



EARTH SYSTEM PREDICTABILITY RESEARCH AND DEVELOPMENT STRATEGIC FRAMEWORK AND ROADMAP

A Report by the

FAST TRACK ACTION COMMITTEE ON EARTH SYSTEM
PREDICTABILITY RESEARCH AND DEVELOPMENT

of the

NATIONAL SCIENCE & TECHNOLOGY COUNCIL

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The NSTC Fast Track Action Committee (FTAC) on Earth System Predictability Research and Development (R&D) was established as a short-term effort to develop plans and identify actions for focused U.S. Government coordination in this R&D area.

About this Document

This document provides an overview of the Earth System Predictability R&D Strategic Framework and Roadmap developed by the FTAC.

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Abbreviations and Acronyms

AI	Artificial Intelligence
CPU	Central Processing Unit
DOD	Department of Defense
DOE	Department of Energy
ESM	Earth System Model
ESP	Earth System Predictability
FTAC	Fast Track Action Committee
GPU	Graphic Processing Units
HPC	High Performance Computing
ML	Machine Learning
NASA	National Aeronautics and Space Administration
NASEM	National Academies of Sciences, Engineering, and Medicine
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
NSTC	National Science and Technology Council
OMB	Office of Management and Budget
OSSE	Observations System Simulation Experiment
OSTP	Office of Science and Technology Policy
R&D	Research and Development
RFI	Request for Information
S2S	Subseasonal-to-Seasonal
UAV	Unmanned Aerial Vehicle
U.S.	United States
USDA	United States Department of Agriculture
USGS	United States Geological Survey

Executive Summary

From predictions of individual thunderstorms to long-term global change, enhanced Earth system predictions are crucial to inform societal resilience to extreme events such as droughts and floods, heat waves, wildfires and coastal inundation. However, in some cases, there is still a lack of clear understanding of whether, or under which conditions, extreme meteorological events and their cascading events are predictable and why. A better understanding of Earth system predictability (ESP) would help the Federal Government target investments to improve predictions and increase public benefit. To help address this gap, and facilitate Federal coordination, the National Science and Technology Council (NSTC) created a Fast Track Action Committee (FTAC) on ESP in February 2020. It was charged with identifying barriers to progress, as well as prioritizing opportunities for activities that could improve our understanding of ESP. Subsequently, the FTAC engaged with the public and the interagency prior to developing an R&D Strategic Framework and a Roadmap to guide the initial R&D activities that address urgent prediction needs within the framework.

The R&D Strategic Framework aims to increase the understanding of ESP to improve predictions through three primary goals that connect theory with observations, process research, and modeling. An additional four cross-cutting goals address these thrusts as well as emphasize advanced technologies, enhanced collaborations, partnerships, and training the next generation of talent. The Roadmap identifies five areas of R&D opportunity focusing on the predictability of Earth's water cycle and precipitation extremes and associated biosphere and human interactions as a springboard to strategically advance the ESP R&D priority. The goal of this R&D is to attain high-resolution predictions and projections of high impact water cycle events, their cascading impacts across the Earth system, and their coupling to human, ecological, and biogeochemical systems.

Introduction

From predictions of individual thunderstorms to projections of long-term global change, knowing the degree to which Earth system¹ phenomena across a range of spatial and temporal scales are practicably predictable² is vitally important to society. Past research in Earth System Predictability (ESP) led to profound insights that have benefited society by facilitating improved predictions and projections³. However, as there is an increasing effort to accelerate progress (e.g., to improve prediction skill over a wider range of temporal and spatial scales and for a broader set of phenomena), it is increasingly important to understand and characterize predictability opportunities and limits. Improved predictions better inform societal resilience to extreme events (e.g., droughts and floods, heat waves, wildfires and coastal inundation) resulting in greater safety and socioeconomic benefits. Such prediction needs are currently only partially met and are likely to grow in the future. Yet, given the complexity of the Earth system,⁴ in some cases we still do not have a clear understanding of whether or under which conditions underpinning processes and phenomena are predictable and why. A better understanding of ESP opportunities and limits is important to identify what Federal investments⁵ can be made and what policies are most effective to harness⁶ inherent Earth system predictability for improved predictions.

The FY 2021 Administration R&D Budget Priorities Memorandum identified ESP R&D as a priority. It called for Federal departments and agencies to:

- Prioritize R&D that helps quantify ESP across multiple phenomena, time, and space scales.
- Emphasize how measures of and limits to predictability, both theoretical and actual, can inform a wide array of stakeholders.
- Explore the application of Artificial Intelligence (AI) and adaptive observing systems to enhance predictive skill, along with strategies for obtaining substantial improvements in computational model performance and spatial resolution across all scales.

¹ “Earth system” here includes processes encompassing the atmosphere-biota-hydrosphere-cryosphere-physical-biogeochemical spheres and human interactions across all Earth system components, across multiple spatial and temporal scales.

² Practicable predictability here indicates predictability theory that can be put into practice successfully.

³ Different from predictability, predictions and projections terms generally refer to an estimate of the future derived in a variety of ways. Although predictions and projections differ in several respects, for brevity here these terms are used interchangeably at times.

⁴ ESP involves knowledge of complex processes that often encompass the physical-biogeochemical spheres and also human interactions across Earth system components (atmosphere, ocean, land, ice, etc.), across multiple spatial and temporal scales.

⁵ There are relevant Federal research activities across agencies and departments, involving national and international coordination and partnerships, spanning observations and process research, modeling, technology and infrastructure.

⁶ To harness predictability typifies using inherent predictability characteristics to improve predictions. For simplicity, the terms the “use” and “harness” of predictability are employed interchangeably in this document.

The FY 2022 Administration Budget Priorities Memorandum reiterated the practical importance of ESP R&D in the context of advancing meteorological services. It specifically called for departments and agencies to:

- Prioritize, coordinate, and collaborate to implement a national strategy to accelerate progress in improving the theoretical understanding and practical utilization of predictability, reducing gaps in the observation of crucial processes, and exploring advanced modeling capabilities using non-traditional approaches such as AI.
- Prioritize the availability of adequate computing and data infrastructure and collaborate closely on the most effective use of research resources via coordination and partnerships.

In response to the FY 2021 Memorandum, the FTAC on ESP was created in February 2020, under the NSTC. Member Federal agencies and departments were charged with considering how to address the ESP R&D priority, identify barriers that are holding back progress, and prioritize opportunities for key activities that could be most valuable to understanding ESP, including transformative “big ideas,” towards the enhancement of Earth system predictions. The FTAC engaged the Federal and non-Federal communities via meetings and an RFI (see Appendix A) to discuss relevant issues and provide feedback on the direction that the Federal Government should take to address the ESP R&D priority.

This report summarizes two key elements of the strategic approach that resulted from the FTAC work, both of which focus on identifying goals and initial key areas of opportunity to address the ESP R&D priority:

1. An **ESP R&D Strategic Framework** that is broad and applicable over the long term to make progress across the suite of ESP R&D needs and opportunities (see Figure 1).
2. An **ESP R&D Roadmap** that focuses initial predictability R&D in areas of opportunity to address urgent prediction needs identified by stakeholders.

National Strategic Framework

Utilizing information collected from community engagement (see Appendix A) and FTAC member agencies and departments, the FTAC developed a National Strategic Framework to make accelerated progress on ESP R&D needs and opportunities. The foundation of the Strategic Frameworks is the vision that

- *Advanced Earth system services⁷ are enabled by increased knowledge and more effective use of inherent Earth system predictability.*
- *A national R&D strategy results in accelerated progress toward both theoretical as well as the practical foundations needed to effectively use inherent Earth system predictability.*

The Strategic Framework includes specific goals and objectives, guided by principles (see Appendix B), to advance the vision for ESP R&D.

⁷ These encompass weather, climate, hydrological, ocean, and related environmental services. The term “services” broadly includes all relevant activities that provide value to society, whether over land, at sea, or in the air, including for the protection of life and property, personal and public health, quality of life, sustainability of the natural world, and economic and national security.

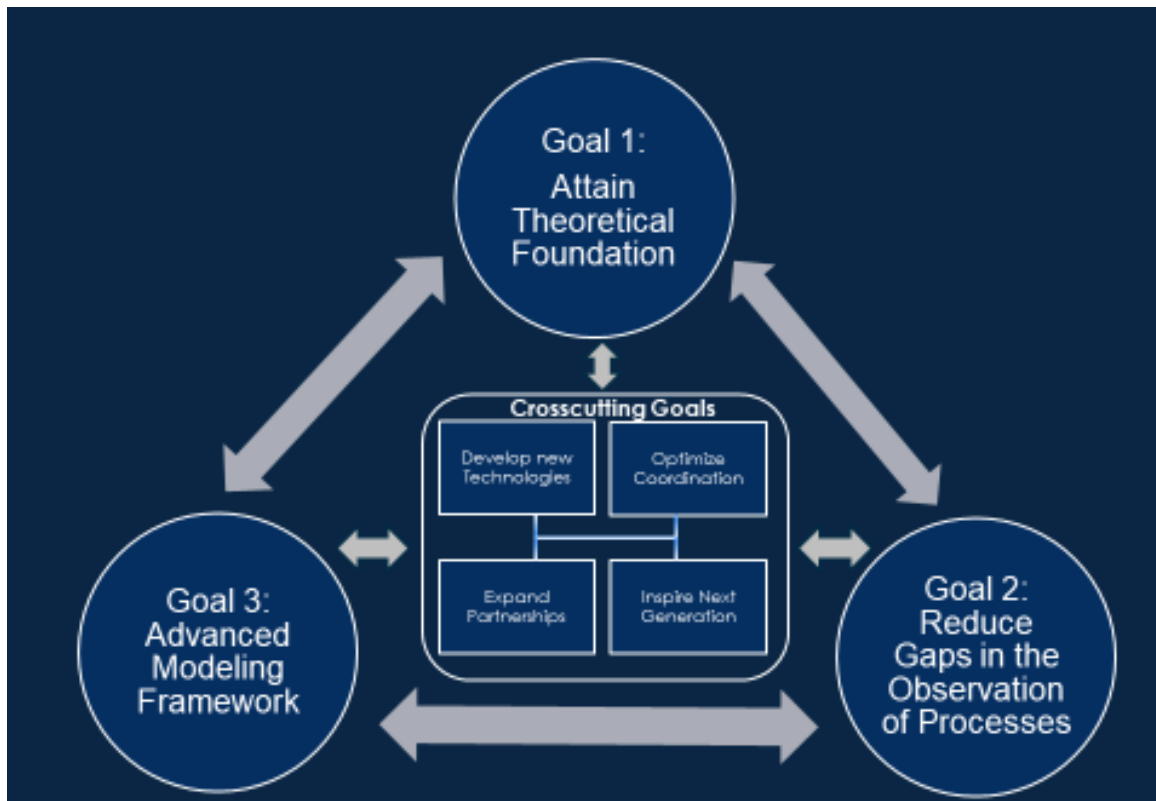


Figure 1: Key elements of the ESP R&D Strategic Framework.

Overarching Goal: The overarching goal of the Strategic Framework is to increase the understanding of ESP via the implementation of a national strategy that connects stakeholder-driven predictability theory with observations, process research, modeling, and technology. More specifically, there are three primary goals underpinned by four cross-cutting goals.

Primary Goals

Goal 1: Advance foundational understanding and theory for an improved knowledge of Earth system predictability of practical utility.

Objectives:

1. Expand foundational knowledge and theory of ESP and synthesize understanding of relevant processes and phenomena.⁸
2. Pursue emerging technologies and approaches⁹ to identify processes whose understanding is crucial for predictability.¹⁰
3. Develop an understanding of Earth system precursor conditions conducive to varying predictability, potentially influencing forecast skill, including for compound phenomena.

⁸ Including human-natural interactions.

⁹ For example, combining ML/AI with process understanding.

¹⁰ Based on observations and model data.

Goal 2: Reduce gaps in the observations-based characterization of conditions, processes, and phenomena crucial for understanding and using Earth system predictability.

Objectives:

1. Utilize new sensor technologies, including the deployment of non-traditional, cost-effective¹¹ adaptable observations that increasingly enable the characterization of conditions and key processes underpinning predictability.
2. Optimize observations and system designs so as to fill gaps in the characterization of processes and sensitive regions that are crucial to predictability.¹²
3. Address knowledge gaps in process understanding to improve the harnessing of predictability in models.¹³
4. Enhance infrastructure for observational data archive, access and dissemination to maximize use of observations in R&D¹⁴ to improve the characterization of sources of predictability.

Goal 3: Accelerate the exploration and effective use of inherent Earth system predictability through advanced modeling.

Objectives:

1. Integrate new observations, process understanding and emerging technologies to reduce model biases.
2. Develop a modeling framework that leverages U.S. efforts to enable extensive exploration of ESP, including high-resolution, integrated, multiscale/seamless Earth system modeling tools.
3. Develop and apply advanced methodologies of model-data assimilation¹⁵ to improve the use of inherent predictability.
4. Use models in targeted experiments and diagnostics to improve model fidelity and probe predictability frontiers including large ensembles, high-resolution experiments and advanced model benchmarking, diagnostics, visualization, and data analytics methodologies.
5. Expand, share, and broaden community access to computing infrastructure for model-data integration, model comparisons, and model exploration of predictability.

¹¹ These include observations from emerging non-conventional platforms that typically have lower costs compared to more traditional ones.

¹² This includes applying understanding of predictability as well as emerging observing and data analytics technologies.

¹³ This includes conducting targeted and interagency coordinated field campaigns and forming interdisciplinary teams.

¹⁴ E.g., process studies, model-data assimilation/fusion, and model evaluation.

¹⁵ E.g., from high-resolution observations and simulations and crowd-sourced information.

Cross-Cutting Goals

Cross-Cutting Goal 1: Leverage emerging new hardware and software technologies for Earth system predictability R&D.

Objectives:

1. Develop a framework for hybrid predictive modeling that exploits ML/AI¹⁶ in order to accelerate the exploration and effective use of ESP.
2. Develop a strategy for advanced scale-aware modeling, fit-for-purpose ML/AI, and the necessary computational and software infrastructure to achieve high-resolution multi-model ensembles.
3. Increase computational efficiency of models and the effectiveness of model-data input/output, and fully leverage new computer architectures.

Cross-Cutting Goal 2: Optimize coordination of resources and collaboration among agencies and departments to accelerate progress.¹⁷

Objectives:

1. Foster interagency collaboration and coordination around the Strategic Framework to maximize effectiveness and efficiencies for implementation in synergy with relevant standing coordination bodies.
2. Increase incentives, reduce bureaucratic burdens or barriers, and identify mechanisms for enhanced collaboration and coordination of R&D across agencies and departments to meet common goals.

Cross-Cutting Goal 3: Expand partnerships across disciplines and with entities external to the Federal Government to accelerate progress.¹⁸

Objectives:

1. Strengthen coordination and partnership with the private and non-profit sectors that seek to advance various capabilities involving components of the ESP enterprise.¹⁹
2. Increase incentives and reduce barriers for enhanced cross-disciplinary communication and collaborations.
3. Develop and sustain partnerships to successfully implement an approach where prediction needs continuously inform predictability R&D and vice-versa.
4. Seek targeted collaborations with non-U.S. research organizations, networks, and centers with relevant goals to maximize the leveraging of resources.

¹⁶ E.g., involving observed and simulated data, edge computing, data assimilation, multi-model hierarchies, and model diagnostics.

¹⁷ E.g., collaboration and coordination on computing infrastructure, observational assets for field campaigns, process studies, model evaluation, etc.

¹⁸ E.g., partnerships among entities that are public-private and national-international.

¹⁹ E.g., the sectors involved in ML/AI, advanced computing, software, and hybrid predictive modeling.

Cross-Cutting Goal 4: Include, inspire, and train the next generation of interdisciplinary scientists who can advance knowledge and use of Earth system predictability.

Objectives:

1. Foster strengthened coordination and collaboration across academic departments.²⁰
2. Increase educational opportunities, professional pathways, and reward systems that incentivize careers in Earth system R&D areas.
3. Create opportunities for interdisciplinary, cross-organizational, and diverse research collaborations that facilitate professional growth.
4. Create opportunities that increase participation and nurture career development of underrepresented groups in ESP research.

National Roadmap to Advance High-Priority R&D

To accomplish the goals and objectives described in the Strategic Framework, the FTAC developed a National Roadmap that focuses initial R&D efforts.²¹ The Roadmap describes a path forward to advance a specific ESP R&D high-priority topic that targets the improvement of a set of predictions identified by stakeholders as critical.²²

The Roadmap Outline

R&D topic: *The predictability of Earth’s water cycle and precipitation extremes as well as associated biosphere and human interactions.*

Targeted outcomes: *The improvement of high-resolution integrated predictions and projections of high impact water cycle events, their cascading impacts²³ across the Earth system,²⁴ and their coupling to human, ecological, and biogeochemical systems.*

The Roadmap identifies a set of “Areas of Opportunity” that would ensure progress on the goals and objectives of the ESP R&D Strategic Framework. The Roadmap features ESP R&D opportunities for enhanced interagency coordination and collaboration as well as partnerships with the external community. Also, it highlights opportunities to further promote cross-disciplinary collaboration—particularly between Earth system scientists, computer, and data scientists—and to more purposefully train the next generation of diverse talent that is the key to the success of this R&D endeavor. Finally, embedded in the Roadmap is a “value cycle approach” envisioning sustained feedback between R&D and prediction activities (i.e., prediction needs drive predictability research and research informs the development of improved predictions).

²⁰ E.g., by creating interdisciplinary alliances to address specific research challenges involving experts in Earth system science, computational sciences, engineering, and applied mathematics.

²¹ The roadmap approach provides a “proof of concept” and sets the stage for addressing other R&D topics to follow.

²² The FTAC considered phenomena among those of particular national societal need (e.g., those that produce the largest impact) as well as those that present the greatest opportunities for benefit because they are presently underexplored. It also considered stakeholders’ most crucial and broadly shared prediction needs that would directly benefit from predictability R&D.

²³ Such as droughts, floods, hurricanes, extratropical cyclones, atmospheric rivers, and wildfires, etc.

²⁴ Includes land, coasts, and oceans.

Areas of Opportunity

Area 1. Expand Theoretical Foundations of Earth System Predictability²⁵

A comprehensive theory to describe predictability in the Earth system does not currently exist. While *Lorenz Theory*²⁶ provides tremendous insights into a low-order chaotic system, it also has its limitations when applied to the issue of practical atmospheric predictability due to the complexity of the Earth system. Current understanding of ESP is still insufficient to inform how to rapidly advance accurate and reliable Earth system predictions across spatial and temporal scales.

A focused cross-disciplinary interagency research effort could spearhead the development of theoretical frameworks to more accurately and comprehensively understand the limits of predictability of Earth system phenomena. This effort would fully exploit observational data, models, and advanced methodologies for the understanding of the behavior of the complex Earth system. Research efforts could include an enhanced understanding of precursor conditions, the role of external forcings, the characteristics of component and system-level error growth, the role of high frequency/small scale chaotic processes on large-scale dynamics, shifts in predictability regimes, and improving the understanding of processes relevant to subseasonal-to-seasonal (S2S) phenomena, among others. Approaches could leverage a hierarchy of idealized-to-comprehensive complex models, advanced mathematics and information theory, and ML/AI methods to analyze and detect the coexistence of chaotic and non-chaotic components from model and observational data. To realize practical utility, these efforts would include rapidly synthesizing and conveying new understanding of predictability for improved predictions.

Area 2. Fill Knowledge Gaps for Processes that are Crucial for Predictability²⁷

Knowledge of processes and phenomena that play a crucial role in the predictability of extreme events is still significantly lacking, despite substantial progress in recent decades. For the predictability of water cycle, precipitation extremes and their cascading effects, important processes and phenomena include, for example, the role of convection and clouds across all scales; physical and biogeochemical interactions in the boundary layer between the atmosphere and the land surface; and the biogeochemistry of land, river, coasts, lakes, ocean and related ecosystems. At play are local mechanisms as well as lower frequency large-scale precursors of phenomena such as the phase of the Pacific Decadal Oscillation, El Niño Southern Oscillation, the Madden-Julian Oscillation, and other modes of variability. Improved understanding of the role of human activities and its subsequent representation in Earth System Models (ESMs) is essential to predict water cycle extremes and their cascading effects. In order to advance predictability of water cycle extremes across scales, the most critical challenge is advancing our understanding and modeling of precipitation and biogeochemical processes. While biogeochemical processes have been incorporated in ESMs for over a decade, predictability of marine and terrestrial ecosystems is a topic of current research that could lead to various practical applications.

²⁵ This area is of particular relevance to Goal 1 and cross-cutting Goals.

²⁶ Lorenz, Edward N. "Deterministic nonperiodic flow." *Journal of the atmospheric sciences* 20, no. 2 (1963): 130-141.

²⁷ This area is of particular relevance to Goal 1 and cross-cutting Goals.

R&D efforts could include conducting targeted and interagency coordinated field campaigns, potentially involving public-private partnerships and international coordination; forming interdisciplinary teams to address those high-priority knowledge gaps in process understanding and modeling; innovative mathematical approaches to data analysis and model-data diagnostics; broadly sharing and utilizing the data for R&D; and conducting research to improve the simulation of those processes in models and harnessing of predictability in ESMs.

Area 3. Tap into Underutilized Observational Data to Examine Sources of Predictability Using Advanced Technologies²⁸

There is a gap between available observations from all platforms and their full utilization to address the understanding of ESP and accelerate the advancement of predictions and projections. ML/AI approaches are ideally suited for discovering predictors and precursors of Earth system phenomena given a large suite of observational, model data and reanalysis, covering many variables across a wide range of spatial and temporal scales. These new techniques, used jointly with more traditional and well-understood data analysis approaches, can potentially provide new insights. Coupled data assimilation as well as traditional reanalysis products provide opportunities to examine predictability. Collaborations between Earth scientists, data assimilation, and ML/AI experts could lead to accelerated progress in utilizing observations, reanalyses, and models to tap unknown sources of predictability.

For example, R&D efforts could provide more efficient analysis of observational data and reanalysis data, and diagnostic methodologies that combine the various types of data to potentially reveal new insights into sources of predictability. Novel approaches could help advance predictability theory, for example: ML/AI to identify combinations of precursors of Earth system phenomena, used in conjunction with other more traditional methodologies and mechanistic studies to better understand the interdependence of physical and biogeochemical processes contributing to their predictability. Examples of opportunities also include tapping into underutilized satellite data using advanced numerical and technical tools such as data assimilation and ML/AI to better estimate poorly-constrained model parameters and improve process representation—as well as using data and reanalysis products to discover episodes and regions with enhanced predictability to provide information about sources of predictability that could be further exploited (e.g., for forecasts of opportunity).

Area 4. Observational Networks and Advanced Technologies Deliberate for Predictability and Predictions²⁹

There is an opportunity to improve the way data are collected and used to significantly accelerate predictability and prediction R&D, with several factors currently at play. There is an explosion in new types of observing and communications technologies (e.g., Argo floats, unmanned aerial vehicles [UAVs]), new satellite data (e.g., small satellite constellations), non-traditional observations (e.g., mobile phone data), and a robust and growing ecosystem of commercial providers. Researchers can leverage these resources with emerging ML/AI methods and exascale computing—together with simulation experiments and process studies—to more deliberately design, deploy, and utilize an observing system that optimally integrates new observations with more traditional sustained observations to advance the understanding and harnessing of ESP.

²⁸ This area is of particular relevance to Goal 1 and cross-cutting Goals.

²⁹ This area is of particular relevance to Goal 2 and cross-cutting Goals.

A Network of Innovative Sensors Integrating Advanced Technologies

R&D efforts could design, deploy, and utilize large networks of low-cost, innovative sensors and integrate these with other more traditional observations crucial for practicable ESP, with an initial focus on the predictability of extreme events. R&D could determine how to optimally interweave modeling, data assimilation, and ML/AI tools to identify the variables, locations, and time scales where observations would most effectively reduce stakeholder-relevant uncertainties in the understanding of ESP. R&D could develop and tailor such networks that span from small satellites to UAVs, platforms such as the Argo floats, and crowd-sourced observations (e.g., from mobile phones), specifically for ESP and prediction research.

Utilizing Adaptable Networks Using Advanced Technologies

R&D efforts could explore the opportunity for prediction models to increasingly benefit from data collected by adaptable observational networks, complementing the historical use of fixed, pre-planned, and routine data collections. This could potentially result in reduced cost and power needs with more sensing platforms deployed ad-hoc, allowing the targeted deployment of sensors on schedules and along flight paths to drive down uncertainty. R&D could explore the opportunity for autonomous or other innovative platforms in combination with ML/AI and model simulations to redirect sensors or reposition in order to collect the best measurements for predictability; this could also be an innovative approach to conduct Observations System Simulation Experiments (OSSEs) that aim to optimize observations for predictability. R&D could explore how this capability may be applied both to collecting new observations in strategically optimized locations and timings to improve the accuracy of our understanding of the Earth system as well as to optimize the choice of initial conditions of ensemble forecasting models to improve both accuracy and precision of those predictions. The opportunity here is to optimize the efficient use of the limited observational and computational resources available to make predictions. The benefit could be to alleviate trade-offs among number and choice of initial conditions, frequency with which predictions are recalculated, the horizon into the future in which predictions are made, and the accuracy and precision of those predictions.

Optimize Observations to More Deliberately Target Practicable Predictability

R&D efforts could optimize observations and better understand those that efficiently address the predictability challenges. This could include developing metrics and experiments, including OSSEs, to understand the impact of existing observations as well as the scientific and societal value of new types of observations. These efforts also have the potential to identify data gaps that have been limiting practicable predictability. For example, for meteorological predictions at the S2S timescale, it may be necessary to increasingly incorporate specific land surface observations as well as subsurface and sea surface conditions. Current data gaps for practicable predictability also include data beyond those that are currently utilized to predict temperature, precipitation, or sea surface temperature, and also include forecasting decision-relevant quantities such as energy production and consumption, water availability, and agricultural yield. In order to improve tools and models for these kinds of derivative forecasts, R&D could explore how to expand the observation network beyond the physical measurement of the Earth system to also measure societal decision-making processes, along with the context of extenuating factors that influence decisions. R&D could explore whether approaches such as ML/AI combined with satellite and the integration of innovative observations might be useful to fill in some of the noted gaps. Across the various types of platforms, R&D could identify which observations are most important for informing the design of an optimally integrated observing system for practicable predictability.

Enhancing Coordination and Collaboration for an Observing System that More Deliberately Targets Predictability

Agencies and departments could enhance benefits by having increasingly focused coordination and collaboration efforts to more deliberately target predictability through observational networks. This includes internally in the U.S. Government and also collaborating with external partners including non-profit partners, industry, academia, and internationally. Harnessing improved coordination and collaboration mechanisms, the scientific community and the public could benefit from a more integrated approach to observational networks across all disciplines relevant to ESP. Agencies and departments could enhance collaboration across science disciplines and sustained engagements with stakeholder organizations. They could also explore suitable approaches for sharing of information on societal impact and decision making relevant to ESP often restricted by privacy laws. Agencies and departments could enhance their existing coordination and collaboration on investments for the infrastructure necessary to handle the large amounts of data generated by all observational platforms to ensure data are findable, accessible, interoperable, and reusable.

Area 5. Advanced Modeling and Technology, and Enhanced Collaborations³⁰

ESMs are key tools for the exploration of predictability, and they are unique platforms to harness it from observational data to make more robust and accurate Earth system predictions. In spite of major progress during the past decades to simulate and predict many important geophysical quantities, even the best state-of-the-art models and prediction systems world-wide are currently lacking in key desired characteristics foundational to accurate modeling of ESP, and making skillful predictions over multiple time scales. Examples of current shortcomings include model biases that have persisted over time, missing or overly-simplified Earth system process representations, insufficient spatial resolution, and lack of satisfactory prediction skill in the S2S range and beyond (e.g., for precipitation).

Integrate ML/AI in Modeling

Innovative ML/AI algorithms have shown initial promise in providing new strategies for exploring parameter space and for accelerating the model development cycle of tuning and retuning. These methods may also be employed to more systematically generate ensembles of initial conditions and evaluate structural model differences, so as to produce ensembles weighted using statistical methods across different model systems that more faithfully represent the full probability density function of possible future states of the Earth system. Investigations of this kind are only beginning, so there is an opportunity for R&D to further explore how to apply these methods.

For example, R&D could explore the use of ML/AI for improving the fidelity and accuracy of process representations and reducing model systematic errors and biases; increasing computational efficiency of scale-aware parameterizations for high-resolution simulations; generating ensemble simulations and forecasts of unprecedented size with full-model emulators and hybrid models;³¹ and analyzing simulations in ways that can help to highlight key geographic regions affecting predictability of the Earth system.

Reduce Model Errors

R&D activities could address improving the fidelity of ESMs by reducing model biases and tapping into the simulation of processes that are key for predictability. In spite of the many successes of the Earth

³⁰ This area is of particular relevance to Goal 3 and cross-cutting Goals.

³¹ Deterministic and stochastic models with ML/AI sub-models.

system modeling community in past years, there are still some model biases that are limiting the application of models for understanding of ESP and making reliable/accurate predictions. Several of these biases, such as the double Inter-Tropical Convergence Zone, have been present in ESMs for decades, defying improvement despite efforts by the community. Improving understanding of how to resolve these biases has been a focus of some past efforts, but additional R&D with innovative and focused approaches could allow more substantial and rapid progress to reduce key biases. For example, R&D could explore the use of scale-aware parameterizations of sub-grid processes in the atmosphere, ocean, and land as well as their coupling with dynamics for the simulation of extreme events; the development of higher resolution models that explicitly resolve rather than parameterize key mesoscale processes; and improving the representation of model errors and error growth.

Explore Signal-to-Noise Ratio with Large Ensembles

Along with the reduction of model biases and tapping of broader sources of predictability, another key predictability R&D area is large ensemble modeling to allow exploration of the high-dimensional space of Earth system processes and the occurrence of extremes. Such large ensembles could go beyond those currently available from low-resolution models to more realistically simulate high impact extreme events such as hurricanes, droughts, and wildfires. R&D with large ensembles could explore signal-to-noise ratio and roles of internal variability versus external forcings, develop ML/AI-based model emulators to enable very large ensembles, and explore ML/AI as a means to generate more “intelligent” ensembles.³²

Increasingly Integrate Biosphere and Human Systems in ESMs

In order to represent predictability sources and key interactions that contribute to future states of the Earth system and practical outcomes of importance to humans, it may be necessary to increasingly expand the range of processes included in ESMs. There are key uncertainties to be propagated that have not traditionally been part of ESMs, but may be relevant to reducing model errors and harnessing predictability. Biogeochemical, biological, hydrogeological and human processes provide feedback to the global Earth system—for example, aerosols such as dust and black carbon are an integral part of many monsoon systems.³³ The seasonal greening and browning of vegetation and human activities such as urban processes, irrigation, and water management may also provide sources of ESP through land-atmosphere interactions. State-of-the-art ESMs now have varying degrees of information on biosphere and human systems built-in their codes, with coupling and complexity of representation depending on the specific models. There is the opportunity to potentially advance the representation of such processes and their bidirectional coupling with physical processes to better represent the wide range of possible environmental conditions.

Explore the Impact of Resolving Clouds and Ocean Eddies in ESMs

Recent results obtained with global ESMs have shown that they are able to resolve mesoscale circulations in the atmosphere and the ocean. Despite progress in the ability of models to capture non-linear interactions, the mesoscale motions and the phenomena associated with them—such as deep convection—are often parameterized in most ESMs. The parameterizations are typically based on conceptual models that encapsulate how the complex circulations affect the resolved scales, with parameters tuned to match observational constraints. By resolving processes such as clouds and ocean eddies in ESMs, these parameterizations may become less crucial, thus making the models potentially

³² For example, ensembles with members perturbed or restarted during the model runs to maximize their impact.

³³ Monsoons affect the aerosol distributions, which in turn affect monsoon circulation and precipitation.

less dependent on tuning. Increasing model resolution to sufficiently high, so as to resolve clouds and ocean eddies, could be transformative in reducing persistent model biases and improving the harnessing of predictability. Fully representing sub-grid moist convection processes could help more faithfully typify chaotic behavior in the models and hence help improve the simulation of the signal-to-noise ratio used to estimate predictability. Similarly, fully simulating mesoscale ocean eddies could improve modeling of air-sea interactions that contribute to predictability. While there are tantalizing benefits to high resolution, there are also important trade-offs between model resolution, complexity, and ensemble size yet to be explored and assessed. R&D could examine and assess potential benefits and tradeoffs associated with cloud and ocean eddy resolving simulations in terms of representing processes crucial for predictability. This type of experimentation would likely require broad coordination of resources and collaborations (nationally and internationally) on topics such as experimental design, model availability, computational platform, and diagnostics.

Enhance Computational Infrastructure and Efficiency for Extensive Modeling Explorations

Enhanced computational capacity and increased efficiency underpin the acceleration of predictability and prediction R&D, particularly when ML/AI are utilized. This is a major limiting factor in aggressively making progress in improving ESMs capabilities and in most effectively using observational data for R&D. Computational platforms may now have accelerators, may combine graphic processing units (GPUs) and central processing units (CPUs), and are increasingly hosted in cloud computing environments. Current ESMs are challenged in exploiting some of these features, including the increasing parallelism in the latest computing systems. Managing, transporting, and using large amounts of data for ESMs is also a challenge.

R&D could involve Earth system model developers, computer and data scientists, software engineers and computer manufacturers to address issues such as “big data” input and output for R&D and model-data assimilation; exploring algorithmic advances necessary to make performance gains; discovering how to take advantage of emerging programming languages and evolve models so that they can exploit features of emerging computational architectures; potentially reimagining the future architectures for ESMs in order to better leverage new platforms; and also better tailoring models to specific decision contexts. Enhanced coordination, communication, and partnerships could provide the opportunity to more effectively convey computational and communication ESMs requirements to manufacturers and increasingly co-design future computing; pursue a more scalable cyberinfrastructure to streamline efforts and improve accessibility of models to a larger fraction of the community; and augment cyberinfrastructure capacity for Earth system R&D.

Coupled ESM Data Assimilation to Harness Predictability

Recent advances in ensemble data assimilation have made it possible to make use of the parallel supercomputing power to perform advanced data assimilation on complex coupled Earth system models directly, rather than component by component. Data assimilation is useful for both optimizing the model parameters to best represent processes important for predictability and also for improving predictions.

R&D could advance from weakly coupled toward fully coupled nonlinear ESM data assimilation for all Earth system components. The nonlinearity allows increasing the information extracted from the observations (at the moment, part of that information is not used due to linearity assumptions). Efforts could aim at increasing the data-assimilation performance, and could include ML/AI techniques wherever useful together with other methods. R&D could also explore the use of nonlinear data-assimilation and ML/AI capabilities in order to infer missing model physics (or improve model

parameterizations) at the space and time scale of the discretized model equations. Part of this effort could include producing coupled reanalysis products for advanced predictability R&D.

Enhancing Coordination and Collaboration for Earth System Modeling to Understand and Harness Predictability

Given the increasing resource demands underpinning the acceleration of ESM improvements, an enhanced approach for coordination and coordination across agencies, departments and modeling centers could build on current activities to more efficiently use available resources for rapid and targeted experimentation and diagnostics. This would help provide the computational and modeling infrastructure that enables broad collaborations to experiment with new ideas; to systematically evaluate the models and impacts of parameterizations and resolution; analyze simulations (e.g., within a multi-model context); and to facilitate interactions of researchers working on each of these specific areas. A hierarchy of modeling approaches could enable the understanding of the behaviors of simple to complex models, and strengthen the theoretical foundation of ESP. Enhanced collaborations across modeling centers could generate the very large ensembles necessary to characterize model uncertainties, internal variability, and for long-term projections and scenario uncertainties. Enhanced coordination, collaborations, and partnerships could enable the development and analysis of clouds and ocean eddy-resolving ESM simulations and also more effectively tapping into available Earth system data for validation and model-data assimilation. This approach could also facilitate multi-agency multi-model comparisons aimed at process understanding and bias correction, and sharing of methodologies and portability of methods allowing for ESM testing and improvement. Targeted management strategies could increasingly prioritize, support, and reward collaborative modeling advances and community breakthroughs (including high risk/high payoff research). A more deliberate framework for collaboration across the Federal agencies and departments, and with the external community could break down the complexity of Earth system modeling and predictability into an increasingly coordinated and collaborative outcome-driven effort. This framework could advance ESM experimentation and utilization, focusing on enhancing synergies and collaboration, while preserving model diversity.

Appendix A: FTAC Engagement Activities to Inform Strategy and Roadmap

To inform its activities, the FTAC actively engaged stakeholders from both Federal agencies and departments and the broader community for feedback and discussion on topics related to the predictability of the Earth system in several formats.

In March 2020, the FTAC surveyed agencies and departments participating in the ESP effort to understand the current ESP R&D landscape within the Federal Government and identify agency research needs and opportunities as well as gaps and barriers. Key R&D themes across responses concerned observational data, theoretical processes understanding, Earth system modeling, infrastructure, technology, and coordination.

On April 13, 2020, on behalf of the FTAC, the National Aeronautics and Space Administration (NASA) issued an RFI on future ESP R&D activities of Federal agencies and departments as well as their partnerships with the external community. Via the RFI, the FTAC made an open call to the public to provide input on a number of relevant questions, including needs for enhanced Earth system predictions and benefits to meeting those needs; top R&D gaps or barriers impeding progress in understanding ESP; and top R&D opportunities and related activities for making substantial progress in the understanding of ESP. The RFI received 58 responses from across the community, including from academia (both individuals and institutions), individuals or groups employed by the Federal Government (typically Government laboratories and Federally Funded Research and Development Centers), non-profits and think tanks, industry, and professional societies.

On April 16, 2020, the National Academies of Sciences, Engineering, and Medicine (NASEM) and OSTP co-sponsored a virtual roundtable on ESP R&D to promote a discussion and solicit feedback on the direction that the Federal Government should take in this area. The Roundtable participants included over 60 representatives from academia, research laboratories, non-profit and for-profit organizations, Federal and State government agencies, philanthropies, and the international community. The roundtable included panel discussions in plenary as well as discussions in breakout groups. It was framed around the following themes: the impacts of practical ESP, key R&D opportunities in this area, needs and opportunities for enhanced coordination and partnerships, and consideration of relevant education and training of a diverse workforce.

The Roundtable inspired follow-up community-organized engagement activities during June-September 2020 that the FTAC was invited to participate in.

Appendix B: Principles

1. Outcomes address issues of high societal relevance to the Nation.
2. Scientific objectives are tractable.
3. Goals are beyond incremental improvement.
4. Goals address missions of agencies and departments.
5. Interagency coordination and collaboration result in outcomes that are beyond the sum of the parts.
6. The approach is grounded in foundational understanding and integrates across disciplines, spatial scales, and timescales.
7. The approach is scalable and phased, addressing a more comprehensive set of issues over a period of several years.
8. The development of a diverse cadre of scientists and the enhancement of computational infrastructure are key to the approach.
9. Enhanced partnerships are critical to the effort (interagency, across Federal and State Governments, across public and private entities, and internationally).