Climatic Change (2025) 178:84
https://doi.org/10.1007/s10584-025-03888-6

Projections of future climate for U.S. national assessments: past, present, future

Samantha Basile[1] · Allison Crimmins[2] · Fredric Lipschultz[3] · Kenneth E. Kunkel[4] · Kate Marvel[5] · Adam Terando[6] · Claudia Tebaldi[7] · David Pierce[8] · Wenying Su[9] · L. Ruby Leung[10] · Katharine Hayhoe[11]

Received: 10 August 2024 / Accepted: 17 February 2025 / Published online: 15 April 2025

Abstract
Climate assessments consolidate our understanding of possible future climate conditions as represented by climate projections, which are largely based on the output of global climate models. Over the past 30 years, the scientific insights gained from climate projections have been refined through model structural improvements, emerging constraints on climate feedbacks, and increased computational efficiency. Within the same period, the process of assessing and evaluating information from climate projections has become more defined and targeted to inform users. As the size and audience of climate assessments has expanded, the framing, relevancy, and accessibility of projections has become increasingly important. This paper reviews the use of climate projections in national climate assessments (NCA) while highlighting challenges and opportunities that have been identified over time. Reflections and lessons learned address the continuous process to understand the broadening assessment audience and evolving user needs. Insights for future NCA development include (1) identifying benchmarks and standards for evaluating downscaled datasets, (2) expanding efforts to gather research gaps and user needs to inform how climate projections are presented in the assessment (3) providing practitioner guidance on the use, interpretation, and reporting of climate projections and uncertainty to better inform decision-making.

Keywords Climate change · Assessment · Projections · Scenarios

1 Introduction: how scientific assessments talk about the future

A major goal for the U.S. National Climate Assessment (NCA) is to provide policy-relevant information to decision-makers, particularly as decisions must be made today without perfect certainty of the future (Crimmins et al. In Review; USGCRP 2023a). This goal is underscored by the consensus-based process common to scientific assessments—one in which experts weigh evidence and uncertainty to provide credible, authoritative scientific statements (Avery et al. 2025; Crimmins 2020). To report uncertainty in a standardized way

Extended author information available on the last page of the article

across all chapters' findings, NCA authors use calibrated terms for levels of confidence and likelihood adopted from the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (Tables 1–2 from Avery et al. 2023).

Consensus findings within climate assessments have evolved alongside climate projections and scenarios as key tools to highlight a range of plausible future conditions based on human choices starting from the present-day period (Basile et al. 2023). Climate projections (henceforth *projections*) are computer simulations from global climate models (GCMs) that capture the responses of Earth's climate system to a *scenario:* a distinct, internally consistent, and plausible future pathway that often describes future greenhouse gas emissions and concentrations based on socioeconomic and policy choices (Grade et al. 2023).

An ongoing challenge for the development of climate assessments is meeting the needs of a growing spectrum of audiences and users of climate information. Early international and national climate assessments focused on building the evidence basis to detect and attribute climate change signals, which could be relayed to policy-makers (Table 1). Over the last decade, NCAs have highlighted the scientific consensus on climate change, demonstrated increasing confidence in climate change trends, gathered input from an interdisciplinary community of experts, and expanded communication beyond physical science (Crimmins et al. In Review; Jacobs et al. 2016; Weaver et al. 2017).

The Global Change Research Act of 1990 (GCRA 1990) established the U.S. Global Change Research Program (USGCRP) and tasked them with developing the NCA. The act mandates that the NCA be a recurring federal report that projects major trends in global

Table 1 Use of climate models, scenarios, and downscaling across NCAs

Assessment	CMIP Phase	Scenarios	Specific uses	Downscaling
NCA1		IS92	IPCC IS92a	Delta approach
NCA2	CMIP3	SRES	SRES A1FI SRES A2 SRES B1	Quantile mapping or direct use of global models
NCA3	CMIP3 CMIP5	SRES RCPs	SRES A2 SRES B1 RCP2.6 RCP4.5 RCP8.5	Asynchronous Regional Regression Model; North American Regional Climate Change Assessment Program (NARCCAP)
NCA4	CMIP5	RCPs	RCP4.5 RCP8.5	Localized Constructed Analogs Version 1 (LOCA)
NCA5	CMIP6	SSPs	SSP1-2.6 SSP2-4.5 SSP3-7.0 SSP5-8.5 SSP1-1.9 (not always available)	Localized Constructed Analogs Version 2 (LOCA2); Seasonal Trends and Analysis of Residuals, Empirical-Statistical Downscaling Model (STAR-EDSM)

change for the forthcoming 25 and 100 years, as well as describes climate impacts within the United States (Avery et al. 2025). Though the official NCA audience is Congress and the President, the definition of the intended audience for the Fifth National Climate Assessment (NCA5) included “national, state, local, and Tribal governments, city planners, public health officials, adaptation specialists, nurses, farmers, business owners, community organizers, researchers, water utilities, ecosystem managers, educators, students, the media, and concerned individuals who need to make timely decisions about the climate impacts they are facing” (USGCRP 2023a). In the third decade of national assessments, there is momentum and urgency to deliver information on impacts, risks, and responses to climate change at finer geographic scales and across a broadening range of topics— including downstream effects on social and economic systems (Crimmins et al. In Review; USGCRP 2023a). Recent assessment advancements have led to new efforts to understand who is using different elements of climate assessment information, why and how different audiences are using it, and whether the climate projections presented in NCAs are fulfilling those different user needs (Lustig et al. In Review; NASEM 2023).

All five NCAs published to date have included projections of future climate trends and impacts, guided by advancements made by the international modeling community (Table 1, Fig. 1). Across the NCA cycles, the selection of climate projections and downscaled datasets has been continuously refined (Basile et al. 2023; Kunkel et al. 2016; Moss et al. 2010; Ullrich 2023; USGCRP 2015). The first National Climate Assessment (NCA1; National Assessment Synthesis Team, 2000) relied on simulations from two global climate models

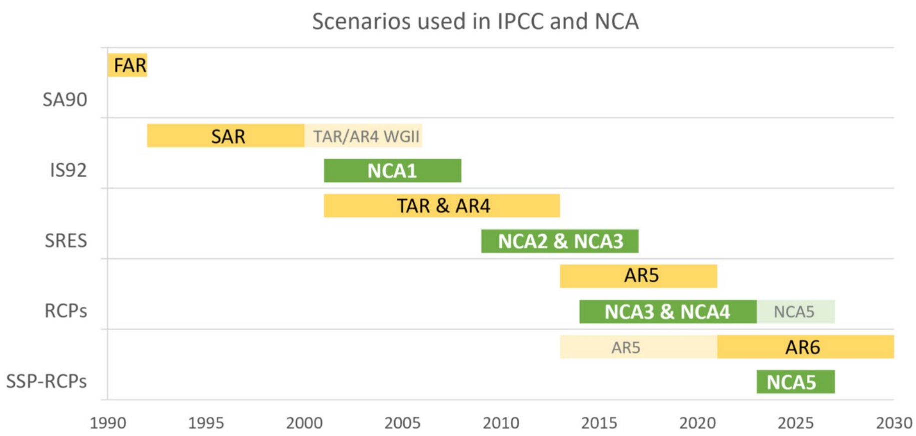

Fig. 1 The inherent mismatch between IPCC and NCA cycles is depicted by darker-colored bars representing the years in which different IPCC (yellow) and NCA (green) assessment report cycles used the scenarios listed along the y-axis as their primary source for physical climate projections (e.g., greenhouse gas emissions and atmospheric concentrations; temperature, precipitation, sea-level rise, etc.). Lighter-colored bars denote where a subset of IPCC volumes or NCA chapters were still basing findings on sources that rely on scenarios from the prior CMIP cycle. Thus, the lighter bars reflect the fact that the broader scientific literature base, particularly regarding climate impacts and risks, is slower to incorporate shifts in CMIPs across assessment cycles. For example, the IPCC Second Assessment Report (SAR) primarily used IS92 scenarios while Working Group I (WGI) and WGIII of the Third Assessment Report (TAR) and Fourth Assessment Report (AR4) used SRES scenarios; however, WGII of TAR and AR4 also assessed literature that used some of the IS92 scenarios. Similarly, while new SSP-RCP scenarios from CMIP6 were available during the development of NCA5, most of the downstream impacts literature (e.g., climate impacts on ecosystems, health, economics, etc.) utilized the RCP scenarios from CMIP5. Adapted from Fig. 2 in Pedersen et al. 2022

that followed one future scenario (IS92a). NCA1 used a simple delta approach to calculate sub-global climate change information from differences between historical and future model simulations combined with historical observations. The second NCA (NCA2; USGCRP 2009) was developed from 26 synthesis and assessment products that drew information from the Coupled Model Intercomparison Project Phase 3 (CMIP3; Meehl et al. 2007) as well as the Special Report on Emissions Scenarios (SRES; IPCC 2000) of the Intergovernmental Panel on Climate Change (IPCC). In addition to global model output from the IPCC, NCA2 incorporated a quantile mapping technique to generate localized information. The third NCA (NCA3; Mellilo et al. 2014) recommended that authors use two SRES scenarios (A2, B1) to show a range of potential emissions futures, while the subsequent generation of scenarios, the Representative Concentration Pathways (RCPs) were used sparingly (Moss et al. 2010; van Vuuren et al. 2011).

The fourth NCA (NCA4) was written in two volumes, with NCA4 Volume I focused on physical science (USGCRP 2017) and NCA4 Volume II focused on impacts, risks, and adaptation (USGCRP 2018). NCA4 Volume I was titled the Climate Science Special Report (CSSR), which utilized model output from CMIP Phase 5 and included four RCPs (Table 1; CMIP5; Taylor et al. 2012). NCA4 Volume II demonstrated differences in “impacts, vulnerability, and adaptation responses.” by contrasting a higher scenario (RCP 8.5) with a lower scenario (RCP 4.5; Table 1; USGCRP 2015). NCA4 Volume II authors could also utilize other scenarios where it was instructive, such as in analyzing mitigation options. Additionally, NCA4 mainly focused on projections from CMIP Phase 5 but also included model output CMIP Phase 3 for comparison. For national and regional information, NCA4 used a statistically downscaled climate dataset based on spatial analogs from observations and models as well as federal sea-level rise scenarios (Table 1; Pierce et al. 2014; Sweet et al. 2017; https://atlas.globalchange.gov/pages/nca4archive).

The fifth NCA (NCA5; USGCRP 2023a) was published in 2023. A decision memorandum on the NCA5 selection process for projections states that “[no] one set of models, scenarios, or climate projections was implemented across NCA5” and that authors could assess and reference any climate scenarios that met legally required evidence quality standards (USGCRP 2023b). NCA5 utilized an array of scenarios but emphasized the combined Shared Socioeconomic Pathways and Representative Concentration Pathways (SSP-RCP, commonly abbreviated as SSP; O’Neill et al. 2017; Riahi et al. 2017) as well as CMIP Phase 6 models (CMIP6; Arias et al. 2021). Two statistically downscaled products – Localized Constructed Analogs Version 2 (LOCA2, Pierce et al. 2023) and Seasonal Trends and Analysis of Residuals, Empirical-Statistical Downscaling Model (STAR-EDSM, Hayhoe et al. 2024) – were used to represent regional and local climate changes, and NCA5 authors could use scenario timelines or global warming levels (GWLs) to frame chapter findings (Basile et al. 2023; Hayhoe et al. 2024; Pierce et al. 2023). Additionally, separate from the CMIP6 archive, the Sea Level Rise Interagency Task Force published an updated set of specific sea-level scenarios that influenced how sea-level rise was described in other NCA5 chapters and provided technical assistance to improve consistency across the report (Sweet et al. 2022). See Section 2 below for further discussion of decisions around the use of downscaled products. Additional information on uncertainty within each of the projected climate datasets can also be found in their underlying methodology references (Hayhoe et al. 2024; Pierce et al. 2023; Sweet et al. 2022).

In this paper, experts involved in the development of NCA5 reflect on using climate projections to meet the information needs of both assessment authors and users (Section 2), describe several modeling challenges and advancements made in the NCA5 process (Section 3), and provide context for the use of projections beyond NCA5 (Section 4). Opportunities for future assessments are discussed for evaluating projections, identifying research gaps and end-user needs, as well as providing practitioner guidance.

2 Describing climate projections to support NCA5 authors and audience

Beyond the GCRA mandate to describe future avenues of global change in national climate assessments, climate projections supported the NCA5 Director's overall assessment priorities to advance the conversation around climate change in the United States and to speak to a broad range of audiences across the country (see Crimmins et al. In Review). From the NCA5 development stages to post-release, several questions related to future climate projections have arisen through public comments and agency feedback, which reflect different user needs:

What are the worst outcomes that could happen as a result of climate change?
What climate impacts should we prepare for? What are we already preparing for?
What changes are most likely to happen? How are extreme events changing?
What is the full range of plausible future conditions?

These questions highlight the several challenges involved in modeling society and the climate system while addressing the need for salient and credible climate information for timely decision-making and planning. These challenges include projecting future emissions and land use changes (i.e., social science and integrated assessment models), projecting the climate system's response to these drivers (i.e., physical science and climate models), and compiling results for a diverse range of stakeholders. The optimal strategy for one challenge may not be desirable for another. Two chapters within NCA5 broached these modeling questions: Climate Trends (Ch. 2; Marvel et al. 2023) and Earth System Processes (Ch. 3; Leung et al. 2023). These chapters provided foundational physical science information not only for NCA5 readers, but also the authors of the other NCA5 chapters, as this physical climate information was cited throughout the report. The NCA5 assessment cycle brought opportunities and challenges for the development of the physical science chapters. The previous NCA cycle had a separate volume— NCA4 Volume 1: Climate Science Special Report—dedicated to physical science (USGCRP 2017). For NCA5, this meant that authors for Ch. 2 and Ch. 3 had extensive foundational material on which to build from the previous NCA cycle as well as the IPCC Sixth Assessment Report (IPCC 2021). However, the NCA5 chapters had more concise space in which to present information as well as the requirement that their writing be aimed at a non-technical audience. Coordination across author teams was reinforced throughout the NCA5 process; however, the unique questions faced by the physical science chapters necessitated a consistent collaboration from an early stage in the development process to provide projection information for the rest of the assessment. The leads for Ch. 2 and Ch. 3 met on a regular basis, and authors from both chapters participated in an internal USGCRP roundtable with experts in model downscaling to determine a cohesive approach for framing and describing climate projections.

There is an inherent lag between the development of new international climate projections (i.e., CMIP cycles), the uptake of new projections in broader climate impact research and publications, and the availability of those publications to be assessed in each IPCC and NCA cycle. Often a year at minimum is needed for climate projections to be applied in climate impact studies. This mismatch between timing and data availability is a recurring issue for NCAs, including NCA5: namely, the questions of whether and how to incorporate the latest international climate projections into the national assessment. This is particularly challenging because the decisions around which scenarios to use in each NCA must be made early in the multi-year development process. As NCA5 was being written over the course of several years (primarily 2021–2023), results of CMIP6 were steadily being published, meaning only a limited number of CMIP6 models or scenarios were available in scientific literature at the time of NCA5 development (Fig. 1). This highlights how the desire for the latest and most localized information at national and local levels and the pace of releasing scientific findings can be out of step.

As CMIP6 model information began to be utilized by the broader research community and coal use dropped globally, concerns were raised regarding the use of the highly fossil fuel—dependent, and development-intensive, SSP 5–8.5 scenario (Hausfather and Peters 2020; Schwalm et al. 2020). However, USGCRP's guidance to the NCA5 authors was that they should not be constrained to a specific subset of climate scenarios—that if they showed scientific reasoning behind choosing a particular scenario, they could use it in their respective chapter.

Another challenge that Ch. 2 and Ch. 3 authors faced was deciding on an approach to accurately characterize uncertainty across climate model projections. The approach of "model democracy" (Knutti 2010) that constructs an unweighted climate model ensemble was discussed extensively by a USGCRP expert interagency group (see Section 2), but ultimately deemed insufficient based on research evaluations of the CMIP6 experiments which identified several climate models that projected a less-plausible global warming response. These evaluations were based on the latest scientific understanding of a physical process known as Earth's equilibrium climate sensitivity, or "ECS", which is defined as the change in equilibrium temperature in response to an instantaneous doubling of atmospheric carbon dioxide concentration from the preindustrial level (Fig. 3.3 in Leung et al. 2023; Hausfather et al. 2022; Sherwood et al. 2020).

Subsequently, two methods were used to characterize uncertainty in climate sensitivity across NCA5. First, the USGCRP expert interagency group (see Section 2) took a Bayesian approach that included available CMIP6 models and down-weighted overly "hot" models based on the physical science knowledge of ECS (Massoud et al. 2023). Model weights were then applied to downscaled data used in NCA5 (Basile et al. 2023). There is precedent for this approach as seen in NCA4, where individual downscaled climate model outputs were weighted based on a combination of model skill and model independence to create ensemble projections of climate variables (Sanderson and Wehner 2017). The advantage of this weighing approach is that the full timeseries of model outputs are preserved (i.e., projected climate variables can be calculated for any year or decade), which is desirable for

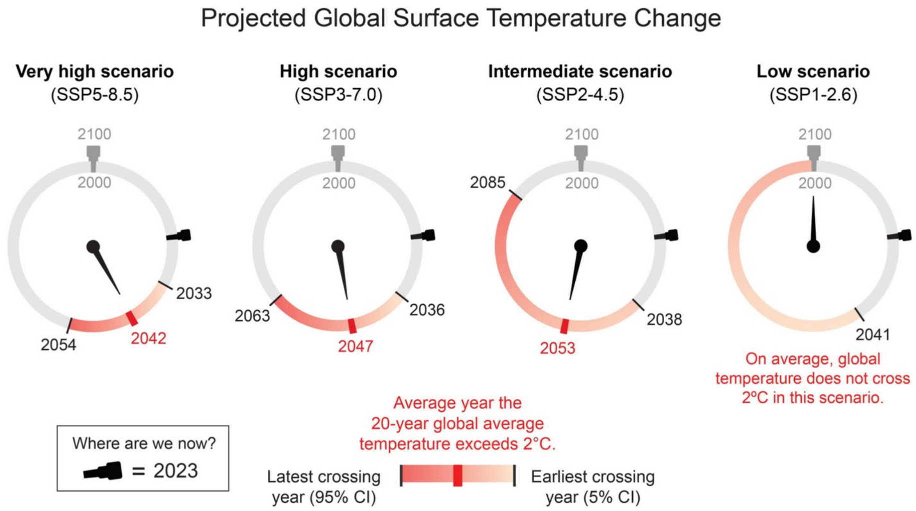

Fig. 2 Figure 2.14 in Marvel et al. 2023 (https://nca2023.globalchange.gov/chapter/2#fig-2-14). When (or if) the world reaches 2 °C of global warming depends on future greenhouse gas emissions and the sensitivity of the climate system to those emissions. Shown are the IPCC AR6 assessed warming projections for four future scenarios, with projected years at which the 2 °C (3.6°F) GWL would be reached. For example, under a very high scenario (SSP5-8.5), models project reaching 2 °C between 2033 and 2054, with an average estimate of 2042. Under a low scenario (SSP1-2.6), the 5% CI (confidence interval) range begins in 2041, but the average projection shows that warming would actually stay below 2 °C. Figure credit: Project Drawdown, Stripe Inc., NOAA NCEI, and CISESS NC

impacts-based assessments (e.g., adaptation and mitigation planning in advance of climate impacts).

The second method shown in Ch. 2 and Ch. 3 used a GWL framing to focus on policy-relevant global temperature thresholds. Using climate model output for calculations at a set of GWLs reduces the temporal influence of any one CMIP6 model by focusing on characterizing specific warmer climate states, instead of on time periods (e.g., individual decades or even climate periods often termed "mid-century" or "late century"). Individual climate models cross global thresholds at different years depending on the climate scenario, so focusing on a GWL instead of a specific year or decade captures this model variety (Fig. 2). Presenting GWLs also connects to a physical process that is already occurring (i.e., changes in Earth's average temperature) with real-world impacts already taking place in response to observed warming of about 1°C. Furthermore, policymakers from local to international levels have used GWLs as universal targets to measure societal action in mitigation and adaptation. International negotiations and assessments have used standard measures of future GWLs (e.g., 2.7°F or 1.5°C and 3.6°F or 2°C; IPCC 2023, 2021; UNFCCC 2016).

3 Takeaways from the development and analysis of projections in NCA5

Each NCA faces a unique decision-making environment regarding the choices of datasets—including projections. NCA authors balance their decisions against uncertainties about the timing of dataset availability, the potential demands on staff time and computational expense, and the needs of assessment users. The timing of the availability of datasets, the creation of derived variables, and deadlines for figure development created ongoing challenges for the National Oceanic and Atmospheric Administration Technical Support Unit (TSU) during NCA4 and NCA5. The TSU science team was tasked with processing downscaled data for NCA5, including creating applied (derived) variables and figures for national assessment authors. The TSU staff includes more than 20 experts who assist authors in developing hundreds of figures and identifying scientific findings from climate model datasets, all within the same time constraints of the broader NCA5 process.

The international CMIP experiments have historically produced output on time frames between 5 and 7 years (Eyring et al. 2016; Taylor et al. 2012). Conversely, the NCA cycle is driven by the congressional mandate for publication of a federal report every 4 years (GCRA 1990). Thus, the timing of CMIP and NCA cycles is often not aligned—which may prompt the NCA author teams to incorporate model output from the latest CMIP phase for the straightforward mapping and descriptive statistics of future climate projections, but assess the literature base from the prior CMIP phase for more in-depth analyses and results. This mismatch also affects the IPCC assessment reports, especially the working group 2 work (i.e., Impacts, Adaptation, Vulnerability) which mostly relies on the older phase of CMIP compared to the working group 1 report (i.e., The Physical Basis). As the cycles continue for international and national assessments, as well as CMIP, for there is no obvious solution to these issues related to publication timing, and as such these issues will remain a challenge for future NCAs.

For each NCA report, there is an involved process to decide on the use of climate projections based on input from experts in federal agencies and the recent work of the broader modeling community. As climate projections are large datasets, the time required for processing must be managed alongside other science support required by the NCA authors. To help make these decisions for the NCA5 development process, a USGCRP expert interagency group was tasked with evaluating the best-available climate model projections for use in NCA5 and with providing recommendations to the Federal Steering Committee (USGCRP 2023b). As previously mentioned, projections used in the NCA5 process were drawn from the global simulations in the CMIP6 archive, as well as subsequent downscaling efforts (Table 1). There was an opportunity to incorporate two independent sub-global downscaled datasets that were being created in the academic community using statistical methods. These two datasets were LOCA2 (Pierce et al. 2023) and STAR-EDSM (Hayhoe et al. 2024). The USGCRP expert interagency group recommended that both be incorporated into NCA5 projections products to accommodate uncertainties arising from the choice of the statistical approach as well as the different underlying gridded datasets that act as "ground truth" for the downscaling techniques (Ullrich 2023). Thus, the downscaled data from 16 CMIP6 models, available from both LOCA2 and STAR-EDSM, were weighted and then averaged together to form an ensemble for NCA5 (Basile et al. 2023). Other considerations for including both datasets were the ability to build on the use of LOCA in

NCA4 with the LOCA2 update, as well as the inclusion of STAR's downscaled weather station information—especially for areas outside of the contiguous United States (Basile et al. 2023, 2024). An independent validation on the historical temperature and precipitation data from these two downscaled products (Ullrich 2023) found that LOCA2 and STAR-ESDM are largely consistent with each other and with a separate gridded reference product, the Parameter-elevation Relationships on Independent Slopes Model (PRISM). Ullrich (2023) found minor differences between products could be attributed to climate variability, downscaling methodology, and observational uncertainty, but that "Both products represent the state of the art in high-resolution regional climate data over the contiguous U.S., and so are viable for use in scientific research and for use in relevant applications."

A challenge for incorporating the two downscaled products was to match the pace of NCA5 development in time for author teams to develop their chapter content. First, the academic groups that created LOCA2 and STAR-ESDM had to rapidly accelerate their work following the CMIP6 release – which was voluntary and supported only by the academic groups' external resources. Next, several USGCRP decisions had major impacts on TSU staff workloads – including selection of projection datasets (i.e., both global and downscaled), derived variables, future framing, and figure support services offered to authors. However, TSU staff had to complete numerous figure iterations in response to public and peer review comments. Overall, the decision to process the latest downscaling datasets from CMIP6 was worth the effort, as the full suite of derived variables is publicly available through the NCA Atlas and the Climate Mapping for Resilience & Adaptation (https://resilience.climate.gov/) tools. These projections are already being used widely across federal climate efforts and will likely form the foundation for NCA6, as its production timeline is anticipated to occur before the release of CMIP7. Additional datasets that were not available in time for NCA5 but will be available for NCA6 may be considered to better capture the uncertainty space across multiple downscaled products with different characteristics (OSTP 2024).

Across previous NCAs, several graphics were computed directly from global CMIP model data. In NCA3 and NCA4, climate model simulation data were downloaded to local computational resources for processing. This required considerable time for file management. In NCA5, analysis of CMIP6 model data was performed in a cloud-local mode on Amazon Web Services (AWS; CMIP6 archive, https://registry.opendata.aws/cmip6/). This eliminated the file management burden so that computations were much faster compared to using local cluster resources. This shift represented a major advance in providing climate model data analysis in a timely and flexible manner. A list of potential derived variables from the downscaled temperature and precipitation data was offered by the TSU to NCA5 authors during team orientation at the beginning of the writing process.

NCA5 authors could request TSU assistance in developing additional derived datasets if judged to be feasible within the assessment development time and resource constraints. For instance, authors from the Southern Great Plains chapter requested an analysis of spring freeze events (Allstadt et al. 2015) for a figure on projected change in risk of false-spring freeze risk (Fig. 26.9 in McPherson et al. 2023). This analysis was time-consuming but was completed by TSU for inclusion in NCA5. Because of the computational lift for such requests, these were approved and developed for authors on a case-by-case basis.

Given the large amount of computational effort that is necessary to provide the authors with access to numerous projected variables, one innovation in the NCA5 process was a public NCA Atlas (https://atlas.globalchange.gov). The Atlas built on the NCA4 approach that provided access to the projections used in the report via the Climate Explorer tool (https://crt-climate-explorer.nemac.org). Both approaches aimed to improve the usability of the report by enabling users to customize their projections, with the NCA Atlas also allowing for selection of sub-national geographic scales (i.e., the ability to zoom into maps at the county level). Future updates to the Atlas can allow for the addition of more variables as they become available (e.g., relative humidity, sea-level rise), more options for the desired projection approach (e.g., GWLs vs. scenario timelines), and better coverage of regions outside the contiguous United States (Basile et al. 2024). This access will continue to be important for future NCA cycles with the growing number and sophistication of datasets.

For NCA5, equilibrium climate sensitivity at the global scale was used to down-weight models with excessively warm projections, and the set of weights were applied to the 16 global models that were common between the LOCA2 and STAR-ESDM downscaling products (see Section 1, Basile et al. 2023; Massoud et al. 2023; https://atlas.globalchange.gov/pages/about-atlas). However, weighting techniques are still being scrutinized as they may overly constrain a model ensemble (i.e., the discounting or reduced influence of individual models based on only one metric or method of evaluation; McDonnell et al. 2024). There remains a need to assess if and how the use of global climate sensitivity for model weighting affects certain metrics or variables at sub-national geographic scales (Lehner 2024). The IPCC did not explicitly apply any weighting procedures to the CMIP6 output but rather used a combination of context-dependent techniques, such as the use of simple climate models and climate model emulators, when assessing warming-related climatic changes (Chen et al. 2021). There is no clear scientific consensus on whether to use a weighting approach versus equally accept all models (model democracy) for different datasets, or on how to weight the different global models that become available for any given national assessment. Each assessment cycle will need to revisit this topic in light of the latest evaluations of CMIP outputs and understanding of their applications at the national scale. It is worth noting that the use of GWLs alleviates some of the concern with model weighting for climate sensitivity because all the models that the reach the specific warming level contribute to the ensemble average, regardless of the ECS value.

4 What is coming next for climate projections?

Over the next century, the rate and magnitude of global climate change primarily depends on three things: how sensitive Earth's climate system is to human-produced greenhouse gas and other radiatively active emissions, how the carbon cycle will respond to warming, and highly uncertain societal choices. A recent review and synthesis on climate sensitivity (Sherwood et al. 2020) highlighted progress on narrowing the first layer of uncertainty—the estimate of Earth's sensitivity to a doubling of carbon dioxide concentrations in the atmosphere (ECS). Meanwhile, understanding and projecting carbon cycle feedbacks remains a major and urgent research question, one that CMIP Phase 7 (CMIP7) will tackle by driving Earth system model simulations directly with greenhouse gas emissions, rather than greenhouse gas concentrations (Dunne et al. 2024; Sanderson et al. 2024).

As computer server and cloud resources have increased, statistical downscaling approaches have improved to enhance the ability to realistically capture extreme events (e.g., LOCA2, STAR-ESDM) or decompose temporal changes in observed data or model output into long-term trends, seasonal climatology, and daily anomalies (e.g., STAR-ESDM). Dynamically downscaled products are also improving in scale and speed to include multiple scenarios and global models (e.g., ClimRR, https://climrr.anl.gov). Dynamically downscaled products provide a broader suite of physically based variables compared to statistically downscaled products but remain limited in the number of global climate models utilized, which limits the consideration of uncertainties in the GCM ensemble. Additional dynamical downscaling datasets are already being planned based on CMIP6 (NA-CORDEX, https://na-cordex.org). New approaches include hybrid statistical and dynamical downscaling, which use dynamical methods for a region and then develop statistical models to mimic dynamical model behavior over complex landscapes (Walton et al. 2015). Some global models are approaching regional and local spatial resolution (< 10 km) and sub-daily output over continental scales (e.g., E3SM, https://e3sm.org/towards-ultra-high-resolution-e3sm-land-modeling-on-exascale-computers/). Even more options are on the horizon, such as machine learning approaches (Eyring et al. 2024; Hobeichi et al. 2023). With this proliferation of new data and user demand, there are new opportunities and challenges for tailoring the most appropriate climate information for applications and decision-making.

To address the effects of societal choices on global warming, arguably the most important long-term uncertainty (Lehner et al. 2020), the climate modeling community largely relies on a set of scenarios developed by World Climate Research Programme's Scenario Model Intercomparison Project (ScenarioMIP, https://wcrp-cmip.org/mips/scenariomip/, O'Neill et al. 2016). These scenarios are developed in a broader policy landscape associated with international climate negotiations under the United Nations Framework Convention on Climate Change. However global climate scenarios are also designed to address science questions about the effects of anthropogenic climate forcings and their impacts, and to support users of climate information for decision-making beyond the scientific community. By their nature and role, however, these scenario sets (RCPs in CMIP5, SSP-RCPs in CMIP6, and a proposed new set of of carbon emission scenarios in CMIP7; Sanderson et al. 2024) result from a compromise among their different uses. In particular, there are long-standing tradeoffs between the need to develop scenarios that can adequately sample the vast number of plausible and policy-relevant outcomes on multi-decade or even multi-century time frames – and the constraints surrounding the number of scenarios that can be prescribed to climate modeling groups due to the large computational costs involved in running the latest global climate models. Thus, even if they constitute a solid base for most forms of future projections, scenarios prescribed by ScenarioMIP cannot be in and of themselves the only input to decision-making, especially at the level of local concerns.

Climate change increasingly affects nearly every aspect of life on the planet, and this means almost every community and decision-maker will require actionable, interpretable climate projections. These different communities will have vastly different needs. A federal or state policymaker making mitigation decisions will be interested in how and when emissions reductions will begin to affect global or regional climates. By contrast, a water manager or coastal engineer may require a spectrum of likely and worst-case scenarios for adaptation planning. The agricultural or health sectors may require projections on higher temporal frequency than the insurance sector or homebuyers.

How, then, should scientists talk about the future? In NCA5, the Climate Trends chapter (Marvel et al. 2023) was tasked with explaining and reporting the climate projections that would underpin the regional and sectoral chapters of the report (see Section 1). Chapter authors chose to report projections at different GWLs to avoid the use of ScenarioMIP terminology (e.g. SSP and RCP) that may be confusing to non-specialists. This issue is also recognized by ScenarioMIP itself, which is proposing that CMIP7 will avoid these labels and use intuitive names for its scenarios, such as “high,” “medium,” “low,” and “very low” (https://wcrp-cmip.org/scenariomip-cmip7-proposal/). However, there remains a potential disconnect on what the labels inherently refer to, i.e., emissions, greenhouse gas concentrations, temperatures, or a combination.

Finally, the use of GWLs raises the question of *when* the world may reach these warming levels (Fig. 2). The answer is that it depends on societal choices for both mitigation and adaptation (IPCC 2023). The GWL framing does not explicitly provide future outcomes by year (e.g., 2050 or 2100), but it can highlight the role of human actions in increasing or decreasing the risk of climate impacts. It also shifts the focus from the regional scale to the global scale by reporting on the modeling of global temperature alone. Regional scale impacts can be analyzed for individual climate models as each reaches a specific GWL, but that information is often reported independently of a scenario and/or time series. Different scenarios of emissions—dependent on human choices about energy use but also on assumptions of economic growth, technological progress, intra- and inter-regional cooperation, and equality—will determine *when* the world reaches a specific GWL (O’Neill et al. 2016). Additionally, individual climate scenarios need to be considered to understand impacts and risks experienced by human systems, since the dimensions of exposure and vulnerability are driven by socio-economic pathways (Bukovsky et al. 2021; Fei et al. 2023; Shindell et al. 2024; Terando et al. 2020).

Some characteristics of climate variable responses, geophysical impacts, or decision contexts do not lend themselves straightforwardly to a GWL framing. Some phenomena, like sea-level rise, depend on the accumulated history of global temperature change. For those, it matters if a given GWL is a single crossed point along a path that is rapidly moving to higher levels or if the GWL has been reached by a path that has stabilized at that level for a while. The same GWL on one side or the other of a peak-and-decline pathway will also mean very different behavior in the case of non-reversible (or very slow to reverse) impacts, like ice sheet melt, ecosystem transitions, or desertification (IPCC 2023). Further, some impacts depend on the rate of global temperature change and not just the anomaly (Fischer et al. 2021). The GWL framework also elides the roles of different forcings: A world whose GWL is moderated by the counteracting effects of being warmed by extremely high greenhouse gas concentrations (warming) and cooled by large aerosol loadings (cooling) will look different than a world warmed only by moderate greenhouse gas concentrations.

Framing the findings of NCA5’s chapters 2 and 3 around GWL was a new approach for presenting a complex topic to a non-technical NCA audience. Without a user evaluation of its efficacy as a communication tool, it is too soon to tell how well a GWL or time-based scenarios storyline approach meets the needs of different users. Since the GWL is relatively new, its use may have been limited by the fact that the bulk of the extant literature for authors to assess still uses the more traditional scenario, or timeseries approaches. In considering the future of climate services, engaging with users can help scientists understand which approach is more effective in answering user questions. Providing authors, and the NCA audience, with access to both approaches via the NCA5 Atlas and other online approaches supports flexibility for readers to determine their own framing.

5 Discussion: lessons learned and future opportunities

For decades, climate projections and assessments have informed international policy decisions and are increasingly being used in risk management and community planning including decisions around infrastructure development and ecosystem conservation, public health recommendations and communication approaches, and prioritization of public budgets (Kotamarthi et al. 2021). Modeling efforts supported by U.S. federal agencies inform the content of NCAs (Mariotti et al. 2024). In turn, NCA findings can inform federal, state, local, and Tribal policy processes (Lattanzio et al. 2021; EPA 2023; Holmes et al. 2020; Kirchhoff et al. 2019). For example, Executive Order 14008, Section 211, outlines an interagency effort to "facilitate public access to climate-related information that will assist Federal, State, local, and Tribal governments in climate planning and resilience activities" (Executive Order 14008 2021). The use of this climate information in policies and planning can also influence the development of climate projections, both in terms of determining which scenarios researchers explore and therefore what potential futures the models might project. As an outgrowth of climate projection discussions for NCA5, a federally funded workshop was organized around options for evaluating regional climate projections and addressing practitioner information needs (SERDP-ESTCP 2023). These discussions continue as planning for NCA6 progresses and as part of USGCRP's efforts to support climate services (USGCRP 2024). It is anticipated that additional efforts will continue to build a strong "community of practice" to improve the state of knowledge about climate projections.

Future NCA cycles will need to confront their role in an ongoing assessment of scientific confidence in different types of climate projections given an inherently uncertain future. However, a number of questions for climate assessments remain. First, as the use of climate-relevant information continues to grow along with the complexity of the climate projection landscape, how can future assessments leverage climate projections to better meet evolving user needs? Additionally, are there emerging strategies to evaluate the myriad projections to best capture and convey the spread of future uncertainty, including the socioeconomic uncertainties? And lastly, can the NCA process be leveraged to gather downscaled projections into a cohesive comparison framework— much as the CMIP process sets data requirements for the broader climate modeling community?

With the above context, several opportunities can inform the next phase of NCA development:

(1) **Identify and use benchmarks for downscaled datasets**

The complexity of climate projections and downscaled datasets will increase with more variables, higher spatial resolutions, higher temporal frequency, and new methodological approaches (Mariotti et al. 2024). The modeling community is expanding evaluation metrics for sub-global and sub-national projections based on regional performance, bias correction, model weighting, variables beyond temperature and precipitation (Ullrich 2023). In this broader context, there is an opportunity for future NCAs to minimize the data production planning and processing challenges faced by past assessments. For example, documenting metadata, developing common terminology, and setting criteria for testing skill across data products (benchmarks) for downscaled projections (Dixon et al. 2016) would reduce the TSU staff time and resources needed to produce information for NCA authors.

These efforts would also align with federal laws and policies regarding data (EBPA 2019; OMB 2004). Furthermore, a process to develop downscaled data submission standards for NCAs, comparable to those used in existing model comparison projects (e.g., CMIP or CORDEX), could ease the burden of post-hoc evaluation after datasets are created, while identifying appropriate datasets that are fit-for-purpose based on user needs. For NCA6, a Federal Register Notice was released requesting information on downscaled datasets for use in the report, which initiated a review process for climate projections that comply with NCA submission requirements (OSTP 2024; https://www.federalregister.gov/documents/2024/11/27/2024-27858/notice-of-request-for-information-downscaled-climate-projection-datasets-available-to-be-considered). As part of that process, the datasets would be benchmarked against each other to form the basis for evidence-based decisions when choosing which datasets to use for different purposes.

(2) **Build on previous NCA products to gather information on research gaps and identify user needs**

Throughout the assessment development process, NCA teams (i.e., authors, staff, collaborators) want to understand who is using climate projection data, how they are using it, and what the user needs are. Tracking this information has historically been difficult, particularly as laws such as the Paperwork Reduction Act limit the federal government's ability to conduct surveys or hold focus groups (Avery et al. 2025). However, USGCRP has already made significant advances in public engagement (Lustig et al. In Review), which allow assessment developers to gather information and feedback via public webinars, workshops, and comment periods, as well as outreach and communication efforts. There is an opportunity to build upon these efforts through climate services, which can help USGCRP agencies target recognized and emerging research gaps—such as high-resolution estimates for humidity, inland flooding, and wildfire—that are informed by climate projections. Additionally, USGCRP can consider the recommendations of a National Academies Advisory Committee to develop a strategy for evaluation of national climate assessments (NASEM 2024). Conducting such evaluations of published NCAs in a timely manner would make it possible to inform the next NCA cycle.

The modeling community also continues to improve the knowledge base of the strengths and weaknesses of available climate projections to inform decision-making (Ullrich 2023) and efforts to include data users in model development are expanding (SERDP-ESTCP 2023). There are opportunities to leverage interagency and community-of-practice strategies to achieve these improvements. For example, the guidance from a Subcommittee on Climate Services (USGCRP 2024) can better inform the federal choices for what projection information is incorporated into future NCAs.

(3) **Provide additional guidance on using climate data**

People from an array of diverse backgrounds and with varying levels of technical expertise can now access extensive climate datasets (e.g., NCA Atlas, https://atlas.globalchange.gov, and the U.S. Geological Survey [USGS] National Climate Change Viewer, https://www.usgs.gov/tools/national-climate-change-viewer-nccv). This includes users who are not experts in climate scenarios but who need to use climate projections to understand potential impacts and inform resilience planning. Despite increased data access to new websites and to comparative analysis of datasets, there is still a gap in guidance for users who must navigate the burgeoning landscape of data options to determine which datasets might be appropriate for their climate-related questions. Guidance to fill this gap could inform users on how best to use the projection data and how to interpret the results to inform decisions. This issue has long been recognized as the "practitioner's dilemma," where information users face difficult decisions on how to "choose an appropriate data set, assess its credibility, and use it wisely" (Barsugli et al. 2013). Providing the needed educational resources to train a "climate-ready nation" (NOAA 2024) and support a national effort towards climate services (NSTC 2023) requires not just datasets or comparative information, but also lesson plans and resources to guide users towards determining the best information for their needs.

Along the lines of science communication, text descriptions of uncertainty as well as visualization of uncertainty in maps and figures have always been an important consideration for each NCA. Although standardized calibrated language is used across the assessment to report uncertainty in the likelihood and confidence of key chapter findings, the ways in which uncertainty is reported or visualized for specific projections may differ based on the underlying methodology of the sources. NCA5 authors were also provided with guidance on reporting uncertainty of the future such as providing multiple scenarios (e.g., SSP2-4.5 and SSP3-7.0) or including not just the mean value for a projection but also the range, whether it be a climate variable, impact, or cost. Guided by the expertise of the TSU, NCA figures have employed a range of standard scientific practices for illustrating uncertainty in climate projections, including whiskers or error bars on charts, shaded uncertainty ranges for time series showing projections for various scenarios, and hatching on maps of projected climate variables (Maycock et al. 2023). Some NCA5 examples include Figs. 1.1 and 1.13 in the Overview (Jay et al. 2023), and Figs. 3.1, 3.3, 3.5, 3.6, and 3.7 in Chapter 3 (Leung et al. 2023), along with other figures across the regional and sectoral chapters. Yet both user needs and best practices for data visualization are always evolving. As more people access NCA datasets for their own decision-making, future guidance on how to best use and interpret projection data should also include guidance on how to report and contextualize uncertainty. Further, many of the decisions made around data visualization in NCAs have included consideration of how an average reader might interpret, misinterpret, or ignore overly complicated figures. NCA5 author teams received feedback on figures during the peer and public review cycles that helped shape their final format. The TSU also considers best practices for audiences using screen readers and other federal compliance standards when developing report elements, including figures, tables, color palettes, and fonts. See supplemental materials for Avery et al. (2025) for demonstrations of consideration of different visual impairments in the development of maps and figures. The NCA process can provide users with context on how to use data from projections and understand the inherent uncertainty in climate projections and societal choices (e.g., greenhouse gas mitigation, adaptation efforts, policies, and technological change).

6 Conclusions

There is no one-size-fits-all approach to deploying climate projections in climate assessments. There are important advantages and drawbacks to decisions made about climate models, scenarios, downscaling approaches, and even terminology —particularly as uncertainty in future climate change indicators (e.g., temperature, precipitation, etc.) grows relative to uncertainty sources over time and geographic scale (e.g., human emissions and climate scenarios, model structure and parameters, and natural variability in the climate system; Fig. 3.6 in Leung et al. 2023). The role of science in a national assessment will continue to evolve to provide targeted, useful projections for communities to respond to climate change through mitigation, adaptation, and resilience-building actions. This will require a continuous, iterative process of understanding who is asking for this information, what needs the information is meant to address, and how the information will be used. It will also require consistent engagement with multiple scientific communities to ensure that the available information sources assessed by NCA authors report climate projections in ways that are useful to end users. For projection developers and users, it remains important to recognize and reiterate that our future climate pathway is not yet determined, is always subject to change, and is a choice that humans are making today.

Acknowledgements The authors sincerely thank the members of the USGCRP downscaling workstream, working groups, the organizers and attendees of the Understanding Decision-Relevant Regional Climate Projections Workshop, the National Academies Advisory Committee, and others in the broader community of practice who have undertaken discourse on these difficult topics over the past two decades. Additionally, thank you to the following colleagues for their feedback on this paper and coordination of the NCA5 special issue: Aaron Grade, Neil Matouka, Chris Avery, Mike Kuperberg, Alexa Jay, and Peter Schultz.

Authors' contributions All authors contributed to the article's conception and literature review. Additional author contributions are as follows:
Samantha Basile (project administration, analysis, writing-original draft, writing-review & editing); Allison Crimmins (analysis, visualization of Fig. 1, writing-original draft, writing-review & editing); Fredric Lipschultz (analysis, writing-original draft, writing-review & editing); Kenneth E. Kunkel (analysis, writing-original draft); Kate Marvel (analysis, writing-original draft);
Adam Terando (writing-review & editing); Claudia Tebaldi (writing-review & editing); David Pierce (writing-review & editing); Wenying Su (writing-review & editing); L. Ruby Leung (writing-review & editing); Katharine Hayhoe (writing-review & editing).

Funding F.L. was supported by NASA's SSAI contract NNG17HP01C. Support for K.E.K was provided by NOAA through the Cooperative Institute for Satellite Earth System Studies under Cooperative Agreement NA19NES4320002. The views expressed in this document are those of the authors and do not necessarily reflect those of any federal agency. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Data availability This article is a review of previously published research and does not provide new data.

Code availability This article is a review of previously published research, all published materials are available through the associated references.

Declarations

Ethics approval and consent to participate This article does not contain any studies with human or animal participants performed by any of the authors.

Consent for publication All authors have provided consent for this article to be published.

Competing interests The authors have no competing interests to declare that are relevant to the content of this article.

References

Allstadt AJ, Vavrus SJ, Heglund PJ et al (2015) Spring plant phenology and false springs in the conterminous US during the 21st century. Environ Res Lett 10(10):104008. https://doi.org/10.1088/1748-9326/10/10/104008

Arias PA, Bellouin N, Coppola, E et al (2021) Technical summary. In: Masson-Delmotte V, Zhai P, Pirani A et al (eds) Climate Change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp 33−144. https://doi.org/10.1017/9781009157896.002

Avery CW, Crimmins AR, Basile S et al (2023) Front matter. In: Crimmins AR, Avery CW, Easterling DR et al (eds) Fifth national climate assessment. Washington, DC, USA https://doi.org/10.7930/NCA5.2023

Avery CW, Crimmins AR, Lustig AR et al (2025) Navigating complex waters: Designing a process for the development of the National Climate Assessment. Clim Change 178:44. https://doi.org/10.1007/s10584-024-03854-8

Barsugli JJ, Guentchev G, Horton RM et al (2013) The practitioner's dilemma: How to assess the credibility of downscaled climate projections. Eos Trans Amer Geophys Union 96:424–425. https://doi.org/10.1002/2013EO460005

Basile S, Avery CW, Grade A, Crimmins AR (2024) To be policy-relevant, future climate research must include the noncontiguous United States. Proc Natl Acad Sci 121(13):e2315505121. https://doi.org/10.1073/pnas.2315505121

Basile, S, Crimmins AR, Avery CW et al (2023) Appendix 3. Scenarios and datasets. In: Crimmins AR, Avery CW, Easterling DR et al (eds) Fifth national climate assessment. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.A3

Bukovsky MS, Gao J, Mearns LO, O'Neill BC (2021) SSP-based land-use change scenarios: a critical uncertainty in future regional climate change projections. Earth's Future 9(3):e2020EF001782. https://doi.org/10.1029/2020EF001782

Chen D, Rojas M, Samset BH et al (2021) Framing, context, and methods. In: Masson-Delmotte V, Zhai P, Pirani A et al (eds) Climate Change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 147–286 https://doi.org/10.1017/9781009157896.003

Crimmins A (2020) Improving the use of calibrated language in US climate assessments. Earth's Future 8(11):e2020EF001817. https://doi.org/10.1029/2020EF001817

Crimmins AR, Avery CW, Reidmiller DR, Grade AM (In Review) Innovations in the climate assessment development process. Clim Change

Dixon KW, Lanzante JR, Nath MJ et al (2016) Evaluating the stationarity assumption in statistically downscaled climate projections: is past performance an indicator of future results? Clim Change 135:395–408. https://doi.org/10.1007/s10584-016-1598-0

Dunne JP, Hewitt HT, Arblaster J et al (2024) An evolving coupled model intercomparison project phase 7 (CMIP7) and fast track in support of future climate assessment. EGUsphere [preprint]. https://doi.org/10.5194/egusphere-2024-3874

EBPA (2019) Foundations for evidence-based policymaking act of 2018. H.R.4174, 115th Congress, Pub. L. No. 115–435, 132 Stat. pp 5529–5557 https://www.congress.gov/bill/115th-congress/house-bill/4174/text. Accessed 5 Aug 2024.

EPA (2023) Report on the social cost of greenhouse gases: Estimates incorporating recent scientific advances, 2024. https://www.epa.gov/system/files/documents/2023-12/epa_scghg_2023_report_final.pdf. Accessed May 27

Eyring V, Bony S, Meehl GA et al (2016) Overview of the coupled model intercomparison project phase 6 (CMIP6) experimental design and organization. Geosci Model Dev 9:1937–1958. https://doi.org/10.5194/gmd-9-1937-2016

Eyring V, Gentine P, Camps-Valls G et al (2024) AI-empowered next-generation multiscale climate modelling for mitigation and adaptation. Nat Geosci. https://doi.org/10.1038/s41561-024-01527-w

Fei C, Jägermeyr J, McCarl B et al (2023) Future climate change impacts on US agricultural yields, production, and market. Anthropocene 42:100386. https://doi.org/10.1016/j.ancene.2023.100386

Fischer EM, Sippel S, Knutti R (2021) Increasing probability of record-shattering climate extremes. Nat Clim Chan 118(11):689–695. https://doi.org/10.1038/s41558-021-01092-9

GCRA (1990) 101st congress, Pub. L. No. 101–606, 104 Stat. November 16, 1990 pp 3096–3104. https://www.congress.gov/bill/101st-congress/senate-bill/169/text. Accessed 5 Aug 2024

Grade AM, Crimmins AR, Basile S et al (2023) Appendix 5. glossary. In: Crimmins AR, Avery CW, Easterling DR et al (eds) Fifth national climate assessment. U.S. global change research program. Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.A5

Hausfather Z, Peters GP (2020) RCP8.5 is a problematic scenario for near-term emissions. Proc Nat Acad Sci 117(45):27791–27792. https://doi.org/10.1073/pnas.2017124117

Hausfather Z, Marvel K, Schmidt GA et al (2022) Climate simulations: recognize the ‘hot model’ problem. Nature 605:26–29. https://doi.org/10.1038/d41586-022-01192-2

Hayhoe K, Stoner A, Wuebbles DJ, Scott-Fleming I (2024) STAR-ESDM: a generalizable approach to generating high-resolution climate projections through signal decomposition. Earth’s Future 12(7). https://doi.org/10.1029/2023EF004107

Hobeichi S, Nishant N, Shao Y et al (2023) Using machine learning to cut the cost of dynamical downscaling. Earth’s Future 11(3):e2022EF003291. https://doi.org/10.1029/2022EF003291

Holmes KJ, Wender BA, Weisenmiller R et al (2020) Climate assessment moves local. Earth’s. Future 8(2):e2019EF001402. https://doi.org/10.1029/2019EF001402

IPCC (2000) Special report on emissions scenarios. A special report of working group III of the intergovernmental panel on climate change. Cambridge University Press, p 570. http://www.ipcc.ch/ipccreports/sres/emission/index.php?idp=0. Accessed 5 Aug 2024

IPCC (2021) Climate change 2021: the physical science basis. In: Masson-Delmotte V, Zhai P, Pirani A. et al (eds) Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p 2391. https://doi.org/10.1017/9781009157896

IPCC (2023) Sections. In: Lee H, Romero J (ed) Climate change 2023: synthesis report. Contribution of working groups I, II and III to the sixth assessment report of the intergovernmental panel on climate change. IPCC, Geneva, Switzerland, pp 35–115 https://doi.org/10.59327/IPCC/AR6-9789291691647

Jacobs K, Moser S, Buizer J (eds) (2016) The US national climate assessment: innovations in science and engagement, Springer Cham. https://doi.org/10.1007/978-3-319-41802-5

Jay AK, Crimmins AR, Avery CW et al (2023) Ch. 1. overview: understanding risks, impacts, and responses. In: Crimmins, AR, Avery CW, Easterling DR et al (eds) Fifth national climate assessment. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.CH1

Kirchhoff CJ, Barsugli JJ, Galford GL et al (2019) Climate assessments for local action. Bull Am Meteor Soc 100(11):2147–2152. https://doi.org/10.1175/BAMS-D-18-0138.1

Knutti R (2010) The end of model democracy? an editorial comment. Clim Chang 102(3):395–404. https://doi.org/10.1007/s10584-010-9800-2

Kotamarthi R, Hayhoe K, Wuebbles D, Mearns LO, Jacobs J, Jurado J (2021) Downscaling techniques for high-resolution climate projections: from global change to local impacts. Cambridge University Press. https://doi.org/10.1017/9781108601269

Kunkel KE, Moss R, Parris A (2016) Innovations in science and scenarios for assessment. In: The US National Climate Assessment, Jacobs K, Moser S, Buizer J (eds), Springer Climate, pp 55–68. https://doi.org/10.1007/978-3-319-41802-5_5

Lattanzio R, Leggett JA, Procita K, Ramseur JL, Clark CE, Croft GK, Miller RS (2021) U.S. climate change policy. Congressional Research Service, p R46947. https://crsreports.congress.gov/product/pdf/R/R46947 Accessed 27 May 2024

Lehner F (2024) Climate model large ensembles as test beds for applied compound event research. iScience 27:111113. https://doi.org/10.1016/j.isci.2024.111113

Lehner F, Deser C, Maher N et al (2020) Partitioning climate projection uncertainty with multiple large ensembles and CMIP5/6. Earth Syst Dyn 11(2):491–508. https://doi.org/10.5194/esd-11-491-2020
Leung LR, Terando A, Joseph R et al (2023) Ch. 3. earth systems processes. In: Crimmins AR, Avery CW, Easterling DR, Kunkel KE, Stewart BC, Maycock TK (eds) Fifth national climate assessment, U.S. global change research program, Washington, DC, USA https://doi.org/10.7930/NCA5.2023.CH3
Lustig AR, Grade AM, Grecni ZN, Hoffman JS, Matouka N, Novak R, Parris A, Crimmins AR (In Review) Public engagement in climate assessment: lessons and opportunities. Clim Change
Mariotti A, Bader DC, Bauer SE et al (2024) Envisioning US climate predictions and projections to meet new challenges. Earth's Future 12(6):e2023EF004187. https://doi.org/10.1029/2023EF004187
Marvel K, Su W, Delgado R et al (2023) Ch. 2. climate trends. In: Crimmins, A.R., Avery CW, Easterling DR et al (eds) Fifth national climate assessment. U.S. global change research program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.CH2
Massoud E, Lee H, Terando A, Wehner M (2023) Bayesian weighting of climate models based on climate sensitivity. Commun Earth Environ 4. https://doi.org/10.1038/s43247-023-01009-8
Maycock T, Allen J, Essig M et al (2023) SY23B-0899 science communication in the fifth national climate assessment. AGU fall meeting abstracts. https://agu.confex.com/agu/fm23/meetingapp.cgi/Paper/1341846. Accessed 27 Jan 2025
McDonnell A, Bauer AM, Proistosescu C (2024) To what extent does discounting "Hot" climate models improve the predictive skill of climate model ensembles? Earth's Future 12:e2024EF004844. https://doi.org/10.1029/2024EF004844
McPherson RA, Fay PA, Alvarez SG et al (2023) Ch. 26. southern great plains. In: Crimmins AR, Avery CW, Easterling DR et al (eds) Fifth national climate assessment. U.S. global change research program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.CH26
Meehl GA, Covey C, Delworth T et al (2007) The WCRP CMIP3 multimodel dataset: a new era in climate change research. Bull Am Meteorol Soc 88:1383–1394. https://doi.org/10.1175/BAMS-88-9-1383
Melillo JM, Richmond TT, Yohe G (2014) Climate change impacts in the United States. Third Nat Clim Assess 52:150–174. https://nca2014.globalchange.gov/
Moss RH, Edmonds JA, Hibbard KA et al (2010) The next generation of scenarios for climate change research and assessment. Nature 463(7282):747–756. https://doi.org/10.1038/nature08823
NASEM (2023) Review of the draft fifth national climate assessment. The National Academies Press, Washington, DC. https://doi.org/10.17226/26757
NASEM (2024) Developing a strategy to evaluate the national climate assessment. The National Academies Press, Washington, DC. https://doi.org/10.17226/27923
National Assessment Synthesis Team (2000) Climate change impacts on the United States-overview report: the potential consequences of climate variability and change, foundation report. Cambridge University Press, Cambridge UK, p 620. https://www.globalchange.gov/reports/climate-change-impacts-united-states-potential-consequences-climate-variability-and-change-foundation. Accessed 5 Aug 2024
NOAA (2024) NOAA administrative order 216–127: providing for A climate-ready nation. United States Department of Commerce, Washington, DC. https://www.noaa.gov/sites/default/files/2024-04/NAO_216-127_Providing_For_A_Climate-Ready_Nation.pdf. Accessed 5 Aug 2024
NSTC (2023) A federal framework and action plan for climate services: product of the fast track action committee on climate services of the national science and technology council. https://www.whitehouse.gov/wp-content/uploads/2023/03/FTAC_Report_03222023_508.pdf. Accessed 17 Jun 2024
O'Neill BC, Tebaldi C, Van Vuuren DP et al (2016) The scenario model intercomparison project (ScenarioMIP) for CMIP6. Geosci Model Dev 9(9):3461–3482. https://doi.org/10.5194/gmd-9-3461-2016
O'Neill BC, Kriegler E, Ebi KL et al (2017) The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century. Glob Environ Chang 42:169–180. https://doi.org/10.1016/j.gloenvcha.2015.01.004
OMB (2004) Final information quality bulletin for peer review. M-05–03. U.S. office of management and budget, Washington, DC. https://obamawhitehouse.archives.gov/sites/default/files/omb/assets/omb/memoranda/fy2005/m05-03.pdf. Accessed 5 Aug 2024
OSTP (2024) Notice of request for information; downscaled climate projection datasets available to be considered for use in the sixth national climate assessment. U.S. Office of Science and Technology Policy, Washington, DC. https://www.federalregister.gov/documents/2024/11/27/2024-27858/notice-of-request-for-information-downscaled-climate-projection-datasets-available-to-be-considered. Accessed 5 Aug 2024
Pedersen JTS, van Vuuren D, Gupta J, Santos FD, Edmonds J, Swart R (2022) IPCC emission scenarios: how did critiques affect their quality and relevance 1990–2022? Glob Environ Chang 75:102538. https://doi.org/10.1016/j.gloenvcha.2022.102538
Pierce DW, Cayan DR, Thrasher BL (2014) Statistical downscaling using localized constructed analogs (LOCA). J Hydrometeorol 15:2558–2585. https://doi.org/10.1175/JHM-D-14-0082.1

Pierce DW, Cayan DR, Feldman DR, Risser MD (2023) Future increases in North American extreme precipitation in CMIP6 downscaled with LOCA. J Hydrometeorol 24:951–975. https://doi.org/10.1175/jhm-d-22-0194.1
Riahi K, Van Vuuren DP, Kriegler E et al (2017) The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Glob Environ Chang 42:153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009
Sanderson BM, Booth BB, Dunne J et al (2024) The need for carbon-emissions-driven climate projections in CMIP7. Geosci Model Dev 17(22):8141–8172. https://doi.org/10.5194/gmd-17-8141-2024
Sanderson B, Wehner M (2017) Weighting strategy for the fourth national climate assessment (APPENDIX B). Publications, agencies and staff of the U.S. department of commerce, p 576. https://digitalcommons.unl.edu/usdeptcommercepub/576. Accessed 5 Aug 2024
Schwalm CR, Glendon S, Duffy PB (2020) Reply to Hausfather and Peters: RCP8.5 is neither problematic nor misleading. Proc Nat Acad Sci 117(45):27793–27794. https://doi.org/10.1073/pnas.2018008117
SERDP-ESTCP (2023) Understanding decision-relevant regional climate projections workshop. Berkeley, California. https://serdp-estcp.mil/events/details/5e5f7a42-4b96-42e8-9979-d4b97854527d/understanding-decision-relevant-regional-climate-projections-workshop. Accessed 17 Jun 2024
Sherwood SC, Webb MJ, Annan JD et al (2020) An assessment of Earth's climate sensitivity using multiple lines of evidence. Rev Geophys 58(4):e2019RG000678. https://doi.org/10.1029/2019rg000678
Shindell D, Faluvegi G, Nagamoto E, Parsons L, Zhang Y (2024) Reductions in premature deaths from heat and particulate matter air pollution in South Asia, China, and the United States under decarbonization. Proc Natl Acad Sci 121(5):e2312832120. https://doi.org/10.1073/pnas.2312832120
Sweet WV, Kopp RE, Weaver CP, Obeysekera J, Horton RM, Thieler ER, Zervas C (2017) Global and regional sea level rise scenarios for the United States (No. CO-OPS 083). https://doi.org/10.7289/v5/tr-nos-coops-083
Sweet WV, Hamlington BD, Kopp RE et al (2022) Global and regional sea level rise scenarios for the United States: updated mean projections and extreme water level probabilities along U.S. coastlines. NOAA technical report NOS 01. National oceanic and atmospheric administration. National Ocean Service, Silver Spring, MD, p 111. https://oceanservice.noaa.gov/hazards/sealevelrise/noaa-nostechrpt01-global-regional-SLR-scenarios-US.pdf. Accessed 5 Aug 2024
Taylor KE, Stouffer RJ, Meehl GA (2012) An overview of CMIP5 and the experiment design. Bull Am Meteorol Soc 93:485–498. https://doi.org/10.1175/BAMS-D-11-00094.1
Terando A, Reidmiller D, Hostetler SW et al (2020) Using information from global climate models to inform policymaking—The role of the U.S. geological survey: U.S. geological survey open-file report, pp 2020–1058, 25. https://doi.org/10.3133/ofr20201058
Ullrich PA (2023) Validation of LOCA2 and STAR-ESDM statistically downscaled products (No. LLNL-TR-856094). Lawrence livermore national laboratory (LLNL), Livermore, CA (United States). https://climatemodeling.science.energy.gov/sites/default/files/2023-11/Validation%20of%20LOCA2%20and%20STAR-ESDM%20Statistically%20Downscaled%20Products%20v2.pdf. Accessed 17 Jun 2024
UNFCCC (2016) The Paris agreement. Paris climate change conference - november 2015, Conference of Parties p 21. https://unfccc.int/documents/184656. Accessed 27 May 2024
USGCRP (2009) Global climate change impacts in the united states. Karl TR, Melillo JM, and Peterson TC (eds), Cambridge University Press, 2009. https://www.globalchange.gov/reports/global-climate-change-impacts-united-states. Accessed 5 Aug 2024
USGCRP (2015) U.S. Global change research program general decisions regarding climate-related scenarios for framing the fourth national climate assessment: USGCRP scenarios and interpretive science coordinating group. https://scenarios.globalchange.gov/sites/default/files/External/20memo/20NCA4/20scenarios/20framing_20150506.pdf. Accessed 4th Jul 2024
USGCRP (2017) Climate science special report: fourth national climate assessment, volume I. Wuebbles DJ, Fahey DW, Hibbard KA et al (eds) U.S. Global change research program, Washington, DC, USA, p 470
USGCRP (2018) Impacts, risks, and adaptation in the united states: Fourth national climate assessment, volume II. Reidmiller DR, Avery CW, Easterling DR et al (eds) U.S. Global change research program, Washington, DC, USA, p 1515. https://doi.org/10.7930/NCA4.2018
USGCRP (2023) Fifth national climate assessment. Crimmins AR, Avery CW, Easterling DR et al (eds), Washington, DC, USA. https://doi.org/10.7930/NCA5.2023
USGCRP (2023) Selection process for downscaled climate projection data in the fifth national climate assessment. Fifth national climate assessment downloads. https://nca2023.globalchange.gov/downloads/NCA5-Climate-Projection-Selection-Process.pdf. Accessed 17 Jun 2024
USGCRP (2024) Climate services. https://www.globalchange.gov/our-work/climate-services. Accessed 8 Jul 2024
Van Vuuren DP, Edmonds J, Kainuma M et al (2011) The representative concentration pathways: an overview. Clim Change 109:5–31. https://doi.org/10.1007/s10584-011-0148-z

Walton DB, Sun F, Hall A, Capps SB (2015) A hybrid dynamical–statistical downscaling technique, part I: development and validation of the technique. J Clim 28(12):4597–4617. https://doi.org/10.1175/JCLI-D-14-00196.1
Weaver CP, Moss RH, Ebi KL et al (2017) Reframing climate change assessments around risk: recommendations for the US national Climate assessment. Environ Res Lett 12(8):080201. https://doi.org/10.1088/1748-9326/aa7494

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Authors and Affiliations

Samantha Basile[1] · Allison Crimmins[2] · Fredric Lipschultz[3] · Kenneth E. Kunkel[4] · Kate Marvel[5] · Adam Terando[6] · Claudia Tebaldi[7] · David Pierce[8] · Wenying Su[9] · L. Ruby Leung[10] · Katharine Hayhoe[11]

✉ Samantha Basile
sam.jude.b@gmail.com

Fredric Lipschultz
flipschultz@usra.edu

1 Schenectady, NY, USA
2 US National Oceanic and Atmospheric Administration, Washington, DC, USA
3 Universities Space Research Association, Washington, DC, USA
4 North Carolina State University, Raleigh, NC, USA
5 NASA Goddard Institute for Space Studies, New York, NY, USA
6 US Geological Survey, Southeast Climate Adaptation Science Center, Raleigh, NC, USA
7 Pacific Northwest National Laboratory, College Park, MD, USA
8 Scripps Institution of Oceanography, La Jolla, California, USA
9 NASA Langley Research Center, Hampton, VA, USA
10 Pacific Northwest National Laboratory, Richland, WA, USA
11 Texas Tech University, the Nature Conservancy, Lubbock, TX, USA