient temperatures and heat stress

Expected Annual Loss (EAL) – A FEMA metric that estimates the average economic loss in dollars per year from specific natural hazards, based on hazard probability and potential impacts

Exposure – The presence of people, assets, infrastructure, or ecosystems in places that could be adversely affected by climate hazards

Flash drought – The rapid onset or intensification of drought, typically within a timeframe of weeks

Flash flooding – Rapid-onset flooding caused by intense rainfall over a short duration

Flood extent – The total area inundated during a flood event

Floodplain – Low-lying land adjacent to a river or coast that is subject to flooding

Fluvial flooding – Flooding caused by rivers or streams overflowing their banks

Gravity head – The force driving water flow due to elevation difference between two points

Green infrastructure – Network of natural or semi-natural systems that manage water, improve environmental quality, and support resilience

Inland flooding – Flooding that occurs away from coastal areas, often due to heavy rainfall or river overflow

Land subsidence – Gradual sinking or lowering of the ground surface due to natural processes (e.g., sediment compaction) or human activities such as groundwater withdrawal.

Living shorelines – Shoreline stabilization techniques that incorporate natural materials and vegetation to reduce erosion and enhance habitat

Madden-Julian Oscillation (MJO) – An eastward moving disturbance of clouds, rainfall, winds, and pressure that traverses the planet within tropical latitudes and influence weather outside the tropics

Natech disasters – Natural hazard triggered technological accidents

Nature-based solutions – Actions that use natural systems, processes, or features to address societal challenges such as flooding and erosion

Nor'easter – A storm formed along the East Coast of North America with winds typically from the northeast

North Atlantic Oscillation (NAO) – Differences of atmospheric pressure between the Icelandic Low and the Azores High over the North Atlantic Ocean that drive fluctuations of weather in North America and Europe

Nuisance (or tidal) flooding – Minor, recurrent flooding caused by high tides or rainfall that disrupts daily life but does not meet major flood thresholds

Palmer Drought Severity Index – A measurement of drought that uses monthly temperature and precipitation data to estimate dryness in a given region

Pluvial flooding – Flooding resulting from heavy rainfall that overwhelms surface drainage systems, occurring away from rivers or coasts

Radiative forcing – A measure of the influence a given climatic factor has on the amount of downward-directed radiant energy upon Earth's surface

Resilience – Capacity of systems, communities, or infrastructure to withstand, recover, and adapt to adverse conditions

Saltwater intrusion – Movement of seawater into freshwater aquifers, often caused by rising sea levels or excessive groundwater pumping

Stormwater – Rainwater or melted snow that runs off surfaces like roofs, roads, and lawns instead of soaking into the ground

Systemic risk – Risk that spreads across interconnected systems, where impacts in one sector (e.g., energy) create disruptions in others (e.g., finance, telecommunications)

Thermal stress – The physical and physiological reactions of the human body to temperatures that exceed the human thermal threshold

Wastewater overflow – Discharge of untreated or partially treated sewage from sanitary systems into the environment due to heavy rainfall or infrastructure failure

Wet Bulb Globe Temperature (WBGT) – A measure of heat stress in direct sunlight that factors in air temperature, humidity, wind speed, sun angle, and cloud cover

SECTION 6

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