

Climate Change Trends, Impacts and Vulnerabilities for Great Smoky Mountains National Park and Blue Ridge Parkway, USA

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This document seeks to provide climate change vulnerability assessment for a variety of important resources of Great Smoky Mountains National Park and the Blue Ridge Parkway. It originated from a working group formed in September of 2015 that included staff both from the National Park Service and the USDA Forest Service Southern Research Station, Eastern Forest Environmental Threat Assessment Center. The content derives from the Forest Service's TACCIMO (Template for Assessing Climate Change Impacts and Management Options) tool, is a web-based information delivery tool that connects climate change science with forest management and planning needs. TACCIMO is a dynamic database of peer-reviewed scientific findings and forest plan components that has been used to develop a climate change vulnerability assessment and briefing papers for the Nantahala and Pisgah National Forests. The goal of the working group was to combine park-specific knowledge of resources of concern with the scientific literature already summarized in TACCIMO.

We would like to thank Dr. John Gross for his suggestions to improve this document and for early access to the book "Climate change in Wildlands: Pioneering approaches to science and management in the Rocky Mountains and Appalachians," in press.

Historical and Projected Climate Change

Temperature

Across the National Park System (410 units), temperatures have increased from 1895 to 2010 at a rate of $0.9^{\circ}\text{C} \pm 0.2^{\circ}\text{C}$ per century, with two thirds of the system area experiencing statistically significant increases, much of which were in Alaska. The southern Appalachians have been slow to show the warming trend exhibited on a global scale, presumably due to the effects of the North Atlantic Oscillation, the cooling effect of precipitation, El Nino, and other factors. No significant increase in ground-level temperature was detected in Great Smoky Mountains National Park between 1980 and 2011 except for warming of minimum temperatures in the spring, however

average annual temperature changes have been higher in the western half of the park. All Global Climate Models (GCM) project warming across the region by mid century. Ensemble mean changes show mean annual temperature exceeding 2° C over most of the land. The largest changes in mean temperature are in the high latitudes of North America while the smallest changes are over the Southeastern United States. The GCMs project warming over all seasons with most models suggesting the greatest warming occurring during the summer months. Overall, the mean annual temperature is expected to increase between 3 - 5° C (depending on the emission scenario). Within the Smokies, near-stream locations are warmer in the winter and cooler in the summer, and low elevation sites more closely track broader weather patterns than high elevations. If precipitation and cloud cover remain high, high soil moisture may buffer regional temperature change at high elevations, however some models predict the number of days with daily average temperatures below freezing may drop in the southern Appalachians by more than a month, or be eliminated altogether.

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Precipitation

For both the Park and the Parkway, precipitation has been trending upward from 1950-2010 compared to the historical range of variability, but that change has not been statistically significant. Precipitation changes have been highest in the central mountain ridge of the Smokies. Climate models do not agree to the extent, nor even the direction, of change in precipitation in the southeast. Compared to historic (1985-1993) hydrologic conditions for the southeast, annual precipitation and evapotranspiration in 2020 are projected to either slightly increase, or decrease dramatically depending on the general circulation model used. Multiple models are used and the best consensus between them is arrived at. In general, precipitation is expected to increase across most the Southeastern United States. Specifically, the multi-model mean projects an increase up to 6% in precipitation across the eastern states (Tennessee, Kentucky, Alabama, Georgia, South Carolina, North Carolina, and Virginia) of the Southeast and a decrease up to 3% in precipitation over the western states (Western Arkansas and most of Louisiana). The largest decrease in precipitation is expected to occur during the summer months. The multi-mean model projections indicate most of the SE will experience a decrease in summer precipitation up to 15%. Throughout the remaining seasons, the majority of the SE region is expected to experience an increase in precipitation.

Snowfall is predicted to decline, especially during the early portion of winter, and snowpack is also expected to decrease with increased melting between storms.^{2, 6, 11-14}

Extreme Events

Through 2010, data from Coweeta Hydrological Laboratory, south of the Smokies, showed an increase in intensity of storms or short duration, but not an increase in the number of storms per month. Likewise, there has been a trend towards more frequent and more prolonged periods of drought. Different climate change models for the southern Appalachians range from predicting an increase in drought frequency of 6.2 years per decade (over 1.4 years per decade current) and elimination of extreme wet years (CGCM1), to increasing extreme wet year frequency to 2.8 years

per decade (over 0.8 years per decade current) and elimination of drought years. CMIP5 models predict both the frequency and intensity of tropical cyclones to increase.¹⁵⁻¹⁷

Cloud Base Elevation

Predicting cloud base height is important to determining the impact of climate change on high elevation habitats. Thermal inversions and high incidence of cloud fog commonly at or above the regional atmospheric boundary layer may provide resistance to climate warming for high elevation habitats. Over most of the Eastern United States, the cloud base level has seen a positive trend in recent decades. However, one study found that stations south of 37.5 N experienced a decreasing trend in the cloud base level. Those stations included cities in the Southern Appalachian Mountains (i.e. Asheville, NC). Additionally, considering deforestation is known to impact local climate, one study researched how deforestation impacted the lifting condensation level (LCL) in the Caribbean. The study found that areas of deforestation experienced differences in their normal LCL from orographic lifting. In fact, after deforestation, the LCL formation was higher.¹⁸⁻²²

Bermuda High

Li et al. (2012) studied how the Northern Hemisphere subtropical highs would respond in a warming climate. The authors found that the North Atlantic subtropical high (or the Bermuda high) intensified in recent years. This intensification caused the western ridge to shift westward in the summer months. This alteration impacts regional weather, climate, and tropical cyclone movement which inherently impacts the Southeastern U.S. Consequently, the authors sought to determine if this intensification was due to natural or anthropogenic variability. Li et al. (2012) concluded the intensification was due to excess Greenhouse gases. Therefore, the Bermuda high is expected to intensify and expand westward and northeastward in the upcoming decades.²³

Natural Climate Variability

There are numerous naturally occurring factors that can cause the climate to deviate from the norm. The climate can vary on many time and spatial scales. Some climate variability has global impacts while others alter the regional climate. These fluctuations are known as climate oscillations. Climate oscillations cause atmospheric temperature, sea surface temperature, and precipitation to deviate either above or below their average, which impacts the global or regional climate. There are a few climate oscillations that impact the climate of the Southeastern United States. Specifically, the El Niño-Southern Oscillation, Arctic Oscillation, and North Atlantic Oscillation.

The El Niño-Southern Oscillation (ENSO) consists of two phases determined by sea surface temperature (SST) deviations across the equatorial Pacific. If the SSTs are above normal, then ENSO is considered an El Niño or warm phase. If the SSTs are below normal, then ENSO is a La Niña or cool phase. The strongest impacts typically occur during the winter months. Additionally, both phases impact the Southeast quite differently. Higgins et al. (2002) found that an El Niño enhances the subtropical jet stream, which causes above average precipitation across the southern

states. El Niño also reduces the probability of winter temperature extremes across the south. In contrast, La Niña is associated with negative precipitation anomalies and increased risk of drought across the region. Lastly, La Niña can also cause warmer than normal temperature conditions over most of the region.

The Arctic Oscillation's (AO) phase is determined by differing barometric pressure over the polar cap region and midlatitudes. There are two phases associated with the AO, which are a positive and negative phase. A positive AO tends to cause above average temperatures over the Southeast, while a negative AO simultaneously decreases the number of warm days and shift temperatures anomalously cooler.

The North Atlantic Oscillation (NAO) comprises of a positive and negative phase, which is calculated from sea surface pressure differences between the Icelandic Low and Azores High. A positive phase NAO directs warm, moist air from the south into the Southeast, which can cause anomalously warm temperatures and an increased frequency in rain/snow events. A negative NAO favors more cold temperature outbreaks, which causes unusually cool temperatures across the region.²⁴⁻²⁹

Climate Change in the Broader Southeastern United States

Thus far, the Southeastern United States exhibited relatively little warming and a slight increase in precipitation during the 20th century. By the end of the 21st century, the models indicate that this may no longer be the case. The Regional Climate Trends and Scenarios for the U.S. National Climate Assessment used two emission scenarios for the model runs. The A2 represents a high emission scenario and the B1 represents a low emission scenario. The report covers future scenarios for temperature and precipitation.

Both emission scenarios project increasing temperatures across the region throughout the remainder of the century. Figure 1 shows both emission scenarios, which includes annual mean temperature ranges from 1.5-3.5°F by 2035. For the low emission scenario, annual mean temperatures could range between 1.5-4.5°F by 2055 and 2.5-5.5°F by 2085. For the high emission scenario, annual mean temperatures could range between 3.5-5.5°F by 2055 and 4.5-8.5°F by 2085.

Overall, the simulated annual mean temperature change is between 3-5°F above the reference period (1971-2000), with the greatest warming in the northwestern quadrant (Fig. 2). Additionally, Figure 2 shows the mean temperature change during each season. The summer mean temperature ranges 3.5-6°F above with the greatest warming in the northwestern part of the region. The fall mean temperature ranges from 3-5°F above with the most warming occurring in the northern and western part of the region. The winter mean temperature ranges from 2.5-5°F above with the greatest warming in the northern states. Lastly, the spring mean temperature ranges around 2.5-3°F above with similar changes across the region.

Climate model simulations for temperature extremes were run for the high emission scenario (A2), with the threshold of days exceeding a maximum temperature of 95°F and a reference period of 1980-2000. Across the entire region, annual number of days exceeding 95°F are simulated to increase by 2070. The largest increase, in the annual number of days exceeding 95°F, is around south central Florida at about 35 days annually, while the least is along the Southern Appalachian mountains at around 4-10 days annually. In contrast, days dropping below 10°F are simulated to decrease by up to 14 days in the northern tier of the region. Lastly, days less than 32°F are projected to decrease across most of the region. The largest decrease of up to 20 days occurs along the northern states of the region.

The changes in precipitation vary across the region for each emission scenario and projection period. Both the 2021-2050 and 2041-2070 simulation period shows little change in the precipitation amounts (<3% change) across the region (Fig. 3). Both emission scenarios indicate that the western tier may decrease in precipitation, while the central and eastern states may increase. The largest changes occur during the 2070-2099 simulation period. Emission scenario A2 indicates North Carolina and Virginia may see increases of up to 3-6%, while parts of Louisiana may decrease up to 12%.

Under the A2 emission scenario, annual precipitation changes are simulated to increase across much of the Southeast. The largest projected increase in precipitation is along the Gulf coast at around 9-12% annually (Fig. 4). The largest area of projected decrease in precipitation is up to 6% annually in Southern Florida. Additionally, Figure 4 displays the future projections of precipitation changes throughout the seasons. Winter, spring, and fall simulate mostly an increase in precipitation, while mostly decreases in precipitation are simulated during the summer. For the summer, most of the region is projected to decrease in precipitation, with the largest decreases more than 10% in southern Florida. For the fall, most of the region is projected to increase in precipitation, with the largest increases (more than 15%) along the Gulf Coast. The winter precipitation changes are projected to increase for much of the region. The northern tier of the region and southern Florida simulate the greatest increase of more than 15%. Lastly, the spring precipitation simulations show mostly increases (up to 15-20%) across the region. Slight decreases in western Louisiana and southern Florida are projected as well.

Climate model simulations for precipitation extremes were run for the A2 emission scenario, with the threshold of days exceeding precipitation amounts of 1 inch and a reference period of 1980-2000. By 2070, all areas are simulated to increase in days exceeding 1 inch of precipitation totals. The largest simulated increase is along the southern Appalachian Mountains at 20-25% more days annually. The smallest simulated increase is in Arkansas, Louisiana, and Mississippi at less than 10% more days annually.³⁰

CMIP3, MULTI-MODEL MEAN SIMULATION Temperature Difference (F) from 1971-1999

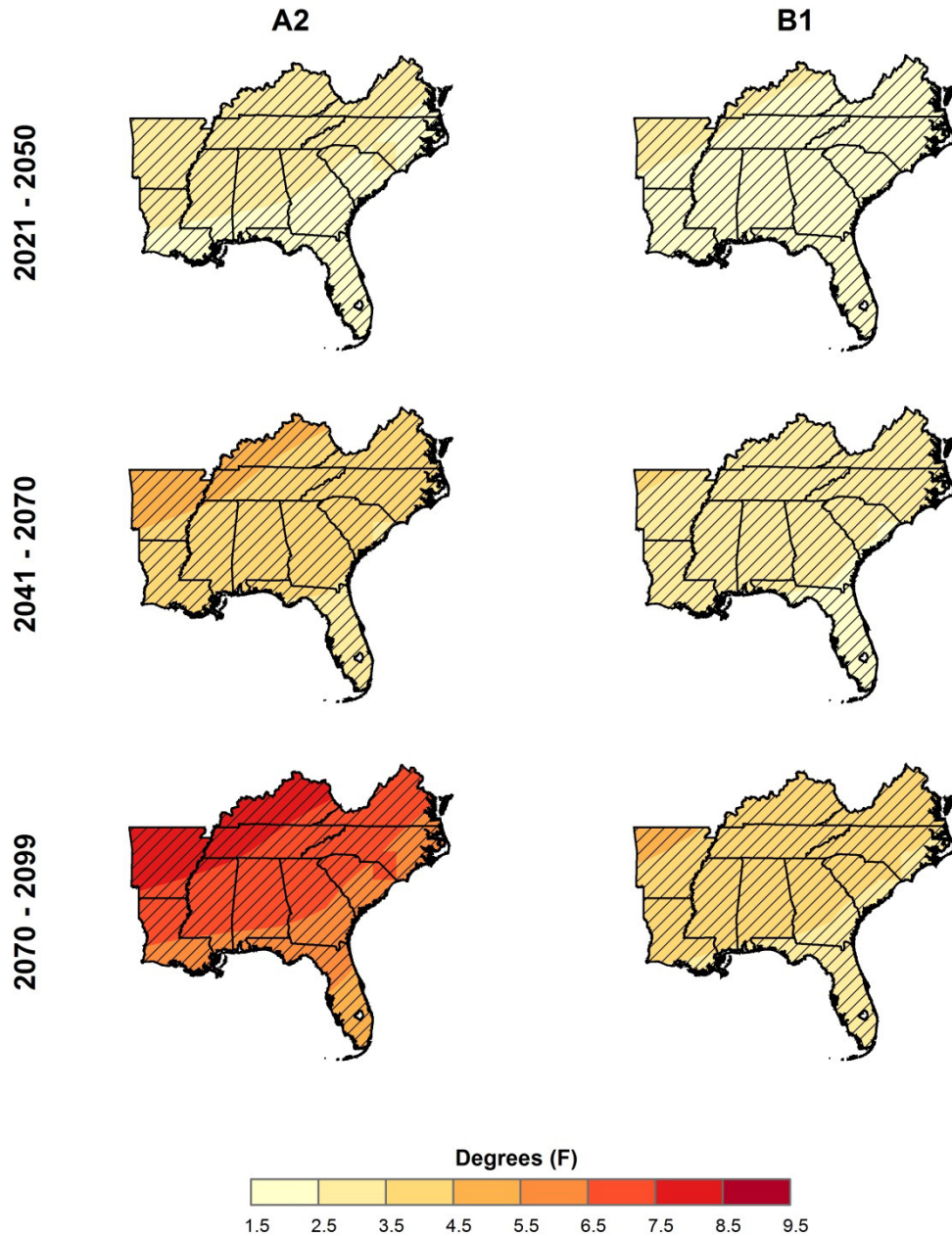


Figure 1. Projected annual mean temperatures ($^{\circ}\text{F}$) across the Southeastern United States. Both high (A2) and low (B1) emission scenarios are shown over each time period (2021-2050, 2041-2070, and 2070-2099). The reference period is 1971-1999. The annual mean temperature is positive for each emission and model period. The hatched indicates that more than 50% of the models agree there is a statistical significance and 67% agree on the sign change. Source: NOAA NESDIS Technical Report.

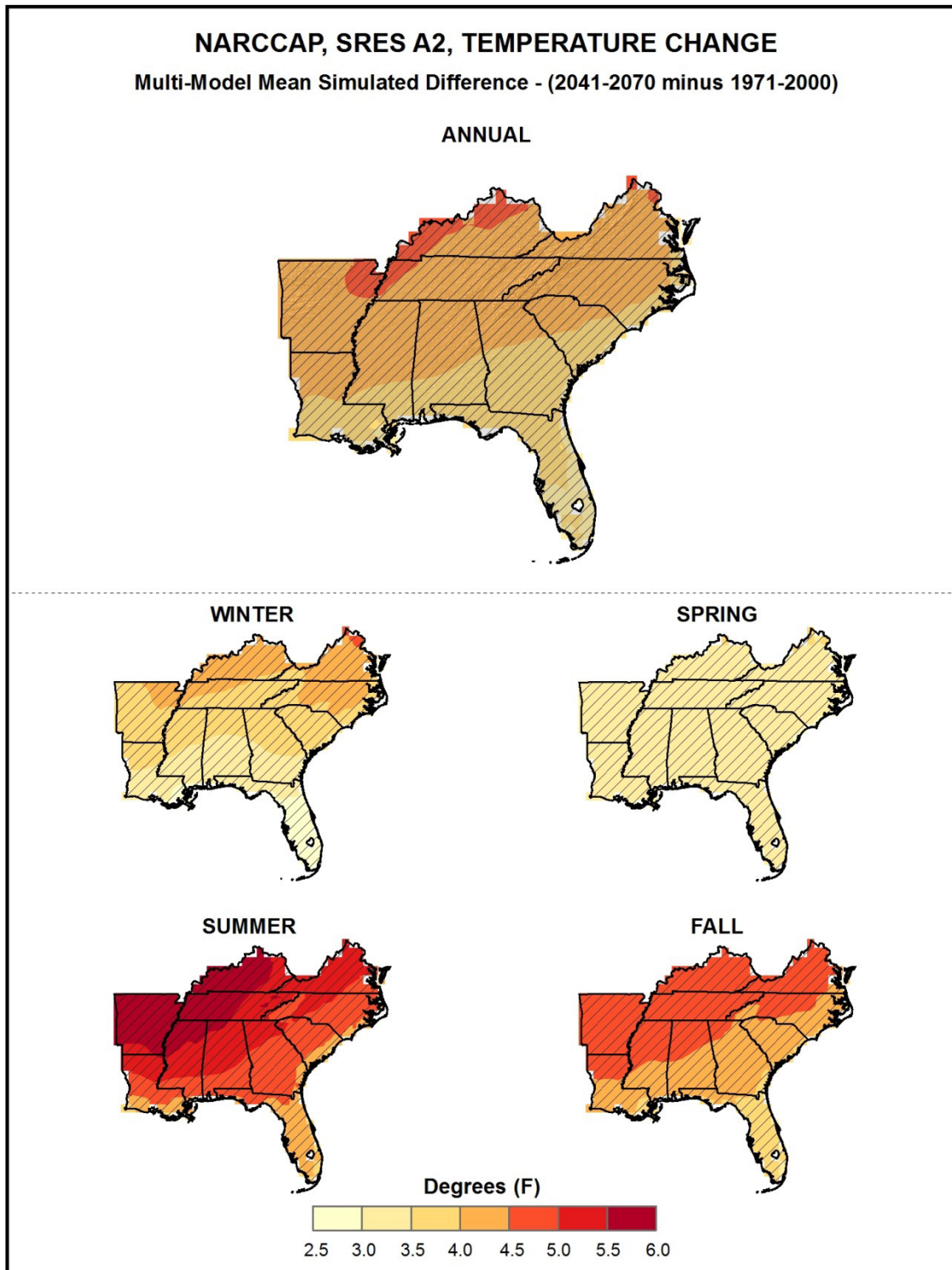


Figure 2. Projected annual and seasonal mean temperatures (°F) across the Southeastern United States. The projections are for the high emissions scenario (A2) during 2041-2070 with a reference period of 1971-2000. The annual and season mean temperature is positive across the entire region. The hatched indicates that more than 50% of the models agree there is a statistical significance and 67% agree on the sign change. Source: NOAA NESDIS Technical Report.

CMIP3, MULTI-MODEL MEAN SIMULATION Precipitation Difference (%) from 1971-1999

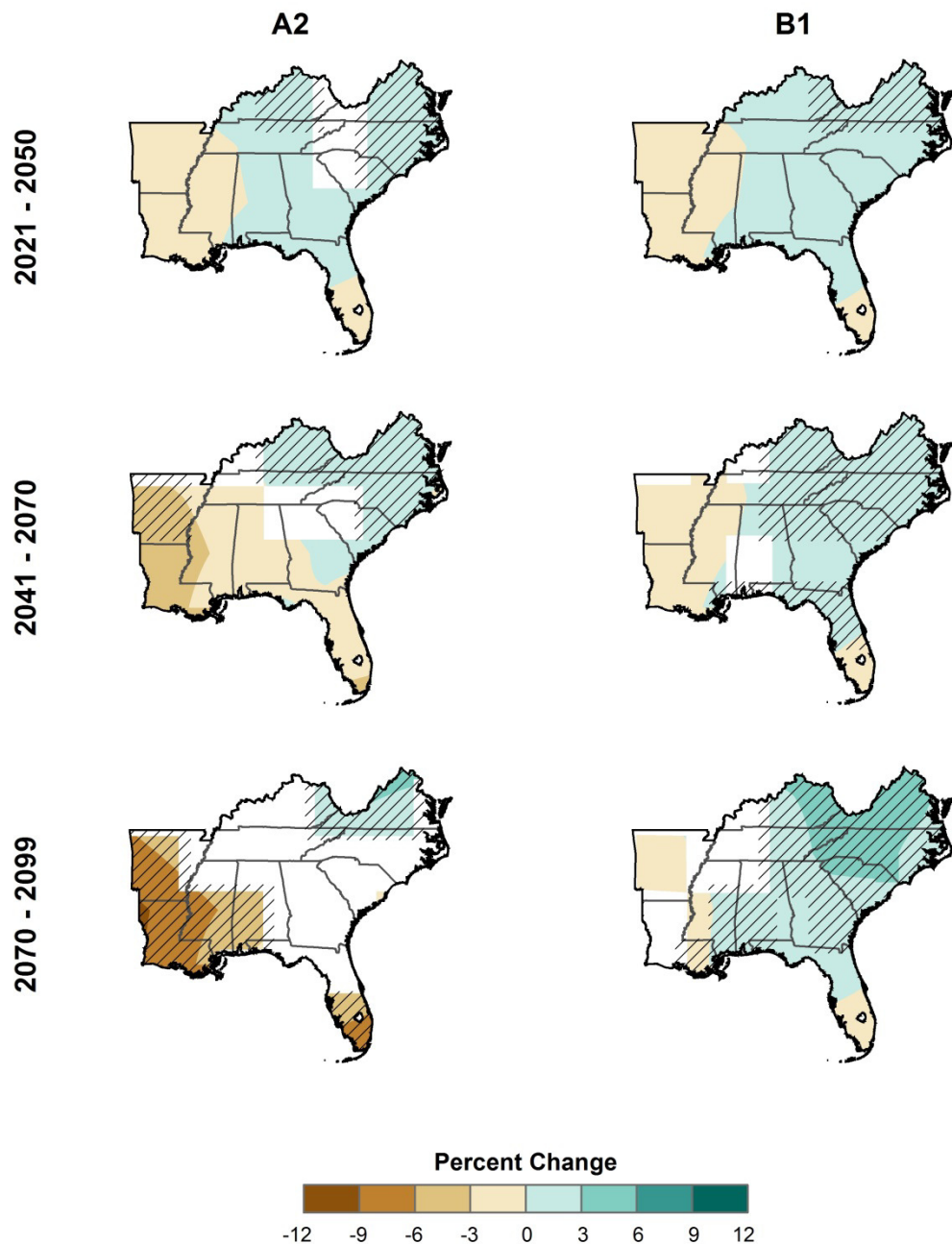


Figure 3. Projected difference in annual precipitation (%) across the Southeastern United States. Both high (A2) and low (B1) emission scenarios are shown over each time period (2021-2050, 2041-2070, and 2070-2099). The reference period is 1971-1999. Color only indicates that less than 50% of models determined the change is statistically significant. Color with hatching indicates that more than 50% of the models agree there is a statistical significance and 67% agree on the sign change. Source: NOAA NESDIS Technical Report.

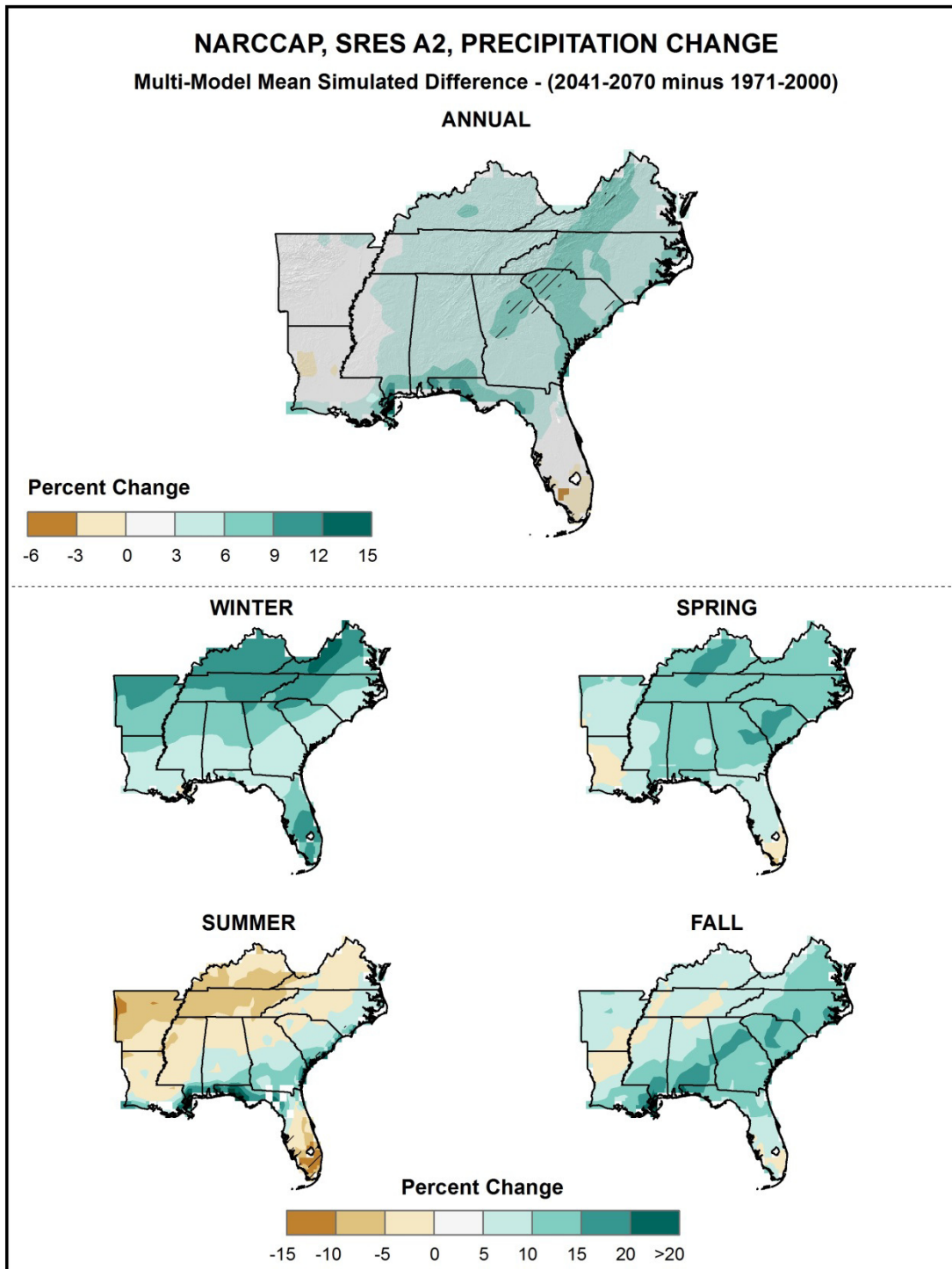


Figure 4. Projected annual and seasonal precipitation change (%) across the Southeastern United States. The projections are for the high emissions scenario (A2) during 2041-2070 with a reference period of 1971-2000. Color only indicates that less than 50% of models determined the change is statistically significant. Color with hatching indicates that more than 50% of the models agree there is a statistical significance and 67% agree on the sign change. White out areas indicate more than 50% of models agree there is a statistical significance, but less than 67% agree on the sign change. Source: NOAA NESDIS Technical Report.

Potential Vulnerabilities

Natural Resources: Physical

Air Quality (Visibility)

CMAQ (Community Multi-scale Air Quality) modeling into 2030 predict reduced emissions of PM 2.5 (particulate matter with a diameter of 2.5 micrometers or less) and its components, mainly due to the decreases in gaseous precursors and primary PM emissions and increases in precipitation in winter, resulting in increased visibility in the southeastern US. Ozone may also decrease.³¹⁻³²

Water Quantity

Drier summers may lead to drier soils and decreases in streamflow below experience. Models predict that streamflow will increase broadly in the spring, decrease broadly in the summer and fall, and at high elevations, will possibly increase again in the winter. Increased evapotranspiration in the fall and winter from lengthened growing season could reduce flows during those seasons beyond what might be expected from rainfall changes, and regionally, there has already been a significant decrease in fall baseflow index (baseflow divided by total streamflow). Evapotranspiration is expected to increase most in the spruce-fir and northern hardwood ecosystems. Overall, the southern Appalachians are projected to have a net positive water balance through 2050 and beyond.³³⁻³⁶

Impaired Watersheds (acid deposition)

The amount of suitable stream habitat for acid-sensitive coldwater species is predicted to decrease. Stress from acid deposition may reduce the adaptability of spruce, affecting the sustainability of refugia from climate change. A significant shift in red spruce temperature sensitivity occurred post-1930s, where positive growth responses to warm temperatures shifted to negative responses and this shift coincided with a period of clear-cut harvesting. Increased number of severe storms can lead to larger number of acid stress events.³⁷⁻⁴⁰

Night Sky

As parks seek to install more energy-efficient lighting, the planning process should also include efforts to reduce impacts of artificial light on wildlife and park visitors, which often would reduce energy use as well.⁴¹

Soundscape

Increases in thunder, stream-flow, and/or heavy rainfall events could potentially alter animals' abilities to communicate, as well as changes in vegetation structure could change how sound moves

through the landscape. Changes in breeding activity will change the phenology of amphibian and bird songs and insect noises.⁴²

Natural Resources: Habitats and Habitat Health

Wildfire and Fuels Management

Increasing temperatures predicted by climate models will lead to greater evapotranspiration, which will in turn lead to substantial increases in average drought index and fire potential by mid-century. Studies suggest that these effects will be most pronounced during the early summer – early fall throughout much of the southeastern U.S., including the southern Appalachian mountains. Additionally, climate forecasts suggest that both spring and fall fire seasons will be extended throughout the region. The uncertainty in climate models regarding precipitation makes it difficult to predict the role that increases or decreases in rainfall may play in mitigating these effects, though scientific consensus indicates that the eastern portions of the southern Appalachians (western NC) may experience increased totals of spring rainfall while the western portions (east TN) may experience little to no change. Scientists conclude that the increasing likelihood of severe droughts, complexity and costs associated with more severe wildfires, and greater air-quality restrictions may limit the use of prescribed burning to manage fuels, creating a negative feedback loop which would exacerbate potential climate change effects.⁴³⁻⁴⁵

Forest Health (Pests, Pathogens, Invasive Plants)

“In the eastern United States, species shifts due to exotic pests and pathogens may be the dominant force driving changes in ecosystem processes over the next few decades, perhaps even overwhelming other environmental changes occurring simultaneously (Lovett et al 2006).” Less frequent severe winter temperatures may result in more pest pressure from HWA (hemlock wooly adelgid), however temperatures exceeding 30C also lead to high HWA mortality. While warmer winters may improve overwinter survival and more generations per year of southern pine beetle (SPB: *Dendroctonus frontalis*), warmer winters may also disrupt synchronization of life cycles that leads to the concentrated spring emergence typical of new infestations and warmer summers can increase brood mortality. Warmer summers also reduce populations of fungi and mites identified as antagonistic to the SPB. Extreme weather events (storms and drought) can stress pines making them more vulnerable to SPB, however increased CO₂ availability may improve the host tree vigor, leading to decreased mortality. Warmer springs, particularly continuous warming in consecutive spring seasons, would tremendously increase the chance of SPB outbreaks, more so than the impact of warmer winters. Changes in temperature and/or precipitation are by themselves not expected to result in increases in endemic species, such as forest tent caterpillar or many hardwood borers, however increased stress to the hosts may increase the impact of these pests. Drier and warmer conditions may improve the viability of dogwood in the mountains, diminishing the incidence of dogwood anthracnose. Warming conditions along with increased CO₂ concentrations increase

growth and competitiveness of kudzu (*Pueraria lobata*) and Japanese honeysuckle (*Lonicera japonica*), and allow them to spread to higher elevations. The death of mature trees to pathogens can accelerate the transition of a forest to a climate mediated new set of species. The combination of the speed with which climate changes and the increase in other stressors (forest pests, ammonia deposition, extreme weather events, etc.) may accelerate decline of some tree species and inhibit other species from occupying climatically suitable habitat. Climate change may reduce the effectiveness of biocontrol agents by creating phenological separation from their target species or reducing the climate suitability for the control agent.⁴⁶⁻⁵⁵

Phenology (fall color, spring wildflowers)

A warming climate can extend canopy duration in the temperate deciduous forest, at both ends of the season, by 5–30 days for a + 4°C warming, the impact on early spring events will likely be more pronounced than on later phenophases. Recent trends in the Southeastern US have been towards a later spring overall, while trends for the western US have moved towards an earlier spring onset. However, spring high pressure systems over western Canada tend to funnel cold air to the southeastern US, and can create specific events of delayed spring or late freezes. When this spring high forms over eastern Canada and New England, it can lead to an early warming period in the midwest and southeast, as was the case in 2012. That event and the subsequent damage to fruit trees from a subsequent hard frost, caused half a billion dollars of economic damage to farmers in Michigan alone in 2012 and also caused a 71% drop in production of apples in western North Carolina in 2012.

Date of bud burst can be accelerated by 1-2 weeks depending on warming. At Oak Ridge, late winter period showed increased warming, while date of last hard freeze did not track any recognizable pattern. Years when buds break early, only to be followed by a hard freeze that causes extensive plant tissue mortality, requiring plants to allocate resources away from growth and reproduction and into replacement of lost and damaged leaves, may become more common with future climate change.

While studies in Europe found that migratory birds were beginning to develop an asynchrony between when they nest and the peak abundance of their caterpillar prey, a study of black-throated blue warblers (*Setophaga caerulescens*) in New Hampshire found that warblers were initiating nesting earlier to correspond with earlier leaf-out, while caterpillar biomass did not show a seasonal pulse. Protection from predators provided by leaf-out seemed to be more important for reproductive success, but though warblers were shortening the time between arrival and egg laying, eventually they will reach a limit to how much they can adapt to earlier leaf-out. Warblers may have adapted this capability to deal with the wide normal range in spring leaf-out time.⁵⁶⁻⁶³

Spruce-Fir

The potential for extirpation of red spruce (*Picea rubens*) from its southern range is possible, especially at lower elevations. American mountain-ash (*Sorbus americana*), Fraser fir (*Abies fraseri*) and

to a lesser extent mountain maple (*Acer spicatum*) may also lose much of their habitat. Interactions with disturbance agents and stressors may influence red spruce persistence, even where climatic conditions remain suitable. Populations of red spruce that have tolerated climate variability (warmer temperature and drought) in the past may provide important insight into where the best opportunities for restoration exist. Drainages and basins may provide the most likely refugia for spruce-fir forests. High elevation species may not be able to disperse fast enough to track with these refugia. Thermal inversions and high incidence of cloud fog commonly at or above the regional atmospheric boundary layer may provide resistance to climate warming for high elevation habitats. Spruce trees have experienced increased radial growth in response to warmer conditions, especially the cumulative effect of warmer conditions during the prior winter and current year growing season, and years with fewer rainy days when soil moisture is maintained, but dry conditions/increased sunlight exposure may prevent regeneration. Research is needed to better understand and project changes in cloud base elevations and other micrometeorological conditions important to red spruce in a changing climate. ^{18, 19, 21, 37, 64-74}

Shortleaf Pine - Oak-Pine

Moisture stress from increased temperature and increased evapotranspiration rates is likely to decrease vigor of oak species found in the park, while increased spring precipitation may cause more oak seedlings to succumb to pathogens. Experimental manipulation of rainfall at an Oak Ridge experimental plot for white and chestnut oak failed to detect sensitivity to either a 30% increase or 30% decrease in rainfall, demonstrating some resilience from mature trees growing in fairly optimal conditions, though dendrological studies show oak growth is limited by low precipitation and high temperatures. Species expected to gain in this region from climate change include southern red oak (*Quercus falcata*), post oak (*Q. stellata*), and slash pine (*Pinus elliottii*), the latter species not yet found in the park. Overall, there is agreement from different modeling efforts that suitable habitat would increase for oaks, pines, and hickories.

Precipitation patterns, which are poorly predicted by models, will influence the distribution of fire disturbance and resulting distribution of fire-dependent communities. Red maple, a competitor species in oak-pine habitat, is not negatively affected by summer temperature and benefits from warmer winters, though it may be less drought tolerant than oaks. Oaks in the red oak group, however, demonstrate increased mortality during periods of lengthy or closely repeating droughts. Reintroduction of fire may be necessary to assist pine and oak stands to persist or spread into shifting habitat zones, especially as prolonged drought may lead to fire intensities higher than desired for oak-pine habitat restoration. Warmer conditions may also increase the number of fire ignitions from cloud-to-ground lightning.

Drought also can trigger outbreaks of southern pine beetle (*Dendroctonus frontalis*). Table mountain pine (*Pinus pungens*) is predicted to be eliminated from the southern and central Appalachians and both Virginia pine (*P. virginiana*) and blackjack oak (*Quercus marilandica*) are modeled to decline as well. ^{11, 17, 67, 69, 74-83}

Northern Hardwoods

Seifert *et al.* (2015) found strong positive relationships between species latitudinal and elevational climatic limits. Winter temperatures were much lower at species poleward limits compared with their upper elevational range limits, but there were close matches between limits for variables related to summer temperature and growing season length. The degree of climatic mismatch was influenced by species dispersal traits; species with unassisted seed dispersal and low maximum height tended to have lower latitudinal than elevational limits. Changes in climate and disturbance regimes in the future by altering exposure, sensitivity, and adaptive capacity of these ecosystems, but the degree to which any species or community responds is still being determined.

Effects of climate change on evapotranspiration in forests has been difficult to predict, in part because evergreen species, such as *Rhododendron*, may benefit more from increasing CO₂ than deciduous species, as well as benefiting from warmer winter temperatures causing less leaf damage. Climate change may be more important as it impacts recruitment than for its impact on mature trees. Forests lower on hillslopes, such as cove hardwoods, tend to be more drought-tolerant than forest higher on hillslopes because of greater ground-water retention, however many cove hardwood species, such as tulip poplar, require more water than oaks and are thus more susceptible to severe droughts than oaks at similar topographic positions.^{67, 71, 84-88}

Caves

Species that can live only in caves (troglodites) are thought to be resistant to impact of climate change, based on their successful passage through Pleistocene glaciation; however over time cave temperatures will change with average above-ground temperatures. Cave-using biota are most likely to be resilient in caves with complex structure where the biota can shift to locate preferred microhabitats in new locations. Vegetation changes could increase the travel time to desirable foraging habitat for roosting bats and climate change may increase the energetic burden on bats, making them more susceptible to pathogens like that which causes white-nose syndrome (WNS). Climate change could impact energy flow into caves by disrupting movement of cave mouth species, such as cave crickets. Drier periods may also alter the karst hydrology and humidity within caves.⁸⁹⁻⁹³

High Elevation Bogs, Wetlands, and Seeps

Bogs may experience mean annual temperature increase of 3.5°C during the next century. There may be a temperature threshold that *Sphagnum* in southern Appalachian bogs may pass to reduce their long-term survival. It is unclear if *Sphagnum* species are mobile enough to shift as their climate shifts, or what species might move into the southern/warmer portions of their range. Changes in water table levels may be more important for the health of *Sphagnum* than temperature, drying up some wetlands and seeps seasonally or all together. In addition to changes in rainfall, altered evapotranspiration rates with warming climate, increased fire, oxidation of organic sediments, and other factors can impact hydrology and wetland persistence. If warming temperatures increase

the rate of decomposition, bogs may shift from carbon sinks to carbon sources. Increased nitrogen levels from acid deposition may improve the abilities of woody plants to encroach on bogs.⁹⁴⁻⁹⁵

Grassy and Heath Balds

Decreased cloud immersion may inhibit woody seedling invasion of grassy balds through photoinhibition. Shifts of preferred climates upslope may provide advantages to species with the potential to encroach on grassy balds.⁹⁶

Soils and Soil Communities

Trees produce more fine roots at deeper soil depths when exposed to higher atmospheric CO₂ levels in studies across a variety of forest types. Soil warming is likely to result in increased decomposition of soil organic matter, though not all components will increase at the same rate. Warmer and drier soils lose carbon into the atmosphere, particularly turning high elevation soils from carbon sinks to carbon sources. Soil warming in one study of mixed deciduous forest resulted in a decrease in soil microbial biomass, however studies of the impact of warming on mycorrhizal fungi vary between studies, with impact coming indirectly from stresses on the host plants and on direct changes in temperature and moisture of the soil. Increased nitrogen deposition on soils can reduce ectomycorrhizal fungi diversity, though the effect varied with study. European studies have found that fungi are already fruiting earlier in the spring and later into the autumn. Erosion from extreme events is the other concern for soils in the projected climate future.⁹⁷⁻¹⁰⁰

Natural Resources: Biological Diversity

Endangered Species

Vegetation changes could alter increase the travel time to desirable foraging habitat for roosting bats and climate change may increase the energetic burden on bats, making them more susceptible to pathogens like that which causes WNS. There may still be sufficient microclimate diversity in mature forests for bats to locate desirable roosting trees during the summer; forests in transition may not support the right species of trees at sufficient maturity or the necessary size of snag for many decades/centuries to support bats moving to new habitat. A model by Loeb and Winters (2013) suggests that once average summer maximum temperatures reach 27.4°C, the climatic suitability of an area for Indiana bat maternity colonies declines, and once the maximum average temperature reaches 29.9°C, the area becomes completely unsuitable, indicating that higher elevation habitat in the southern Appalachians may become increasingly important to this species.

The small-footed bat (*Myotis lebei*), which has not suffered the heavy losses of WNS as its communally cave-roosting congeners may suffer more from climate change as the crevices where they hibernate may be more susceptible to temperature fluctuation than caves or buildings, and hence, to energy depletion that reduces winter survival.

Species tied to the spruce-fir forest, such as the spruce-fir moss spider, may lose their entire habitat under some models, or there may be refugia in shelter portions of the landscape where small patches of suitable habitat may remain. Such areas should be identified and their protection and augmentation be a management priority. It is unclear how fast Southern flying-squirrel may move upslope with warming temperatures, but if moist conditions persist in some areas, it may be possible to plant additional spruce to expand the ecotone with northern hardwoods and increase the range for Carolina northern flying-squirrel.¹⁰¹⁻¹⁰³

Endemics

Conservation may no longer be practical on the community level as community components may respond differently to changing climate and have different abilities to track their preferred conditions, creating new communities with no local equivalent. Management actions must be taken with both present and future locations of populations in mind. Models for future distribution of species often lack important community level factors. For instance, Black-throated Blue Warblers (*Setophaga caerulescens*) model as resilient in the southern Appalachians and Cumberland Plateau, however declines in hemlock separate from climate change may cause a decline in this species. Lumpkin et al. (2012) found evidence of higher nest predation under higher temperatures in western North Carolina, especially for ground-nesting birds. The Appalachian endemic Type I red crossbill (*Loxia curvirostra*), depends on reliable cone crop from a variety of coniferous trees (especially red spruce, hemlock, and white pine), which could be lost from invasive forest pests and climate change; plantings of non-native conifers with soft to medium soft cones could benefit the long-term survival of this species.

A stonefly, *Acroneuria abnormis*, shifted up in elevation in the Little River catchment of the Smokies from 1976 to 2005, broadly consistent with observed temperature change. A similar shift was observed in Georgia for some ant species, possibly spurred by increased competitive advantage of warm-adapted species. Earlier spring may shade streams, reducing primary productivity of algae. Camp et al. (2015) found that aquatic macroinvertebrates preferring colder temperatures were more impacted by temperature changes than those with a moderate optimal temperature. They are developing and refining a niche model that provides a means of biomonitoring for temperature as a stressor.^{60, 104-112}

Salamanders

Salamanders at greatest risk may be those with narrow, mountain-top, cool-temperature habitat requirements, isolated by natural or anthropogenic barriers from where their climate band moves, elevational barriers such as valleys between populations, and isolated populations at the edge of their species range. Salamanders at lower edge of altitudinal range may already be under extreme physiological stress. Salamanders at extremes of climatic zone may farther be hit by increased number of predators/competitors and decrease in preferred prey. Species with more generalized habitat requirements may benefit from climate change.

First signs of climate change may be changes in hybrid zone dynamics, as microclimate preferences may be the most important control of hybrid zone dynamics; increased temperature was correlated with decrease in “pure” *P. shermani*. The red-cheeked salamander (*P. jordani*) population in the western portion of the park extends to lower elevations than elsewhere in the park and it is there that they may show their first impacts from climate change.

Increase of intense storm events may cause increase in scouring events that could damage hellbenders and their eggs, as well as other aquatic salamanders. Stream salamander abundance is highest during warmer, wetter periods and to date tracks the North Atlantic Oscillation.

Reduction in hydroperiod from drier summers may effectively eliminate some ponds for breeding of Ambystomatid salamanders and newts, or at least result in higher predispersal mortality or metamorphosis at a smaller size. Reduction in hydroperiod may also reduce flow in upper reaches of streams, degrading their use for *Eurycea* and *Desmognathus* salamanders. Upland habitat changes can also impact pond-breeding species, altering their ability to forage at or near the soil surface or to disperse. Increases in high intensity precipitation events may not compensate for higher temp and evapotranspiration, which would reduce groundwater recharge and riverine baseflow.

Drier conditions may reduce surface feeding for Plethodontid salamanders, reduce dispersal, and change breeding seasons; may have reduced energy stores by winter. Larger individuals of montane plethodontid salamanders are found on the surface after rains and during wetter years. Change in annual precipitation has been linked to changes in clutch size in Plethodontid salamanders. Some generalist species may benefit from climate change and reduced competition with specialists; northern red-backed salamander is increasing its range north by 80m per year.

Climate change may alter mean body size within a population, but it is unclear if this is a direct effect on energetics, thermoregulation, and/or food availability, or if it derives from alteration in the age structure of the population or other demographic processes, such as recruitment, growth, or survival. Apparent changes in body size could actually reflect changes in body size of the portion of the population able to use the surface, but not that of the overall population.

There is disagreement as to whether climate change is likely to increase the risk from the amphibian pathogen *Batrachochytrium dendrobatidis* (Bd) at higher elevations, but changing climate may have impact on ranavirus and, if it is introduced to North America, *B. salamandrivorans*.^{10, 89, 102, 113-127}

Brook Trout

Stream temperatures track air temperatures and nationally warming has occurred over the past 50 years. With a Goddard Institute for Space Studies (GISS) warming scenario of 3.8°C increase in mean annual air temperature, Flebbe *et al.* (2006) estimated that out of 528 streams in Virginia only 58 (11%) would still have brook trout; in North Carolina, 26 out of 148 streams (18%) would retain brook trout. For a time, trout may be able to remain in areas moderated by groundwater upwelling. Warming conditions may also alter the spawning time for brook and rainbow trout, bringing the period of hatch closer together in the winter. Warmer spring water may improve the egg viability of

brook trout, but may also decrease the number of individuals successfully spawning. There may also develop an asynchrony between brook trout fry and their prey.

Changes in flow may be as important, or more important, than changes in temperature for brook trout in southern Appalachian streams. Climate models predict a loss of 40% to 97% of trout habitat, especially taking into account not just water temperature, but flow and episodic events typical of what is expected from climate change. Rainbow trout habitat is also predicted to decline, but by significantly less, in part because it has higher thermal tolerances. Higher winter and peak spring flows could reduce egg survival of fall and early spring spawning fish by dislodging and damaging the eggs. Low flows in summer could reduce access to food and cool refugia.

Trout habitat is likely to become increasingly isolated and fragmented. Upstream migration will be constrained by acidification of headwater streams. Disease resistance decreases with thermal stress, putting trout at greater risk to introduced or native diseases.^{38, 39, 128-135}

Bears and Elk

Bears are thought to be sufficiently generalist and widespread so that climate change may not impact them greatly, however the diversification of subspecies may be redirected or reversed. Alteration in production and timing of hard and soft mast and other food sources could lead to increased wandering and increased human-bear interactions. Analysis of climate impacts on elk indicate that direct effects of climate will not be as important as climate-influenced changes in vegetation and habitat.¹³⁶⁻¹³⁷

New Species

A key point to understand is that community types we see today may not reform themselves elsewhere, but rather whole new community types may form. Biodiversity may also decline, at least in the short-term, as local extirpation may happen faster than colonization by new species. Species distribution models used to predict species and community responses to climate change have limitations in that they generally do not include biotic interactions, population dynamics, dispersal or evolutionary adaptation, thus projections of what species will win or lose in a given area should be taken as only a first approximation. The ranges of tree species are predicted by one model to shift northward, on average, by 700 km (ranging from 230 km to 1100 km) by the end of this century, though not all species have the dispersal capabilities to move at the same rate as their potential range. Some climate models indicate that much of the Smokies projects to have a climate not currently found in the US, such as a subtropical humid forest similar to southeastern China or southeastern Brazil, therefore it is difficult to predict which species in North America might be able to colonize and succeed in such. Species that have specialized mycorrhizal fungal associations might have a harder time colonizing new range if their fungal associates do not move with them.

The assumption that species from warmer environments (e.g. the Piedmont) may invade the mountains is tempered by increased periods of dryness that could reduce survival of newly arrived seedlings and the persistence of mature trees, limiting the canopy gaps many of the colonizing

species would need to become established. Some species that might be expected to become more common at lower elevations are already present, e.g. sweetgum (*Liquidambar styraciflua*), loblolly pine (*Pinus taeda*), and southern red oak (*Quercus falcata*), while others are currently rare or have not yet made it to the park, e.g. willow oak (*Q. phellos*) and slash pine (*P. elliottii*). Predictions of higher spring precipitation may not help species that are prone to desiccation during summer droughts, such as *Liriodendron* and *Betula* sp.

New animal species could include bird-voiced treefrog (*Hyla avivoca*) and short-distance migrant birds may increasingly spend winters in the park. The majority of bird species monitored by the annual Audubon Christmas Bird Counts showed a northward shift in their core winter ranges from 1975 to 2004 attributable to climate change and Breeding Bird Survey data showed that the northern margin of the range of southern birds was shifting northward on average 2.35 km/year. Studies in the White Mountains of New Hampshire, however, found that most montane species extended their breeding ranges both upslope and downslope, possibly because of shifts in rainfall or habitat structure, even though temperatures generally increased with elevation. A coarse estimate of mammal species turnover for the Smokies indicated 8 species might be lost and as many as 29 species gained with a doubling of CO₂. Nine-banded armadillo (*Dasypus novemcinctus*) has already been seen within a few miles of the Smokies park boundary. Chinese tallow tree (*Triadica sebifer*) could move into the park by mid-century. The leaves of this species can reduce survival of pond-breeding amphibians when the leaves are freshly deposited in the ponds (impact reduced with time and decomposition); warmer winters that encourage earlier breeding in ponds with tallow tree leaves can result in greater mortality. Under some climate models, very limited habitat in and around GRSM and BLRI may become suitable for the Burmese python (*Python molurus bivittatus*) by 2100.⁷⁴

87, 93, 100, 106, 138-150

Built Resources

Roads, Infrastructure and Maintenance

In general, increased precipitation projected for spring, fall, and winter can accelerate degradation of materials made from wood and metal, but decrease the number of days available to maintenance staff to make outdoor repairs.

If precipitation becomes more sporadic and intense, this could lead to flooding, which could disrupt transportation within the Park and weaken or wash out the soil and culverts that support roads, tunnels, and bridges. Traditionally, asset managers have relied on past performance of natural systems and the ability to extrapolate this performance, together with that of the assets across the usable lifetime, to design systems to handle storm-water. Under a changing climate, uncertainty is introduced into the traditional process leaving historic culverts inadequate to handle the new volumes of water. It's also possible that systems installed only a few years ago prove to be too small in the near term.

Regardless of forward-thinking design or restoration methods used for roads, uncertainties associated with rainfall, steep slopes, and the transport of water, sediment, and wood in stream channels make some level of road failure inevitable. Climate change will exacerbate these uncertainties and associated risks. However, several strategies can minimize risk and failure. For example, inventorying and analyzing high-risk areas, such as debris-prone sites, can support development of plans to prevent or manage issues in these areas. In addition, “what if it fails?” scenario analyses can identify likely failures that will result in the most adverse consequences. This information can help to target sensitive areas in strategic planning to emphasize specific actions to avoid these impacts (e.g., specifying more robust design criteria for these areas).

With projected warmer temperatures and more winter precipitation that could fall as rain instead of snow, winter flooding could occur more frequently, especially if the frozen ground cannot absorb precipitation. Landslides and wash-outs could also occur more frequently, as saturated soils are exposed to more rainwater. Drought in areas such as the Southwest could increase the likelihood of wildfires that reduce visibility and threaten roads and infrastructure.¹⁵¹⁻¹⁵⁵

Trails

The grade of a trail can allow for accelerated velocities of water run-off and remove soil particles. Degradation from water flow erosion can occur on even moderate grade trails of 7 to 15 percent grade. The upslope length of the trail directly affects the severity of soil loss. Gager and Conacher (2001) reason that the upslope length is a measure of the catchment of water on the trail tread, which is subsequently channeled along the trail, thereby increasing erosion potential. If precipitation events become more intense, applying more water to trail treads in a shorter amount of time, erosion could be accelerated.¹⁵⁶⁻¹⁵⁸

Cultural Resources and Historic Landscapes

With the predicted increase in precipitation projected for three of the four seasons of the year, if climate change brings increased humidity, it could adversely impact historic built structures and buried archaeological sites. Wooden structures, such as historic homes, would be prone to increased mold and mildew in addition to an increased likelihood of major structural damage as the wood rots and decays. Oxidation, or rusting, of metal structures, artifacts, and structural elements will destroy some cultural resources (e.g. historic stills, etc.) and greatly affect the structural integrity of others (<http://www.nps.gov/hps/tps/briefs/brief39.htm>, accessed December 2011). Stone and brick structures or structural elements will also be impacted by increased moisture levels. Wet stone and brick will be most likely to crack as temperatures drop below freezing. In addition, damp bricks are prone to more rapid decay. Disturbance events and migration of species may do considerable harm to historic landscape integrity.¹⁵⁹

Visitation, Recreation, and Surrounding Land Use

Climate change will affect not only natural and cultural resources within national parks, but also visitation patterns. Where, when, and how many people visit parks is likely to change with continued warming. For example, visitors may avoid extremely warm months in low-latitude parks and the visitation season may extend across additional weeks to months at northern parks. Whether park visitors track climate change and shift their behavior will depend on multiple environmental and socioeconomic factors. However, understanding potential change in visitation based on historical trends and future patterns of temperature change is a crucial first step for park managers and local communities to anticipate, plan for, and proactively influence future visitation. Visitation across NPS sites tends to increase until 25C, above which temperature visitation declines. Visitation for the Smokies and Blue Ridge Parkway are predicted to increase from 101-120% over the next 30-50 years, though that projection will be altered and constrained by economic trends, international travel patterns, and capacity of facilities, among other factors. The timing of visitation is also likely to change. Local ski areas may become economically unviable, thus reducing some of the regional draw during the winter months. Decline in key resources, such as brook trout, spruce-fir forests, or fall foliage color could result in decline in recreation focused around these resources. Recreational opportunities could decline in the wake of extreme events such as fires, landslides, and wind events.

Increases in minimum temperature could increase populations of deer ticks (*Ixodes scapularis*) and other vectors of tick-borne diseases. Vectors of mosquito-borne diseases, such as vectors of viruses for yellow fever, dengue, Chikungunya and Zika, are already present along the periphery of the park (Brian Byrd, pers. com.); warming could increase their longevity, improving their ability to transmit disease. *Aedes aegypti*, the better vector, has been documented only once in the park and is highly tied to human habitation, thus it is not likely to spread into the park. *Aedes albopictus*, which feeds on other hosts besides humans, is more common in the park but may be a poorer vector of disease. Winters may lack the intensity and duration of hard freezes necessary to keep disease vectors in check. Studies that have elevated atmospheric CO₂ in an intact forest ecosystem found increased photosynthesis, water use efficiency, growth, and population biomass of poison ivy, as well as a more allergenic form of urushiol, the main chemical causing a rash in sensitive people. ^{130, 160-166}

Surrounding Development

As the park's resources and threats do not stop at the park boundary, it can be helpful to examine park lands in terms of Hansen et al.'s "protected area-centered ecosystems" (PACE), based on the area required to maintain self-sustaining populations of species, airsheds, watersheds, and regional influences. For the Smokies, this may include a total of 13,627 km², 6.5 times the park acreage itself. The Smokies has high home density within its PACE, as well as a high increase in home density since the 1940s compared to many other park-based PACEs. As a regional increase in temperatures increases visitation, it can be assumed that development will also increase surrounding the Park and Parkway to accommodate both the increase in visitation and the increase in first and second homes for those seeking cooler climate in the higher elevations. Both parks have some buffering from development provided by National Forest lands. Increased development can reduce connectivity

for movements of wildlife across park boundaries, increased sources of invasive species, and increase predation on bird nests. Local biodiversity may take many decades to complete its response to development, thus current and past development may have impacts on biodiversity of the park that will not be fully seen for years.^{107, 167-168}

Management Options

Park managers are often faced with a choice between managing their resources to a “desired future condition” (DFC) or to a “historical range of variability” (HRV). Should a park’s climate trajectory extend outside the HRV, park managers will have to determine what features can be protected in a DFC rather than fighting against the change, forcing a change in “how things have always been done”. Different resources will require different strategies, depending on their climate vulnerability and the severity and nature of the climate-related threats they face. For a period of time, some resources may remain manageable with climate resistance strategies. DFC management requires choices that will need public and stakeholder input. Modeling error and complex interactions between climate change and other stressors mean predicting the locations of refugia is severely limited. Connectivity, provided by adjacent National Forest lands and the length of the Parkway, provides some ability for species to disperse without assistance as their habitat shifts.

Monitoring efforts for new invasive species and forest pests should focus on all portions of the park, including interior and high elevation areas as disturbance and mortality open up opportunities for invasion. In addition to the parks’ ongoing Vital Signs Monitoring Programs, there are several long-term studies that have been following forest response to climate and other long-term changes, including studies GRSM-01030 (James Clark, Duke University), GRSM-00414 (Erin Tripp, University of Colorado), and the NEON relocatable site centered on Twin Creeks in GRSM.^{6, 50, 169-}

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