# Envisioning U.S. Climate Predictions and Projections to Meet New Challenges

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### Abstract

In the face of a changing climate, the understanding, predictions and projections of natural and human systems are increasingly crucial to prepare and cope with extremes and cascading hazards, determine unexpected feedbacks and potential tipping points, inform long-term adaptation strategies, and guide mitigation approaches. Increasingly complex socio-economic systems require enhanced predictive information to support advanced practices. Such new predictive challenges drive the need to fully capitalize on ambitious scientific and technological opportunities. These include the unrealized potential for very high-resolution modeling of global-to-local Earth system processes across timescales, a reduction of model biases, enhanced integration of human systems and the Earth Systems, better quantification of predictability and uncertainties; expedited science-to-service pathways and co-production of actionable information with stakeholders. Enabling technological opportunities include exascale computing, advanced data storage, novel observations and powerful data analytics, including artificial intelligence and machine learning. Looking to generate community discussions on how to accelerate progress on U.S. climate predictions and projections, representatives of Federally-funded U.S. modeling groups outline here perspectives on a six-pillar national approach grounded in climate science that builds on the strengths of the U.S. modeling community and agency goals. This calls for an unprecedented level of coordination to capitalize on transformative opportunities, augmenting and complementing current modeling center capabilities and plans to support agency missions. Tangible outcomes include projections with horizontal spatial resolutions finer than 10 km, representing extremes and associated risks in greater detail, reduced model errors, better predictability estimates, and more customized projections to support the next generation of climate services.

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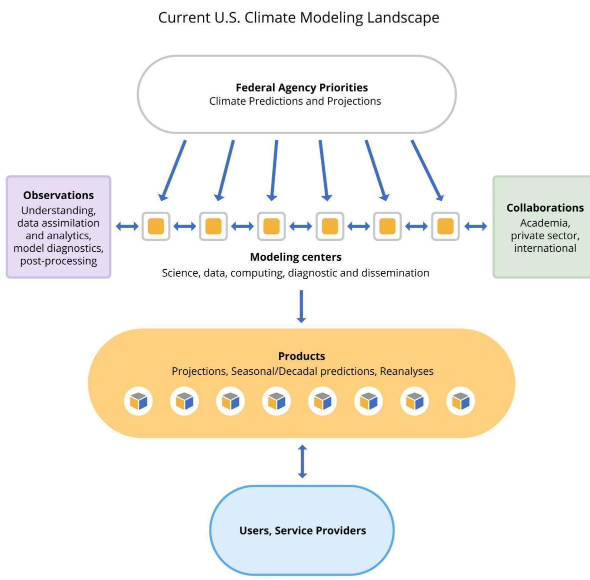


**Supplementary Figure 1**: Federally-funded modeling groups provide state-of-the-art science information and products in support of agency missions and national needs. They leverage an extensive set of national and international collaborations. Observations and partnerships play a crucial role in their success.

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**Abstract**

In the face of a changing climate, the understanding, predictions and projections of natural and human systems are increasingly crucial to prepare and cope with extremes and cascading hazards, determine unexpected feedbacks and potential tipping points, inform long-term adaptation strategies, and guide mitigation approaches. Increasingly complex socio-economic systems require enhanced predictive information to support advanced practices. Such new predictive challenges drive the need to fully capitalize on ambitious scientific and technological opportunities. These include the unrealized potential for very high-resolution modeling of global-to-local Earth system processes across timescales, a reduction of model biases, enhanced integration of human systems and the Earth Systems, better quantification of predictability and uncertainties; expedited science-to-service pathways and co-production of actionable information with stakeholders. Enabling technological opportunities include exascale computing, advanced data storage, novel observations and powerful data analytics, including artificial intelligence and machine learning.

Looking to generate community discussions on how to accelerate progress on U.S. climate predictions and projections, representatives of Federally-funded U.S. modeling groups outline here perspectives on a six-pillar national approach grounded in climate science that builds on the strengths of the U.S. modeling community and agency goals.  This calls for an unprecedented level of coordination to capitalize on transformative opportunities, augmenting and complementing current modeling center capabilities and plans to support agency missions.  Tangible outcomes include projections with horizontal spatial resolutions finer than 10 km, representing extremes and associated risks in greater detail, reduced model errors, better predictability estimates, and more customized projections to support the next generation of climate services.

**New Predictive Challenges**

Climate change is making extremes like floods, fires, heat waves, and droughts more frequent, more intense, and more costly (1,2). These hazards often result in multiple, cascading, interconnected, and compounded effects across the natural and human systems. For example, precipitation and wind extremes have direct effects such as flooding and wind damage, as well as indirect effects such as landslides, coastal inundation, and reduced water quality. Similarly, the local dangers of extreme heat, fire, and dust events can be followed by increased air pollution, with the associated human health impacts that can extend over large regions. All these extremes and their associated damage affect society, economies, health, and livelihoods differently depending on environmental specifics under changing conditions. Impacting individual citizens as well as businesses and governments, these extremes can cost lives and tens of billions of dollars in damages each year (3). Disadvantaged and marginalized communities are more vulnerable to the impacts of such extremes (4). It is clear that damages can be reduced by more skillful and earlier forecasts (5,6). Benefits of improved predictions also include supporting advances in socio-economic activities such as more sophisticated practices for agriculture, water resources, energy management and recreation, among many others. Here we make the case that as we enter the uncharted territory of a changed climate and increasingly complex socio-economic systems, improved predictions and projections[1] allow better decision making and resilience, and repay the investment several times over. Governments, businesses and communities are already formulating strategies to increase their resilience to the consequences of climate change, including adapting to more frequent and/or severe extremes, sea-level rise, increasing temperatures and changing ecosystems. They are using climate projections to inform plans for hundreds of billions of dollars in climate-smart infrastructure for the electricity grid, water distribution, transportation, buildings, etc. For example, they will need accurate information to make

[1] Climate predictions are model simulations that are started from our best estimate of the state of the climate system at a particular time. Climate projections, on the other hand, are simulations started from a statistically representative initial state. While projections are made using considerations of future technological/emission scenarios, predictions can also employ such scenarios. The goal of projections is to look at the statistics of the simulated climate and how they change; the goal of predictions is to forecast the evolution of the actual climate state.

practical decisions such as how to evolve current infrastructure, and how best to configure and build future urban environments so that they are increasingly flood, drought, heat, and fire resistant. There is an urgent demand to quantify the array of risks associated with climate change and their global ramifications to socio-economic systems (e.g., water, food and energy security, population migrations, financial shocks, geopolitical instabilities). For instance, a recent report by the President's Council of Science and Technology Advisors recommends "a focused federal effort to provide estimates of the risk that a weather event of a given severity will occur in any location and year between now and midcentury" (7). Conversely, increasingly advanced socio-economic activities present opportunities that benefit from improved predictive information (e.g., precision agriculture and renewable energy systems). There is demand to develop and understand scenarios and thresholds that represent potentially irreversible changes in the Earth system (also referred to as tipping points). There is the need to better understand which predictions and projections are credible (i.e., what is predictable, at what lead times and what are the uncertainties).

Policymakers are developing strategies for how to mitigate future climate change, balancing costs and benefits of various response options (e.g., clean energy, management of long- and short-lived climate forcers including via carbon dioxide removal, manufacturing and agricultural innovations to decarbonize the economy). They will need to understand the interplay of various climate adaptation and mitigation policies, and also trade-offs and co-benefits with regard to other key priorities (e.g., air quality, national security, economic prosperity and equity, biodiversity, health). They will need the best predictive information within their decision-making timeframe, not constrained by routine assessment cycles, augmenting the predictions and projections available off-the-shelf when the stakes demand it. Certain climate solutions, such as the expanded use of wind and solar renewable energy for climate mitigation, and the pursuit of new socio-economic opportunities, will require improved predictive information. In response to these growing demands for climate services, commercial entities are investing in climate modeling, predictions and projections. These private investments and customers' willingness-to-pay exemplify the economic value of predictive climate information. Indeed, in the face of hundreds of billions of dollars of annual costs associated with U.S. climate change damages as well as preparedness and mitigation solutions, investments in improved climate science, predictions and projections to support services that allow better decision making and improved resilience, appear well worthwhile with several orders of magnitude smaller costs than those of resulting damages.[2] A similar case can be made for the benefits of improved predictive information in support of expanded economic opportunities. If it is considered critical that in the future the best climate predictions and projections still be equitably available to all, and that all underpinning information be openly available (i.e. not proprietary), then it is also critical for the Federal government to continue to lead in the development of next-generation predictive information in partnership with the broader enterprise.

**"Next-generation" Predictions and Projections**

Following significant steady progress over the last few decades (e.g., 8), the predictions and projections that we have today are providing invaluable and freely available information for a broad array of climate and environmental services. However, the new challenges outlined above result in a growing public demand for a "next-generation" of actionable predictions and projections in support of better and expanded services (9, 10). Desirably, these would better represent extremes, hazards and tipping points, integrate across natural and human systems, and provide finer details, higher fidelity and accuracy; they would better quantify predictability, uncertainty, risks and opportunities. To render it more actionable, predictive information could be increasingly customized to decision-making; could simultaneously and more consistently depict climate, socio-economic impacts, adaptation and mitigation responses; could be accompanied by more rapid science-based translations of implications, risks and opportunities. There are several ways in which predictions and projections can be transformed to increasingly meet these new needs. The U.S. modeling enterprise provides a solid basis for this transformation as, thanks to the sustained support by federal agencies and private sector innovation, there is pioneering research and progress that can be accelerated.

[2] As an example, the enacted FY 2022 U.S. Global Change Research Program budget was $3,270 B (https://www.globalchange.gov/about/budget).

**Foundational Game-Changing Ideas**

Over the past several years valuable game-changing ideas to accelerate the pace of improvements in climate modeling, and associated predictions and projections, have been proposed by leading community experts and have been useful to spur discussion and initiatives worldwide, including informing the vision laid out in this perspective (a full review of such ideas is out of scope here; for a review, see e.g., 11). In 2012, the National Research Council (NRC) recommended an evolutionary change in U.S. climate modeling institutions toward a more collaborative approach across agency modeling efforts (12). They recommended greater collaboration around a single common modeling framework in which software, data standards and tools, and model components are shared by all major modeling groups nationwide. The recommended framework was to cut across modeling efforts, across a hierarchy of model types, across modeling communities focused on different space and time scales, and across model developers and model output users. The recommended common national software infrastructure was to support a diverse hierarchy of different models for different purposes; supporting a vigorous research program aimed at improving the performance of climate models on extreme-scale computing architectures. Other key elements of the proposed strategy included: the pursuit of advances in climate science, physical process understanding, and uncertainty research; an annual climate modeling forum; a unified weather-climate modeling effort that better exploits the synergies between weather forecasting, data assimilation, and climate modeling. It recommended training, accreditation, and continuing education for “climate interpreters”, as a two-way interface between modeling advances and diverse user needs; and a training and reward system for computer and climate scientists in climate model development. The strategy emphasized the critical importance of state-of-the-art computing systems, a strong international climate observing system, and national and international infrastructure to support climate model data sharing and distribution. The NRC report was extremely valuable in laying out a comprehensive and balanced approach. Over time, several of its recommendations were implemented at the discretion of the agencies. For example, software infrastructure now enables the sharing of some community modeling components across centers; there are now shared model diagnostic packages for model improvement; several U.S.

modeling systems have been developed for seamless application across timescales, with real-time prediction capabilities (e.g. weather-to-seasonal and seasonal to decadal scales; 13, 14) as well as applications for climate model intercomparisons; and an annual U.S. Climate Modeling Summit[3] organized by the U.S. Global Change Research Program (USGCRP) Interagency Group for Integrative Modeling (IGIM) fosters useful communication and collaborations across modeling centers (e.g., 15, 16), although it has not yet been a forum for the broader coordination envisioned by the NRC report. Internationally, another recurring idea is to have modeling systems that would pursue the increase of model resolution down to ~1 km to explicitly resolve fast-physics processes such as atmospheric convection and reduce the need for some parameterizations (e.g., 17, 18, 19, 20, 21, 22). Ultra-high resolution models have been shown to simulate the spontaneous development of cyclones (e.g. DYAMOND experiments), intense atmospheric convection and ocean eddies, and could be applied from weather forecasts to climate projections. A primary goal of the proposed ultra-high resolution is the capability to simulate fine-grained features of atmospheric and oceanic patterns together with the optimization required to also yield greater realism of the Earth system. There is the anticipated significant reduction of some persistent climate model errors which can affect the ability to simulate climatic phenomena on scales larger than the grid-scale (e.g., 23). The theory behind this is the nonlinear upscale propagation of information whereby any errors introduced by fast-physics process parameterizations could result in a degradation in the representation of climate-scale phenomena. Because of associated costs (an increase by a factor of a million in computational capacity), such a modeling system has been proposed as an international venture with an underpinning unified infrastructure such as that of CERN (Conseil Européen pour la Recherche Nucléaire) for particle physics. Overtime, while the focus on high resolution has remained central, for some in the community a CERN-like approach has become a code word for much larger investments of human and computing resources devoted to developing and applying the most advanced weather and climate models based on the current knowledge of science. With climate

[3] Co-authors of this perspective include the representatives to the Summit from all Federally-funded climate modeling groups.

modeling needing to produce trustworthy information for a wide range of stakeholders, there has been an evolution towards a concept more directly applicable to the climate predictions and projections arena. Most recently, the World Climate Research Program (WCRP) climate modeling community has argued for a "multiverse" modeling approach, among other key recommendations (24). The "multiverse" includes connected modeling approaches to address the many different types of problems, embracing both existing tools and developing new ones such as process-specific models, digital Earths, improved Earth System Models, physical emulators and machine learning approaches. The "multiverse" is to be more responsive and agile to focus efforts on specific scientific discoveries and target user needs. This "multiverse" approach underscores needed advances on multiple fronts, and the need for more effective coordination and collaborations both domestically and internationally.

**Rationale for a New Collective U.S. Approach**

Grounding in Climate Science. There are inherent uncertainties still associated with climate modeling, with repercussions to predictions and projections, with differences from those at weather timescales. For weather forecasting, while model errors do affect forecasts, the primary source of uncertainty is internal atmospheric variability, and initial conditions are most crucial (model errors also impact initial conditions, and in tropical areas can be comparable to initial condition errors). As we move into climate timescales (i.e. annual to decadal to centennial), model uncertainty arising from the physics of the climate system, emission scenarios and external forcings becomes increasingly prevalent, adding on to internal variability uncertainties (25). This is parametric uncertainty (parameter choices that affect the simulations) as well as structural uncertainty (i.e., processes that are entirely missing or represented incorrectly), even at km-scale. For this reason, ensembles of diverse climate models provide seasonal and longer lead predictions that are consistently superior to those of any single model in the ensemble (e.g., the North American Multi-Model Ensemble; 26). At centennial timescales there are additional uncertainties from scenarios (i.e., what will humans do?). Again, ensembles of climate projections from diverse models as part of the Coupled Model Intercomparison Project (CMIP) are deemed more reliable than those from any single model.  Since there are multiple issues and no well-defined single way to make progress and characterize future climates for a growing set of needs, it is critical to have a “multiverse” of modeling approaches as called for by the WCRP climate community. In full agreement with this rationale, we envision an approach that provides the necessary flexibility to push to very high resolution to examine the benefits of such an approach with a number of models, and maintain the model diversity necessary to gauge uncertainties. While it is widely recognized that increasing climate model resolution is highly beneficial (e.g., 27; all U.S. modeling groups are engaged in such experimentation), the optimal balance between increasing resolution and other improvements is still debated (e.g., 28, 29). Hence, our rationale is to combine the focus on high resolution experimentation with increased fidelity and the exploration of modeling uncertainty via a diversity of state-of-the-art models and process representations; the benefits of resolution are examined in conjunction with improved process understanding and representation via mechanistic studies with a hierarchy of models of varying complexity. Climate research aims to address the causes of the spread in, for instance, equilibrium climate sensitivity, aerosol-cloud interactions, full Earth System simulations, and other key physics which dominate the uncertainty in medium and long term climate projections. Given their crucial importance, a key focus is to explore the benefits of high resolution to reduce model biases and better represent extremes.

Building on U.S. Modeling Strengths and Addressing Agency Missions. The U.S. climate modeling enterprise lends itself very well to providing a choice of modeling tools and diverse research approaches for a hierarchy of experimentations and continued innovation by the broad community, as needed to make progress in climate modeling (see Supplementary for more information). High-end experimentation leverages historic U.S. modeling efforts each supporting the specific mission of their sponsoring agency, their demonstrated distinctive strengths, and diverse foci and benefits with models “suit for purpose”. The strength of the U.S. climate modeling community and its long-term success depends on such diversity and independent innovation to scientifically confront climate uncertainty and drive actionable solutions; national and international partnerships are key U.S. strengths. The rationale is for a new collective approach grounded in climate science that builds on U.S. strengths and optimally addresses the diverse missions of U.S. federal agencies and their stakeholders. The intent is to align with and complement plans by individual modeling centers to meet their agency mission needs, and augment them by enabling activities that would otherwise be out of reach via new collective action.

Collective Action on Shared Priorities, Enterprise-Scale Opportunities and Challenges. U.S. modeling centers are capitalizing on scientific and technological opportunities to meet the increasing demands for next generation predictions and projections, prototyping advanced models and techniques (see Figure 1). They are pioneering on multiple fronts (e.g., several are actively practicing the currently highest resolution of climate models being run in the world). Their limitations are not conceptual but rather practical (see Supplementary for a full discussion). Challenges beyond the reach of individual modeling centers are limiting progress on the most transformative outcomes. Thus, the rationale for collective action by the U.S. modeling centers, in collaboration with the broader community, to address this special class of enterprise-scale opportunities and challenges, and accelerate progress on shared priorities. Our envisioned new collective U.S. approach has six main interconnected pillars, two focused on outcomes: transformative science (#1) and co-production of information (#2); and the remainder pillars enabling such outcomes: high-end computing modeling (#3), data storage, data analytics and observations (#4), workforce (#5) and partnerships and external collaborations (#6; see Figure 2 and below for descriptions). While the approach builds on U.S. capabilities and is envisioned in full coordination and synergy with modeling center and agency plans, the proposed collective U.S. action calls for an unprecedented degree of interagency collaboration and coordination around the six pillars that is transformative.

**Six Pillars of Coordination and Collaboration**

Pillar 1: Transformative science. Scientific thrusts with the potential to transform predictions and projections include research on very high spatial model resolutions to represent extremes and reduce climate model biases, global-to-local Earth system process modeling across weather to climate timescales, enhanced integration of human systems, and systematic evaluations of predictability, risks and opportunities, vulnerabilities and uncertainties (see below). A key pillar of the envisioned new collective approach is to have collaborative and evolving goals and activities complement and augment modeling center-specific plans to make progress on these most challenging and high priority opportunities, taking advantage of unprecedented national-scale capabilities (as envisioned under Pillars #3-6) for transformative outcomes (i.e., the most ambitious and high-risk/high-reward experimentation). For all participating modeling centers and experts, success as part of the collaborative program would be assessed by national predictions and projections advances (i.e., knowledge that can be transferred broadly across modeling systems; practical improvements in national predictive information, etc.).

Interdisciplinary teams of experts across U.S. modeling centers and the broader enterprise would collaborate on the transformative common science thrusts listed below, enhancing current collaborations.

- Very high horizontal and vertical spatial resolution and reduced model biases. A key opportunity to vastly improve upon the global-to-local modeling of atmosphere, land, ocean, and sea- and land-ice is to go to very high spatial resolution to represent extreme events at the global scale and in their changing climate context. Fine-scale features that can be better resolved at km-scale include land topography and ocean bathymetry, land-atmosphere interactions driven by surface heterogeneity, mesoscale and submesoscale ocean eddies, atmospheric and oceanic convection (30, 31, 32). Precipitation extremes result from an interplay of dynamics and thermodynamics and are particularly sensitive to spatial resolution. Km-scale resolution will likely better represent the intensity and frequency of extremes (27) such as major hurricanes and intense rain events. At this resolution processes such as cloud convection may be resolved or at least permitted, and certain parameterizations are no longer needed[4]. In addition to benefits for the representation of extremes, higher resolution in tandem with improved process understanding is a key modeling approach as part of a systematic and mechanistic examination of the processes that lead to climate model biases (i.e., model errors in climatological means and variances) that have persisted over generations of models. The fidelity of model simulations will likely be improved by increased spatial resolution (both in the vertical and horizontal directions). Processes underpinning predictability involve fine-scale interactions, e.g., between ocean eddies or fine-scaled

[4] Note that 'gray zone' modeling, where features are only half resolved and not parameterized, may not result in improvements.

topography and the atmosphere, with the allowance of two-way interactions between the smaller spatial scale and larger scale dynamics. Through up-scale propagation of information, fine-scale interactions also influence large-scale climate phenomena, and so higher resolution could also be beneficial for the representation of phenomena like the El Nino Southern Oscillation and for increased accuracy and reliability of predictions and projections, though this has not yet been clearly demonstrated. Arguably, km-scale predictions and projections for a particular region can be produced by downscaling lower-resolution global simulations (e.g., using statistical methodologies, regional dynamical models, or regionally refined global models) and can be useful to better resolve regional processes and for certain applications[5,6]. Indeed, there is a constructive interplay between these various modeling methodologies. For instance, global km-scale models can inform the development of lower resolution models which can be used in combination with novel downscaling approaches (e.g., using machine learning/artificial intelligence, ML/AI hereafter) and run in different modes such as "storylines" (33) to examine driving factors for past events or the plausibility of future events.

- Global-to-local Earth system process modeling. Advancing the understanding and modeling of Earth system processes such as those underpinning clouds and precipitation and reducing persistent model errors are paramount transformative opportunities with far ranging benefits. For example, highly valuable predictions and projections of precipitation extremes and resulting hazards to human systems critically depend on these advances; similarly estimating climate sensitivity to greenhouse gases, as well as other elements such as aerosols, other atmospheric constituents, land use etc., depends on better understanding and representation of cloud processes in models (e.g., 34, 35). Progress on modeling of physical and biogeochemical processes, key to

[5] Outside of the downscaled region, these simulations still lack fine-scale processes and interactions. Because of global teleconnections in the Earth system, this affects the fidelity of the model and predictability on global scales, including in the region of interest.

[6] While the classical forcing of a regional model by larger-scale boundary conditions lacks of two-way interactions between global and regional processes, these interactions are now being accounted for in a new class of atmospheric models e.g. the nested Hurricane Analysis and Forecast System (HAFS) model for Atlantic hurricane track and intensity predictions.

reducing model errors and harnessing predictability, can be significantly accelerated by enterprise-wide research efforts such as interdisciplinary Climate Process Teams (see Supplementary). These efforts will involve full exploitation of existing observations with advanced data analytics, ML/AI, observational campaigns and process studies to fill knowledge gaps and develop improved model representations; systematic diagnostic and mechanistic modeling studies including the use of very high-resolution models to understand and remedy persistent model and prediction errors. The opportunity is to develop process representations that reduce model errors and are suitable for global-to-local Earth system modeling, including for models at very high resolution, and for predictions and projections across weather-to-climate timescales. WCRP community efforts to improve precipitation prediction under the Global Precipitation Experiment (GPEX) represent the type of ambitious efforts that would be facilitated through the envisioned collective action (36).

- <u>Enhanced integration of human systems</u>. Another key scientific opportunity is to enhance the integration of human systems in Earth system models, e.g., the urban built environment, large-scale human infrastructure systems such as for water, food, energy, and transportation. The integration approach (whether embedding human system processes directly in an Earth system model or running offline simulations of impacts) can be determined based on systematic modeling experiments and analysis of the feedbacks of processes on the global system for different applications being pursued. Regardless, what will be game-changing is to have a seamless suite of models effectively spanning the Earth and human systems configurable for coupled and uncoupled simulations. We envision collective action to pursue integrated modeling capabilities that will enable examining simultaneously and consistently the climate, its drivers and impacts and response options rather than with a sequence of disconnected cascading modeling and predictive systems.
- <u>Harnessing predictability and quantifying uncertainties</u>. Next-generation predictive systems could more effectively tap into inherent Earth and human systems predictability, where it exists. The

opportunity is to improve how our predictive systems and methodologies harness precursor information from the initial state, how they simulate the forward evolution and range of future possibilities, and how they extract a future anomaly signal from background noise. These improvements entail incorporating an expanded theoretical understanding of underpinning processes[7]; enhancing observations, optimally utilizing data (e.g., with sophisticated data analytics, ML/AI); and advancing modeling and data assimilation across all Earth system components. Quantification of uncertainties, risks and opportunities can be improved with predictive systems that have a larger number of predictions and projections (hundreds of simulations) using different types of models (including a hierarchy of models with varying complexity) to depict structural uncertainties, and slightly different initial conditions to depict internal variability uncertainties. ML/AI may provide opportunities to significantly and cost-effectively increase the simulations' ensemble size (potentially into the thousands; e.g., for the CMIP ensemble) if adequately trained on a set of simulations from a diverse set of models. These improvements are particularly critical to predict the characteristics of future extremes, the most challenging features of future climate. We envision collective efforts to push the limits of predictability, with rigorous scientific evaluations for credible and authoritative quantifications of uncertainties, risks and opportunities.

Pillar 2: Expedited science-to-service pathways and co-production of information A key opportunity is for the co-production of predictive information so that predictions and projections are most useful and used, information is more customized to address public needs and timelier; includes sound and accessible scientific interpretations of implications, risks and opportunities in support of services and their stakeholders. The opportunity is for a more seamless interface between the development of next generation predictions and projections and the service providers, so that services are using the state-of-art capabilities and the scientific community is addressing service gaps as they arise. Realizing this

[7] In some cases, important model assumptions are going beyond the observations and are thus increasing uncertainty (i.e., cloud microphysics, ice cloud nucleation, ice sheet/ocean interactions, vegetation dynamics etc.).

opportunity entails not only advances in technical capabilities but also collaborations that facilitate culture shifts across all relevant organizations. Hence, we envision interdisciplinary collaborative teams that provide a sustained and bidirectional science-to-service pathway and co-produce actionable information. Examples of co-produced information include storylines of direct relevance to decision making, projections for parameters needed for sectoral or regional applications, etc. Sustained transdisciplinary support for these efforts is critical for success as they may include Earth system scientists, computational and data scientists, as well as service providers and stakeholders in addition to experts embedded from the modeling centers. A data analytics platform (see Pillar #4) is envisioned to support the work of the teams to co-produce information based on models and data. This platform interfaces seamlessly with climate service providers so that APIs, AI/ML applications can be directly built on top of the data and modeling.

<u>Pillar 3: High-end computing modeling.</u> A crucial technological opportunity enabling transformational progress in predictions and projections is to take full advantage of the unprecedented energy-efficient multi-level parallel computing architectures that are disrupting high-end scientific computing. Dedicated hybrid CPU/GPU, scalable, high-end systems for both capability and capacity computing are at the basis of next-generation predictions and projections research and development. Success is dependent on addressing associated technological issues, including code performance and portability across computing architectures, data input-output, and computational challenges associated with execution and analysis of large ensemble simulations. Hence, we envision national coordination for a substantially expanded high-end capability and capacity computing at specific agencies dedicated to a coordinated modeling effort. This would enable an unprecedented enhancement of predictions and projections at existing U.S. modeling centers and programs through joint experimentation on transformative cross-agency priorities (see Pillar #1). The expanded federated computed systems, with long-term recapitalization plans, would support an interconnected ecosystem of high-end agency models, data, and workflows. Software engineers would support modeling centers so that the code is computationally performant. The computing is highly integrated with a scalable data storage and analytics infrastructure (see Pillar #4) and supports workflows for advanced data processing and visualization.

Pillar 4: Data storage, data analytics and observations. Exascale data storage enables creating repositories to facilitate the access to all observational and model data necessary to accelerate research and development, and the data analytics to go from data to actionable knowledge. Advanced data analytics such as ML/AI algorithms provide expanded opportunities to exploit observational and model data. This includes new strategies for exploring models' parameter space, and for using observational data to accelerate model tuning and improve the fidelity and accuracy of models; for generating hybrid systems that incorporate ML/AI-based parameterizations; for systematically evaluating structural model differences; for increasing computational efficiency for high-resolution simulations; for ensembles of simulations and forecasts of unprecedented size; and for identifying predictability precursors and anomaly signals. To be clear, data analytics includes and goes beyond ML/AI: it enables much broader interrogation of data as part of infrastructure to co-develop useful knowledge out of "data lakes". Observations support modeling efforts in a variety of ways – model initialization, process representation, quantitative evaluation, data assimilation, and creation of reanalysis products that are used in scientific studies of the Earth system as well as service applications. In particular, the higher spatial resolution of many observational systems can be critical for modeling systems of increasing resolution. The breadth, quality, and resolution (temporal, spatial, spectral) of the observations that inform predictive models will be dramatically improving over the next few years. These improvements come not only from the incorporation of new technology[8], but there are also new sources of data, especially those from the private sector with small satellite constellations providing higher spatial resolution and/or temporal revisit than by traditional government/agency procured satellites. In addition, the parameters being measured increasingly deal with the properties of the Earth surface (including hydrology, biology, geology, and cryospheric science) and they complement the physical/chemical atmospheric/oceanic observations that have been central to climate modeling efforts to date. This broader set of observed parameters enhances the ability of models to fully represent the interacting Earth system components (including human-created

[8] Including hyperspectral observations, more frequent data coming from use of higher orbits and/or small satellite constellations, enhanced use of active remote sensing techniques to complement the passive techniques that have formed the bulk of the observational suite to date.

ones) that are needed to support the transition from physical climate-focused models to true Earth System models that can effectively interface with humans.

We envision the build-up of coordinated model data storage/management and data analytics capacity and capabilities to turn existing and future observational data and model output into useful knowledge. The coordinated effort would support research, and the co-production with service organizations of actionable predictions and projections. The new federated infrastructure would provide interfaces among individual modeling centers and with the broader Earth system and climate enterprise. It would connect seamlessly with service providers, as appropriate, to expedite the pathway from science to service applications (including operational), facilitating the convergence of methodologies, data, workflows and knowledge across the science and service communities. Stored data would follow common data standards; data types would include predictions and projections, climate model hindcasts, reanalyses and observational data (e.g., for process research, data assimilation). Stored data and workflows would enable data analytics (e.g., ML/AI and visualization). The infrastructure may be a flexible hybrid of physical and cloud storage, the most advantageous solution to meet needs.

Pillar 5: A skilled, diverse and interdisciplinary workforce. A broad set of skilled experts, disciplinary and interdisciplinary, is crucial to advance research, modeling and predictions; co-produce actionable information; operate and interface with the high-end computing and data infrastructure; develop performant code and data analytics (see Pillars #1-4). We envision a workforce program that would assess needs and develops solutions to avoid human resource issues (e.g., current gap in data assimilation experts and software engineers to port models to GPUs) with larger picture policy in place to address training/employment/diversity issues (e.g., training, retraining and retention of experts). Exemplary objectives include enhancing and diversifying pathways from academia to the modeling centers, broadening workforce participation, providing access to the above-mentioned modeling and data facilities, and inherent data, modeling codes and diagnostics packages to students and professionals for career development; a focus on staff retention via changes in the promotion and reward systems and retraining opportunities.

Pillar 6: Partnerships and external collaborations. Modeling centers already productively engage in many successful partnerships and external collaborations that help optimize the use of enterprise resources. The multi-faceted approach envisioned here continues and strategically augments partnerships across all areas. For example, areas where enhanced partnerships may be desirable include the future computer architectures and purpose-built computers, and storage solutions for big-data. New opportunities may arise as U.S. philanthropies and commercial entities are increasingly investing in data and data analytics, research, modeling, predictions and tailored services. Enhanced international cooperation could also accelerate progress on shared problems and solutions, for global benefit, and especially those of less-developed but most vulnerable countries. The envisioned WCRP "multiverse" approach emphasizes the need for broad collaborations and new partnerships[9]. In addition to the technical cooperation that already takes place under the World Meteorological Organization (WMO), WCRP and other programs, there could be enhanced cooperation with-like minded countries on topics of mutual interests. For example, there could be opportunities to coordinate with the European Union Destination Earth (DestinE[10]) 10-year program which aims to develop a high resolution digital "twin" of the Earth to model, monitor and simulate natural phenomena and related human activities. Planned activities include higher resolution reanalysis and forecasts; better and deeper interaction with impact models; and better visualization and more 'interactivity'. Indeed, several DestinE goals closely align with the objectives discussed above and there could be productive synergies. More generally, we envision how a collective U.S. approach around the Pillars outlined above could facilitate strategic and highly beneficial partnerships and collaborations.

**Tangible Outcomes**

We envision how the new collective U.S. approach described above would result in a number of tangible and sought-after outcomes for next generation predictions and projections. These would include projections at less than 10 km representing extremes and associated risk (e.g., in support of the National

[9] For example, Earth Visualization Engines (EVE); https://eve4climate.org/
[10] https://digital-strategy.ec.europa.eu/en/policies/destination-earth

Climate Assessment), reduced model errors, better predictability estimates, and more customized projections. All would be crucial to support the next generation of climate services (9, 10).

Projections of extremes and risks with higher resolution and accuracy. Models have progressively advanced and they are on a trajectory for higher resolution as process knowledge and computational capabilities have improved (e.g., 37). State-of-the-art global climate projections used in the Intergovernmental Panel for Climate Change (IPCC) Sixth Assessment Report (AR6) based on CMIP simulations have nominal spatial scales of ~100 km in the atmosphere[3] and ~50 km in the ocean[11]; projections for the National Climate Assessment are directly derived from these. This means that global climate model projections are limited in their capability to represent extreme events and hazards (e.g., tornados, tropical cyclones, floods, etc.) at the level of specificity needed for local applications. For example, IPCC-class models have been used to study flood statistics, but most of them simulate tropical cyclones that are larger than observed and also with lower intensities. While they may simulate environmental conditions that lead to tornadic outbreaks, they cannot simulate tornados. Some include fire parameterizations and can capture general statistics of naturally-occurring fires but are limited in their ability to accurately simulate burnt area and fire emissions (38). Despite these limitations, current model projections are nonetheless an invaluable tool to inform climate policy and actions. *We envision that the new collective U.S. effort would result in projections with finer spatial details (i.e., at a resolution of 10 km or finer, as recommended by the PCAST), increased fidelity and accuracy, the use of stronger observational constraints, and increased integration of natural and human systems.*

Quantification of predictability, uncertainty, risks and opportunities. There is a growing demand for longer-lead predictions (e.g., from weeks to decades), for earlier alerts and for new types of environmental and socio-economic predictions (e.g., ecological forecasting); for projections for specific communities or even properties. However, demand alone nor the availability of such data establishes whether certain predictions and projections can be skillfully made. Predictability science, grounded in

[11]An overwhelming majority of CMIP6 models use 100 km in all their components. A set of ~25-50 km resolution projections were performed under the CMIP-6 HiResMip protocol, under a variety of experimental configurations.

interdisciplinary observations and decades of research on processes and evaluations, can reliably help assess what types of predictions and projections are feasible and trustworthy, and what types of systems are best suited for certain prediction applications (39). *We envision an improved quantification of predictability, probabilities and uncertainties associated with predictive information. This is foundational for characterizing risks and opportunities, and credibly informing decision making as part of next generation climate services.*

Customized, actionable, and consistent predictions and projections across climate, socio-economic impacts, and response options. A standard set of scenarios underpin CMIP experiments and the IPCC assessments, as exemplary of potential future conditions (i.e., most recently the Representative Concentration Pathways and the Shared Socioeconomic Pathways). There is typically a cascade of sequential modeling and analyses from the scenarios to the actionable information needed by decision-makers. Scenarios drive global climate projections; these are then downscaled (statistically or dynamically) to derive regional and local climate impacts that can be constrained by observational data; regional climate information drives impact models for specific sectors (e.g., agriculture, water resource management, fisheries and coastal planning); global projections drive integrated assessment models; results from integrated assessments are often translated into indices for socio-economic and sectoral applications. It has been invaluable to produce and authoritatively assess all this information based on the standard scenarios at regular time intervals in assessment reports (typically every five to seven years). However, the standard sequential approach to assessing climate impacts has a number of limitations including the lack of possible feedbacks from the impacts to climate and the socioeconomic pathways. This approach also provides little flexibility to interactively examine response options and with a faster pace than the assessment cycles. Critical factors here are the linear knowledge value chain from scenarios to climate models to downscaling to impacts to policy analysis, as well as the definition of scenarios as an enabling step (40). *We envision a next generation of predictions and projections that is increasingly customized and actionable: co-produced with service providers and stakeholders to be most relevant and understandable to them, at a pace closer to the decision-making timeframes (a year or less, depending on* *the specific application), and include flexibility to explore "what if" questions and trade-offs beyond the constraints of predefined off-the-shelf scenarios.* For example, customizable scenarios may be needed to explore what happens to our climate, environment, and society if certain tipping points were to be surpassed (e.g. the thawing of Arctic permafrost), certain mitigation choices were to be made (e.g., in the clean energy technologies portfolio) or certain adaptation solutions were to be implemented (e.g., changes in agricultural or water management practices). Increased flexibility in predictions and projections will be extremely valuable as climate services evolve over the next several years (9, 10).

<u>Integration of natural and human systems</u>. Modeling capabilities that increasingly integrate natural and human systems will enable a next generation of predictive information that is more actionable. There is significant community research on this topic (e.g., 41). Currently, global climate models do not represent cities and critical infrastructure (e.g., for transportation, water, energy and food), and the socio-economic systems that are affected by climate hazards (e.g., supply chains). Hence, they lack the capability to simulate cascading impacts across the natural and human systems and their feedbacks on the global scales. It is debatable, and a matter of research, whether socio-economic processes and impact models need to be included directly in global Earth system models (among other things this depends on the level of expected feedback of a particular process on the global climate system and also the specific model application at hand). However, what is clear is the need for a modeling suite that provides the flexibility to rapidly and consistently go from climate predictions and projections to environmental and socio-economic impacts, and that considers any significant feedbacks to climate projections. *We envision collective U.S. action for a modeling suite that appropriately integrates natural and human systems so as to enable the exploration of options to minimize damages and maximize resilience.* As a result, for example, near-term predictions of extremes such as tropical cyclones could increasingly portray not only the physical hazards (e.g., extreme rainfall and winds) but also the potential biogeochemical and human impacts (e.g., the impact on infrastructure and associated hazardous spills), with potential feedbacks on climate and the extremes.

**The way forward**

This perspective has the intent to generate community discussions and engagements on ways to transform climate predictions and projections and accelerate progress to meet the new challenges posed by climate change as well as support the pursuit of new socio-economic opportunities. Our proposed vision is grounded in climate science, the strength of the U.S. modeling community and its partners, and is to best support agency missions. If a substantial and sustained collective U.S. effort were to be made, building off current capabilities to address the types of enterprise-scale opportunities and challenges we outlined, this could result in much improved and more actionable climate predictive information. What's at stake is going into the uncharted territory of a changed climate, and increasingly complex socio-economic systems, and delivering the best predictive information. Federal capabilities underpin equity in the availability of next-generation predictions and projections and provide opportunities for the private as well as other sectors. The opportunities are at hand to accelerate progress. The effort would need significant resources to support the infrastructure and programs outlined above, and the organization necessary to use them effectively. Overcoming budgetary, bureaucratic, organizational, legislative and cultural barriers, and general inertia would be challenging and would require a concerted national effort[12] (these important aspects are beyond the scope of our paper). White House-level leadership in coordination with the USGCRP IGIM and other relevant interagency bodies[13] could spearhead such an ambitious collective U.S. effort: convene partners and organizations, provide direction, develop governance, and plan for resources. High-level and long-term agreements between agencies on a shared effort could greatly help to overcome barriers and coordinate processes. Community engagement is crucial for the development and ultimate success of the envisioned effort. Ideas outlined in this paper are perspectives, illustrative of the possibilities to transform predictions and projections to meet public demand. We hope they will serve the purpose of engaging the broad community to accelerate progress on this important topic.

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[12] The PCAST recently recommended a "national effort to quantify extreme weather risk" noting that "the work of multiple agencies together with an effective leadership framework is critical because [] this activity does not fit within a single existing administrative unit within the federal government."

[13] ICAMS and also the Interagency Arctic Research Policy Committee (IARPC) are of relevance here, among others.

## Data Availability Statement

No new data has been used for this publication.

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**Figures**

**Figure 1**: Scientific and technological opportunities for transformational progress in climate predictions and projections building on the solid foundations of the U.S. enterprise.

**Figure 2:** A collective U.S. effort to transform climate predictions and projections and support cross-agency priorities. The approach preserves U.S. modeling and research diversity, and advances the missions of the agencies and the interests of their stakeholders; it complements and augments plans by individual modeling centers to meet their agency mission needs.

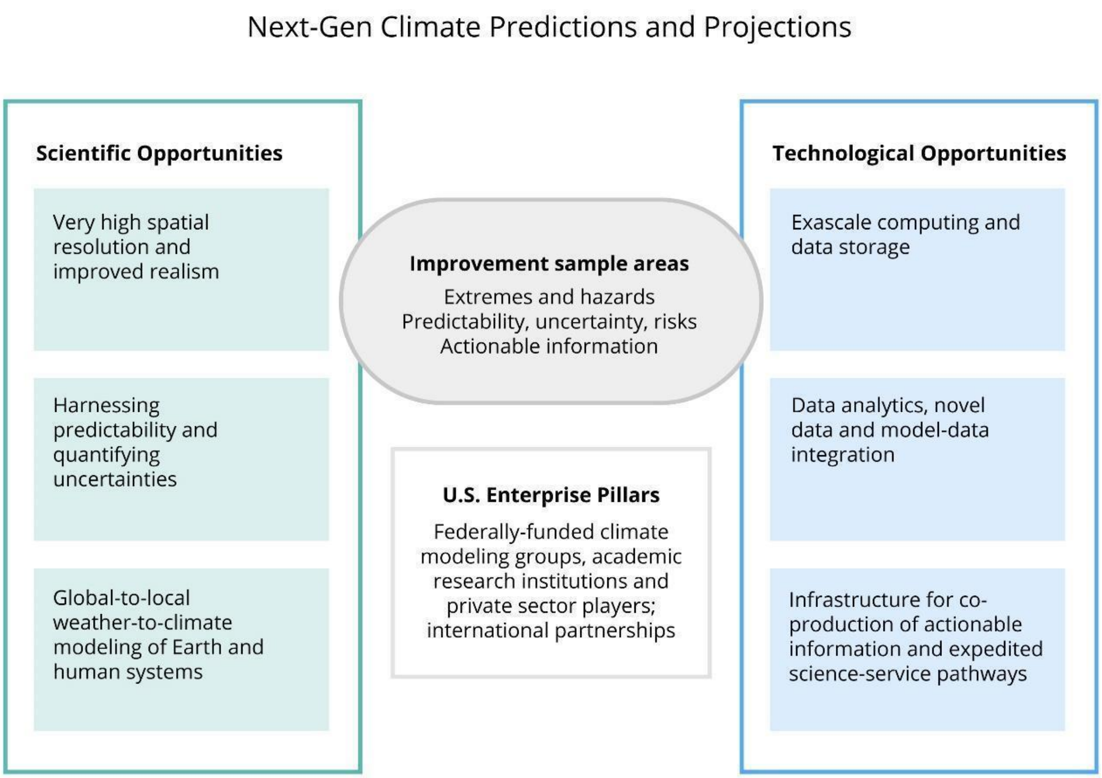


**Figure 1**: Scientific and technological opportunities for transformational progress in climate predictions and projections building on the solid foundations of the U.S. enterprise.

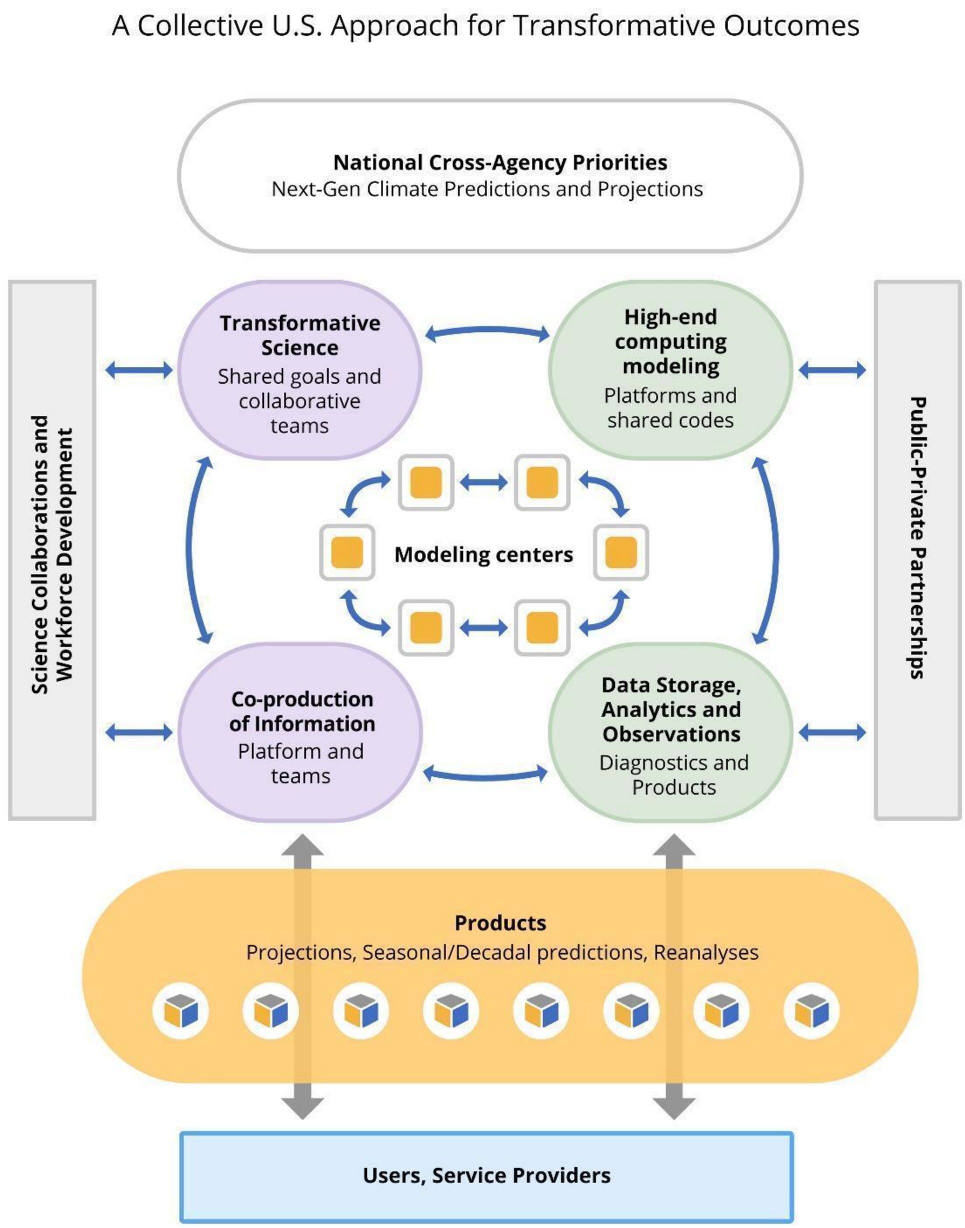


**Figure 2**: A collective U.S. effort to transform climate predictions and projections and support cross-agency priorities. The approach preserves U.S. modeling and research diversity, and advances the missions of the agencies and the interests of their stakeholders; it complements and augments plans by individual modeling centers to meet their agency mission needs.