Drought and deluge—opportunities for climate-change adaptation in US national parks

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In a changing climate, resource management depends on anticipating changes and considering uncertainties. To facilitate effective decision making on public lands, we regionally summarized the magnitude and uncertainty of projected change in management-relevant climate variables for 332 national park units across the contiguous US. Temperature, frequency of extreme precipitation events, and drought exposure are all projected to increase within seven regions delineated in the US National Climate Assessment. In particular, the anticipated collective impacts of droughts and flooding events will lead to unique management challenges, including combinations of management actions that may seem inconsistent. Furthermore, uncertainty in the magnitude of change varied by region and climate variable considered, pointing to specific opportunities for prioritization, transferability, and innovation of climate adaptation regionally and at the park-unit scale.

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Climate change is considered one of the greatest threats to the conservation of natural and cultural resources managed by the US National Park Service (NPS) (NPS 2021, 2023). It impacts the biodiversity that resides within these landscapes (Monahan *et al*. 2016; Holsinger *et al*. 2019), the conservation benefits and recreational opportunities that parks provide (Fisichelli *et al*. 2015), and the efficacy of park management actions (Runyon *et al*. 2020). Importantly, there is irreducible uncertainty in both future climate and the ecological response to a changing climate (Rangwala *et al*. 2021; Crausbay *et al*. 2022). However, land managers are tasked with difficult decisions about how to respond now to current and projected changes in resources (Michalak *et al*. 2022; Runyon *et al*. 2024). These decisions require managers to grapple with uncertainties and incorporate them into their actions through risk-based management planning (Lawler *et al*. 2010).

Existing approaches help managers make decisions that account for the inherent uncertainty in the impacts of climate change (Lawrence *et al*. 2021; Miller *et al*. 2022). One example of a risk-management tool commonly used by land managers, including NPS personnel (Reynolds *et al*. 2024), is climate-change scenario planning—a structured process for making decisions for an uncertain future by considering plausible yet contrasting future conditions or trajectories that encompass the range of critical uncertainties (Miller *et al*. 2022). Successful planning processes draw on expertise from climate scientists and adaptation specialists, resource managers, and other subject-matter experts, and can therefore be time- and resource-intensive (Runyon *et al*. 2020). An increasing need for climate-change scenario planning that incorporates climatic and ecological uncertainty is outpacing capacity for engagement in comprehensive efforts. Furthermore, regional coordination among units administered by the NPS—hereafter "NPS units" or "park units", which include national parks, national preserves, national monuments, and at least sixteen other designations; https://www.nps.gov/aboutus/national-park-system.htm—and other land managers improves the effectiveness of climate adaptation because climate change may reshape landscape connectivity, species distributions (including those of protected and pest species), and recreational opportunities (Fisichelli *et al*. 2015; Monahan *et al*. 2016; NPS 2023). As a result, there is a need to identify commonalities in the magnitude and uncertainty of future changes in climate to support ongoing risk-based management planning on public lands.

Climate-change scenario planning is used extensively by the NPS and has also been adopted by national park offices in South Africa, Finland, Norway, and Sweden. To facilitate climate-adaptive decision making, we investigated atmospheric greenhouse-gas emissions and model uncertainty (inter-model spread) in future climate in NPS units across the contiguous US (CONUS). We evaluated climate projections for 332 CONUS NPS units by quantifying the change in climate and the uncertainty associated with this change across 40 downscaled climate projections (20 global climate models [GCMs] and two representative concentration pathways [RCPs]: RCP 4.5, a moderate emissions scenario, and RCP 8.5, a high emissions scenario]). We focused on five climate variables consequential for park planning: mean annual temperature, mean annual

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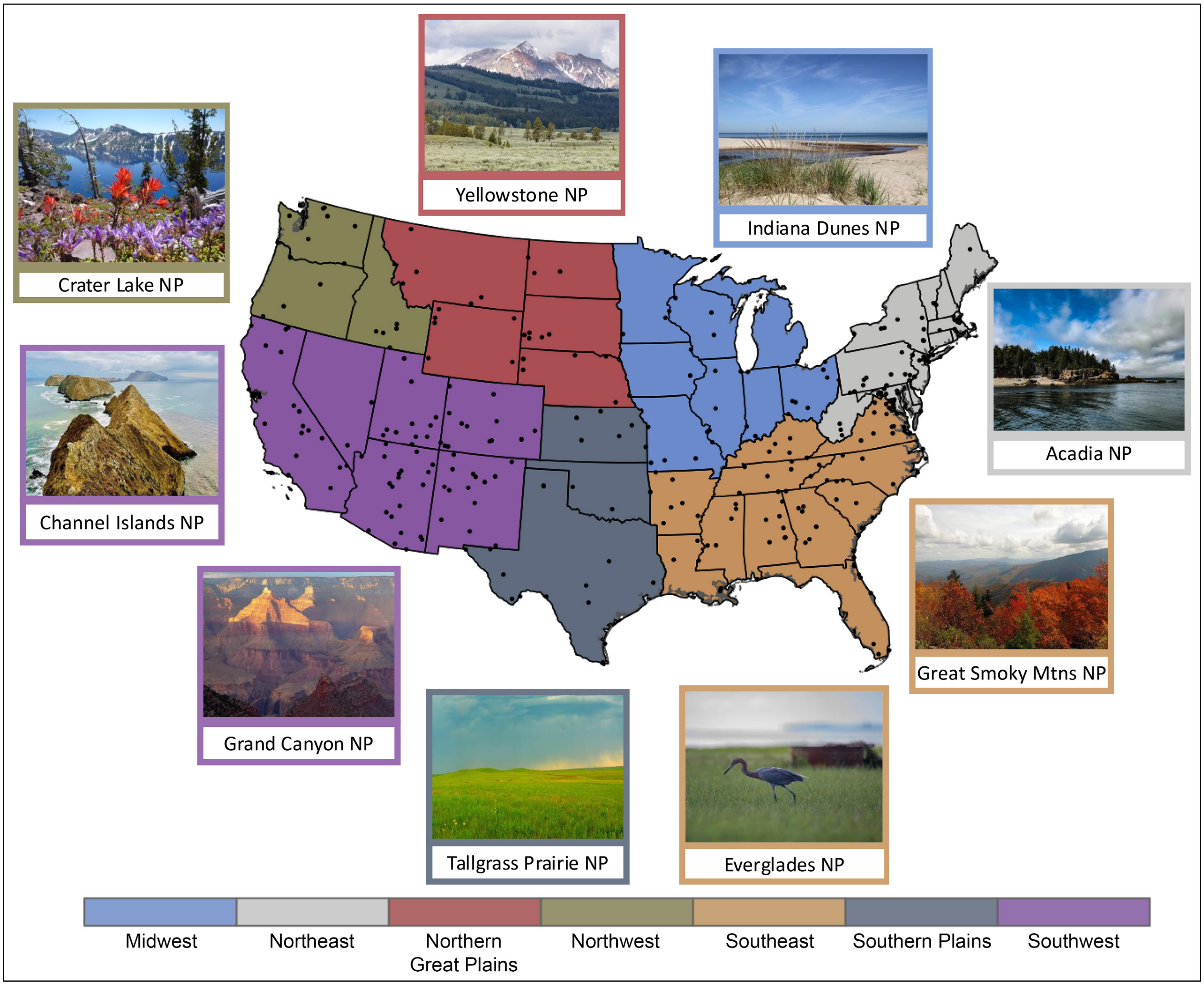

Figure 1. Map of the 332 National Park Service (NPS) units (black circles) included in these analyses across the seven National Climate Assessment regions (groups of adjacent states with assigned colors) in the contiguous US, with associated illustrative national parks and preserves (photographs). Image credits: Acadia (Victoria Stauffenberg/NPS), Channel Islands (Christina Kennedy), Crater Lake (NPS), Everglades (Federico Acevedo/NPS), Grand Canyon (NPS), Great Smoky Mountains (NPS), Indiana Dunes (Jeff Manuszak/NPS), Tallgrass Prairie (Billy Robb/NPS), Yellowstone (Jacob W Frank/NPS).

precipitation, frequency of extreme precipitation events, growing-season length, and annual climatic water deficit (CWD) (Runyon *et al*. 2024). For each park and climate variable, a historical baseline (1979–2012) was compared to a mid-century planning period centered around 2050 (2035–2065). We computed the mean change in climate between these periods as a *z*-score, representing the difference between projected future and historical means relative to the historical standard deviation. Uncertainty in climate change was calculated as the range in *z*-scores across projections. We quantified metrics as *z*-scores to assess changes in climate relative to the historical variability of each park unit—for instance, a *z*-score of one for mean annual temperature indicates that the future mean temperature is one standard deviation greater than the historical mean, such that the average future year is hotter than 84% of historical years. The patterns of change and uncertainty were examined across US National Climate Assessment (NCA) regions (Figure 1), allowing for the identification of common challenges and unique regional considerations in climate adaptation approaches.

Methods

For each of the 332 CONUS park units, NPS Climate Change Response Program (CCRP) staff summarized 40 separate climate projections, which were provided for this study (Runyon *et al*. 2023, 2024). This set of projections was constituted of 20 GCMs and two RCPs (4.5 and 8.5) for 2050 (2035–2065) from the World Climate Research Programme's Coupled Model Intercomparison Project phase 5 (CMIP5) (Taylor *et al*. 2012) and downscaled using the Multivariate Adaptive Constructed Analogs (MACA) method (Abatzoglou and Brown 2012). The MACA approach allows for a physically realistic product at regional scales and is available at daily timesteps at 1/24 degree (~4 km). Historical (1979–2012) time-series data were downloaded and extracted from the ~4-km resolution GridMET dataset, which also has a daily timestep (Abatzoglou 2013). The GridMET dataset was used to bias-correct and downscale GCM outputs to produce the MACAv2-METDATA data, and thus served as an appropriate historical baseline against which future projections could be compared. Runyon *et al*. (2024) extracted projected and historical data from the grid cell overlaying the centroid of each park unit and summarized climate metrics that characterize key resource climate sensitivities identified by NPS resource managers (Lawrence *et al*. 2021). While most metrics (ie temperature, precipitation, growing-season length, and frequency of extreme precipitation) were derived for all 40 projections, CWD involved additional response modeling and was only calculated for the four models that bound the average temperature and precipitation change space (see Runyon *et al*. [2024] for details) to characterize the most extreme projections of climate change.

From the large number of outputs from the climate projections and subsequent water-balance modeling, we focused on five climate variables: mean annual temperature, mean annual precipitation, extreme precipitation events, growing-season length, and CWD. The frequency of extreme precipitation was calculated as the average number of days per year when projected daily precipitation amounts exceed the 99th percentile of daily historical precipitation (Runyon *et al*. 2024). Growing-season length was defined as the number of days between the start of the first span of warm days (six or more days with a mean temperature above 5°C) in the first half of the year, and the start of the first span of cold days (six or more days with a mean temperature below 5°C) in the second half of the year (Runyon *et al*. 2024). CWD was defined as the difference between potential evapotranspiration (PET) and actual evapotranspiration (AET). PET was calculated from a simple water-balance model using the Oudin method (Tercek *et al*. 2021). For each of the five focal climate variables, daily values summarized at an annual timestep were averaged within 1979–2012 representing the historical time period, and 2035–2065 representing a future mid-century planning period centered around 2050.

For each of the five focal climate variables, we also calculated the mean projected change and the uncertainty across all projections for each park unit. To assess changes in climate relative to the historical variability of each park unit, we quantified *z*-scores for the variables listed above. For each projection in every park, we calculated the difference in the variable between the historical and future time periods (delta climate) divided by the standard deviation of the annual historical climate (historical climate variability). For the mean projected change for each park, this value was averaged across all projections. The uncertainty in climate change for each park was calculated as the range in *z*-scores across all projections. Although the range may be sensitive to outliers, as opposed to using a standard deviation or quantiles approach, we chose this method because it most closely represents how NPS assesses divergent projections in scenario-based planning processes (Miller *et al*. 2022; Runyon *et al*. 2024). Furthermore, although uncertainty in climate projections may arise in multiple ways (eg downscaling uncertainty), we focused on the variation among climate models and emissions pathways to best align with the available data and approaches used in applied climate adaptation work currently spearheaded by the NPS (Lawrence *et al*. 2021). For all climate variables except CWD, the calculated mean projected change and uncertainty were based on all 40 park-specific projections. For CWD, the mean and range in the projections were based on the four selected divergent projections. The CWD mean change and uncertainty values for Mount Rainier National Park were removed from all analyses due to unrealistic values (z-score > 100), which were likely attributable to issues with the water-balance modeling for this specific park. Temperatures were converted to Kelvin before proportional relationships were assessed.

Regional analyses focused on NCA regions. Parks were assigned to regions by cross-walking park centroid locations and the NCA polygons (www.arcgis.com/apps/mapviewer/index.html?layers=d6614156fe694956be25f4bb9f52b378). Regional differences in mean projected changes in climate and in the uncertainty in projected climate were quantified using linear regression, with the NCA region as a categorical predictor and the mean change (mean *z*-score for each park) and uncertainty (range of *z*-scores for each park) as the response variables. Regional differences for each climate variable were assessed separately. Least square means were used to determine differences between regions. Pairwise comparisons between regions were based on alpha = 0.05 and are shown in the figures as comparison arrows, with non-overlapping arrows indicating significant differences between groups. Tukey adjustments were used to account for multiple comparisons. All variable calculations, spatial cross-walking, and statistical analyses were performed in R (R Core Team 2023).

Results

We found notable regional differences in projected climate change and its associated uncertainty. The regions with the most and least certain projected change were highly dependent on the climate variable under consideration. Furthermore, a larger magnitude of projected change was often associated with higher uncertainty. Broadly across all park units, projected changes in temperature were the furthest outside the historical variability and most consistent in direction (warming) despite high uncertainty in the magnitude of temperature change. In contrast, projected precipitation had very high uncertainty relative to the projected change, leading to regional uncertainty in both the magnitude and direction of future precipitation. However, even for parks with projected increases in precipitation, higher temperatures led to increases in projected CWD across all regions.

The magnitude of projected warming for the majority of NPS units in all regions was striking. In most parks, the mean projected mid-century temperature would be an outlier relative to historical climate (z-score > 3; hotter than 99% of historical years). Uncertainty in the magnitude of future temperature change was also large across all regions (Appendix S1: Figure S1). Growing-season length, a key derivative of changing temperature for both flora and fauna, was also projected to increase (Appendix S1: Figure S2a). All regions except the Southeast and Southern Plains had increasing and highly uncertain futures for growing-season length (Appendix S1: Figure S2, b and c), with implications for future pests and invasive species in large swaths of the country (Bradley *et al.* 2024).

Mean annual precipitation projections were highly uncertain but, when averaged across all climate models, generally indicated a slight increase in future precipitation (Appendix S1: Figure S3). In particular, the Southwest and Southern Plains had the highest uncertainty in future precipitation, in part due to the difficulty in projecting monsoons (Wang *et al.* 2013). Projected increases in future extreme precipitation events were similar across CONUS (Appendix S1: Figure S4), as increasing temperatures enable the atmosphere to hold more water vapor, which subsequently could promote more precipitation extremes. The uncertainty in future extreme precipitation events was also greatest in the Southwest (Appendix S1: Figure S4c).

Although the mechanisms driving CWD changes are localized and likely vary by region, CWD was projected to greatly increase in all regions because the rise in PET outpaced AET under the projected changes in temperature, despite increases in precipitation (Tercek *et al.* 2021). The projected CWD increase was smallest on average in the Northeast and highest across the Southwest and Midwest (Figure 2). The greatest uncertainty in future CWD was in the Southeast (Figure 2), but this uncertainty was not large enough for any projections to indicate the potential for future decreases in CWD (more mesic futures) for any NPS unit.

Conclusions

The regional patterns of climate uncertainty could be used to support climate adaptation planning processes in four ways. First, scenario-based planning focuses scenario divergence on highly consequential and highly uncertain climate variables (Miller *et al.* 2022). Our analysis summarizes uncertainties for multiple climate variables across all CONUS NPS units (Oldfather 2025) and therefore supports the development of climate and ecological scenarios in relation to system vulnerabilities. For instance, a park unit with low uncertainty in a given climate variable could focus selection of climate futures on other variables (Lawrence *et al.* 2021). Second, this analysis helps to clarify where climate-change vulnerability assessment and risk-management planning efforts can be applied to multiple units (ie units with similar projected changes and uncertainties) or where further site-specific investigation may be warranted. Third, parks that do not align with regional patterns may warrant deeper investigation to understand why they differ from regional trends (eg due to unique characteristics of the park location). Regional outliers may not be good candidates for regional adaptation planning action but may instead serve as refugia or provide leading indicators of regional change due to their unique geographies and climates. For example, Timpanogos Cave National Monument in the Southwest had (both regionally and across CONUS) uniquely large projected change and uncertainty in mean annual precipitation and in the frequency of extreme precipitation events. Fourth, the types of actions considered in response to the decision at hand will also likely depend on the degree of uncertainty in the relevant climate future. With less uncertainty, like for CWD across many of the regions, there may be more willingness to implement intensive, proactive, or innovative adaptation actions (Stein *et al.* 2024). In contrast, with more uncertainty, such as for changes in precipitation in the Southwest, actions may be focused on monitoring and preparing for changing indicators or threshold events and supporting efforts allowing for flexible management options (Lynch *et al.* 2021).

Our analysis focused on describing the uncertainty in future climate, and we show that most park units and regions can expect higher temperatures, more frequent extreme precipitation events, and exacerbated drought stress (higher CWD), regardless of whether mean annual precipitation is projected to increase or decrease. Therefore, climate adaptation may require combinations of investments that might seem inconsistent; for instance, installation of infrastructure to accommodate larger storms may be needed alongside vegetation management to foster more drought-tolerant communities.

Despite some shared expectations for patterns of future climate change across parks, consequential uncertainties remain. For many parks, it is unclear whether they can expect more precipitation or less precipitation. In addition, variation within parks, including in climate, soils, elevation, and aspect, is highly relevant for shaping impacts of both drought and extreme precipitation at a spatial resolution finer than that in our analysis, which used park centroids to demonstrate broad trends across all CONUS park units. For example, flooding often arises from small-scale weather events such as convective precipitation, which may not be adequately captured in the statistically downscaled climate projections, and higher elevation areas may experience a higher rate of warming (Pepin *et al.* 2015).

Moreover, the implications of climatic changes for biological systems are uncertain. Ecosystems responses to climate

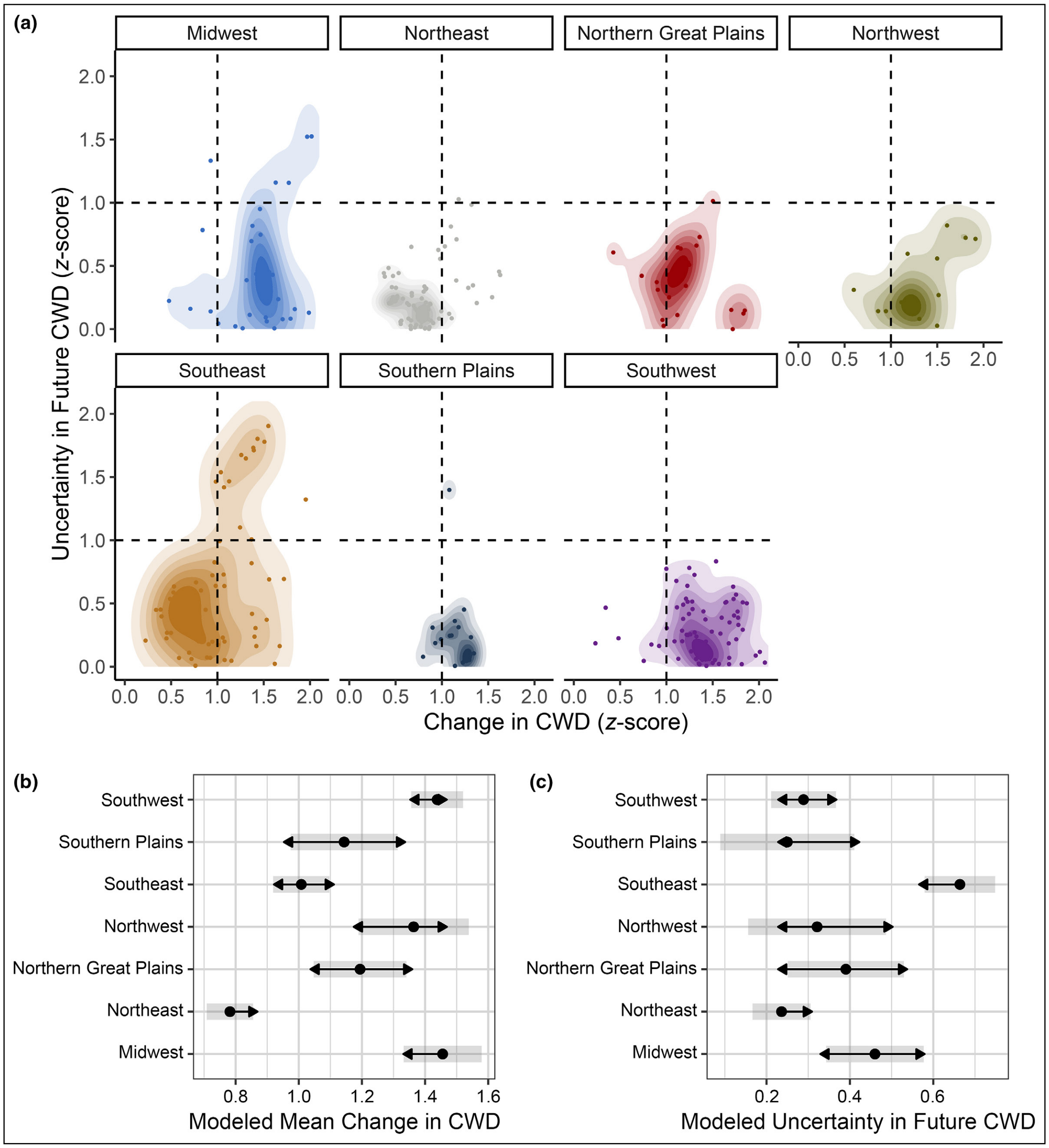

Figure 2. Top panel (a): Mean projected change in climatic water deficit (CWD) and the uncertainty in that change for each park unit across seven National Climate Assessment regions. Each circle represents a single park unit, and shading represents the density of the data. The projected change (mean of the delta) and uncertainty (range of the deltas across climate models) are calculated as *z*-scores, with the axes representing standard deviations away from the historical mean. Dashed lines at one standard deviation are included on both axes to aid in comparison across regions. Bottom panels (b and c): Modeled regional means (black circles), confidence intervals (gray shading), and comparison arrows for the (b) projected change in CWD and (c) uncertainty in future CWD. The comparison arrows are based on pairwise comparisons between all park units within a single region (alpha = 0.05). Non-overlapping arrows indicate significant differences between regions.

change are influenced by the magnitude and rate of climate change, as well as difficult-to-predict factors like disturbances, stochasticity, ecological feedbacks, path dependence, and priority effects, all of which create uncertainty in ecological projections (Littell *et al*. 2011; Crausbay *et al*. 2022). Both sensitivity to climate change and the magnitude of uncertainty in ecological response likely vary in importance across regions (Turner *et al*. 2020). By distilling climate uncertainty across regions, we have taken an initial step to link the patterns of climate uncertainty to the patterns, and major drivers, of ecological responses. Future work, both in monitoring and modeling, is needed to strengthen this link between climate and resource outcomes, which will support crucial ongoing climate-adaptive planning and decision making on public lands facing an uncertain future (Baron *et al*. 2009; Lawler *et al*. 2010).

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Data Availability Statement

Details and code for summarization of climate data are available as part of the US National Park resource report by Runyon *et al*. (2024) at https://doi.org/10.36967/2302720 and associated code (Runyon *et al*. 2023) at https://doi.org/10.5281/ZENODO.10253237. Climate data that can be used for the provided code are available for the multiple global climate models from the University of Idaho's Northwest Knowledge Network in the dataset at http://thredds.northwestknowledge.net:8080/thredds/reacch_climate_CMIP5_macav2_catalog2.html. Park-unit summary statistics (Oldfather 2025) are available on Figshare at https://doi.org/10.6084/m9.figshare.27198798.v1.

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Supporting Information

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