PRECIPITATION PREDICTION GRAND CHALLENGE
STRATEGY

WEATHER, WATER, AND CLIMATE BOARD
OCTOBER 30, 2020

Precipitation Prediction Grand Challenge

Strategy

October 30, 2020

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The Precipitation Prediction Grand Challenge Strategy is a living document that will be updated on a regular basis based on new inputs. Please see Appendix E for the version control table.

1.0 Introduction

When will it rain? Where will it rain? How much will it rain? Will the precipitation fall as rain, snow, or sleet? The answers to these questions are needed by every person and business in the United States and at almost every timescale, spanning from the next hour to daily to decadal. For instance, farmers need to know if they will need to irrigate their crops in the next few days, mariners need to efficiently avoid hazardous storms developing over inland seas, ice, and oceans, emergency managers need to pre-position supplies ahead of a flood event, engineers need to set design standards for roads and bridges, and water managers need to know if they should be holding back reservoirs due to future drought conditions or releasing water because of future precipitation. Overarchingly, these decisions include assessing and reducing risks, reducing damages by motivating mitigation actions, and promoting social and economic well-being associated with continued changes in precipitation event frequency and intensity.

These needs for accurate precipitation forecasts over land and ocean have increased over time even as precipitation forecast skill has been declining (see Figure 1). Today's state-of-the-art global coupled models exhibit systematic errors that are as large as the real precipitation signal NOAA is trying to model and the magnitude of these errors has remained essentially the same since the late 1990's.

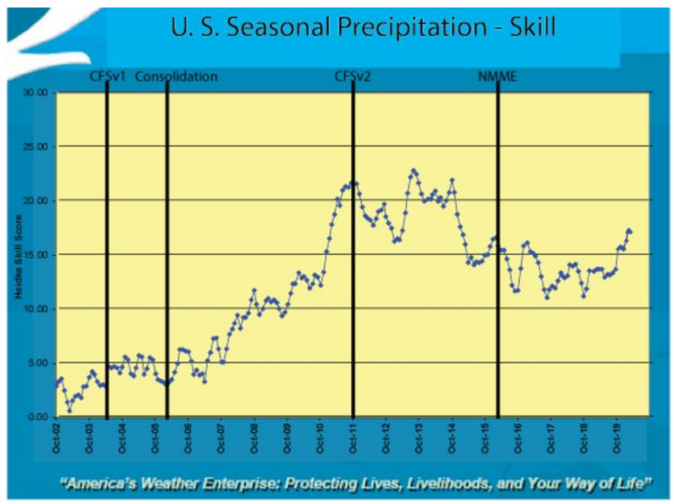

Figure 1. U.S. Seasonal Precipitation Skill

Additionally, while the National Academy of Sciences acknowledges that "it is increasingly recognized that many sources of predictability exist in the Earth system on S2S [subseasonal-to-seasonal] timescales, representing these sources of predictability in Earth system models is challenging,"[1] without improved monthly and seasonal forecast tools NOAA will be unable to provide the precipitation predictions at the timescales required by our nation's decisionmakers. It is time to

[1] National Academies of Sciences, Engineering, and Medicine. 2016. Next Generation Earth System Prediction: Strategies for Subseasonal to Seasonal Forecasts. Washington, DC: The National Academies Press. doi: 10.17226/21873.

address these errors in global models in order to meet the societal demand for improved precipitation forecasts.

Strategic Goal	Provide more accurate, reliable, and timely precipitation forecasts across timescales from weather to subseasonal-to-seasonal (S2S) to seasonal-to-decadal (S2D) through the development and application of a fully coupled Earth system prediction model

Why now?

2019 was the fifth consecutive year (2015-2019) in which 10 or more billion-dollar weather and climate disasters impacted the United States.[2] Many extreme events and the impacts they cause (e.g., billion-dollar disasters; see Figure 2) are associated with a warming climate system that includes an intensified water cycle, leading, for example, to both more droughts and more floods. A key to reducing these impacts is to be able to anticipate when, where and how much precipitation will fall. Although temperature forecasts have generally improved greatly over the last few decades, precipitation forecasts (at all timescales) have not. Likewise, for longer-term climate projections, confidence in future temperature projections is much greater than confidence in the associated precipitation changes, the nature and magnitude of which carry large implications for societal risks. The World Climate Research Programme's *Grand Challenge on Weather and Climate Extremes* echoes the need for reliable predictions of extremes on time scales from days to seasons and centuries.[3]

[2] NOAA National Centers for Environmental Information (NCEI). 2020. U.S. Billion-Dollar Weather and Climate Disasters. https://www.ncdc.noaa.gov/billions/, DOI: 10.25921/stkw-7w73

[3] World Climate Research Programme. Weather and Climate Extremes. https://www.wcrp-climate.org/component/content/article/63-gc-extremes?catid=32&Itemid=266

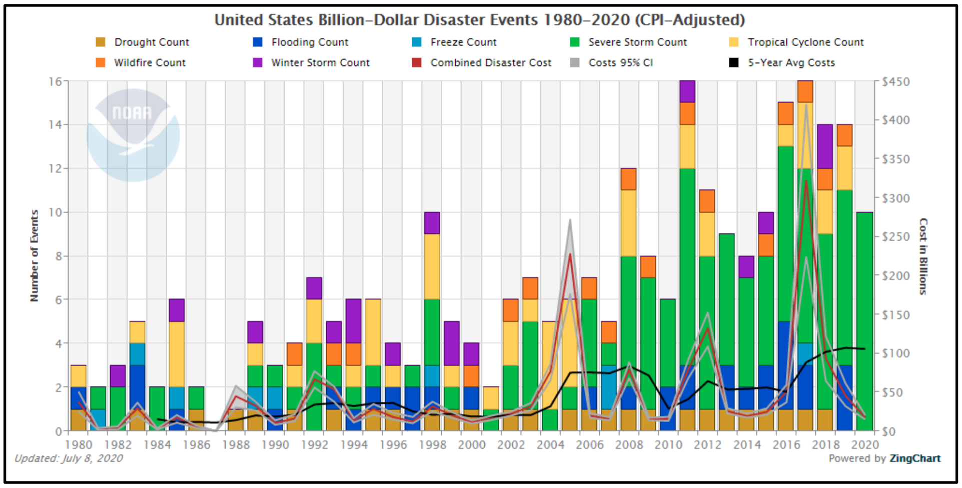

Figure 2. U.S. 2019 Billion-dollar Weather and Climate Disasters[2]

Additionally, the NOAA Water Initiative Vision and Five-year Plan (NWI) envisions "a nation in which everyone from individual citizens to businesses and public officials has timely, actionable information about their vital water resources at their fingertips, and can factor this information wisely into their decisions about water risks, use, management, planning, and security."[4] Providing more skillful, reliable, and objectively verified precipitation forecasts across temporal and spatial scales is a fundamental prerequisite for delivering the water resources forecasts and services required by key stakeholders and partners depending on the NWI. Skillful precipitation forecasts are needed over land, ocean, ice, and inland seas to match the global scope of our nation's interests and activities.

Acknowledging these ongoing challenges and the ongoing needs of decision-makers, the Congress and the Executive Office of the President have established several mandates. The Weather Research and Forecasting Innovation Act of 2017 requires NOAA to collect and utilize information in order to make more usable, reliable, and timely foundational forecasts of subseasonal and seasonal temperature and precipitation.[5] The first phase of the Earth Prediction Innovation Center (EPIC) will improve the global weather element of the Unified Forecast System (UFS), advancing global 7-10 day weather forecasts by incorporating contributions from the external research and modeling community. EPIC will then extend infrastructure and user support for the UFS to a fully coupled Earth system prediction system, transforming the operational suite of models that are critical to improving forecast skill beyond three weeks and addressing the full range of

[4] NOAA Water Initiative Vision and Five-year Plan. 2016. https://www.noaa.gov/water/explainers/noaa-water-initiative-vision-and-five-year-plan

[5] Weather Research and Forecasting Innovation Act of 2017. 2017. 15 U.S.C. (see Title II: Subseasonal and Seasonal Forecasting Innovation).

NOAA's mission applications.[6] The research identified in this Grand Challenge will help NOAA determine the steps needed to improve precipitation prediction skill that will, in turn, inform and support the activities of EPIC.

These legislative mandates are supported by the Executive Office of the President's (EOP) Fiscal Year 2021 Administration Research and Development Budget Priorities Memorandum, in which federal departments and agencies are directed to prioritize research and development that helps quantify Earth system predictability across multiple phenomena, time, and space scales,[7] and the Earth System Predictability Initiative led by Dr. Kelvin Droegemeier, Director of the EOP's Office of Science and Technology Policy.

To fulfill the grand challenge, NOAA will draw heavily on new strategies in key science and technology (S&T) focus areas, especially in the fields of (1) Uncrewed Systems, (2) Artificial Intelligence, (3) Cloud Computing, and (4) Big Data. NOAA must efficiently and effectively adopt the breakthrough S&T applications to help deliver the world's best forecasts and to grow the American Economy.

What is needed?

Here are some of the activities that require the biggest push to make the most significant improvements in precipitation prediction (see the stand alone chapters in Appendix C for additional details):

1. **Improve end-user products through user engagement and social science to more effectively communicate the forecast.**

2. **Assimilate and integrate data, then regularly produce supporting datasets, including reanalyses and reforecasts.** (1) Improve data assimilation, particularly exploiting satellite observations (including AI/ML techniques). (2) Integrate precipitation process datasets (including cloud properties and precipitation). In particular, continue to work with the community to improve current unified precipitation datasets (e.g., GPM/IMERG, NCEP/CPC/CMORPH, etc.) that include observations from satellites, radars, and rain gauges. These will be used for NWP model calibration, validation, and performance tuning to reduce the mismatch between observed and modeled precipitation. (3) Regularly produce supporting data

6 Earth Prediction Innovation Center: Strategic Plan FY 2020-2025 (Draft). https://wpo.noaa.gov/EPIC-Strategic-Plan-2020

7 Executive Office of the President. 2019. Fiscal Year 2021 Administration Research and Development Budget Priorities. https://www.whitehouse.gov/wp-content/uploads/2019/08/FY-21-RD-Budget-Priorities.pdf

sets such as reforecasts across models used in precipitation prediction. (4) Improve post processing, beginning with regular provision of reforecast datasets, as above.

3. **Address model systematic errors** through reformulation of moisture-related parameterizations (deep convection and microphysics), improved resolution, and improved component couplings.

4. **Establish traceability of error sources** and growth patterns to identify primary gaps in observations, data assimilation, representations of key processes in forecast models, and to evaluate improvements in precipitation prediction skill. For example, support additional process-based diagnostics to illuminate model deficiencies.

5. **Change the paradigm and target regions that host sources of precipitation predictability.** (1) Change the paradigm of treating Earth system component interactions. Rather than focusing on their interfaces (e.g., sea and land surfaces), focus on their transition zones in order to fully explore and exploit sources of predictability:
    - For ocean-atmosphere interactions, the air-sea transition zone is the upper ocean, air-sea interface, and atmospheric marine boundary layer.
    - For land-air interactions, the land-atmosphere transition zone is upper soil, vegetation, and atmospheric boundary layer.
    - For ocean-ice-atmosphere interactions, the transition zone is sea ice, marginal ice zone (MIZ), upper ocean in open water and underneath sea ice, and atmospheric boundary layer above sea ice, MIZ, and open water.
    - The coastal transition zone includes coastal land and ocean, estuaries, and the atmospheric boundary layer above land and ocean.

    These transition zones should be treated as integrated identities instead of a sum of different components and this concept should be applied to both observations and modeling. (2) Target regions that are known to host sources of precipitation predictability on multiple time scales across the globe but suffer from major gaps in observations, process understanding, and model representation by developing integrated approaches to observe, understand, and model the processes that have the strongest imprint on the model biases behind precipitation predictability from weather to decadal scales: Consider especially the Atlantic, tropical Pacific, Indo-Pacific Maritime Continent and its surrounding seas, and the Arctic.

6. **Improve water vapor and boundary layer observations and analyses.** Improve observations, with particular attention on water vapor and the land/ocean/air interface (boundary layer) and consistent precipitation analyses. Expand operational observing capabilities and ocean forecasts that acknowledge the critical role of the air-sea interface.

To fulfill the *Precipitation Prediction Grand Challenge* strategic goal, an integrated research-to-operations effort must be developed that focuses on the weather-water-climate-oceans linkages. This includes polar and tropical influences on predictability limits and prediction capabilities, as well as teleconnections between regions. These global processes over land, ice, and ocean influence prediction in the mid latitudes on time scales from weather, to S2S, to S2D. The combined efforts of the research and operational communities in this *Precipitation Prediction Grand Challenge* will result in an increased understanding of the physical process and a clearer picture of the predictability limits within an Earth System Science framework for weather through climate timescales. At the same time, the operational and service communities will apply the scientific advances gained from the *Challenge* to improve prediction capabilities of the basic state dynamic and thermodynamic parameters required for improved precipitation prediction across the same timescales.

The *Precipitation Prediction Grand Challenge* also offers the opportunity to demonstrate an understanding of user needs and their application to one of NOAA's greatest scientific challenges. In essence, the challenge ahead is for NOAA to review and consider its investments in model improvements, observational enhancements, and research in light of the most pressing needs for improved forecast information from the end user community, especially those involved in water resource and emergency management. In addition to significant scientific advances in the prediction and forecasting of precipitation, this tremendous challenge requires a business model shift that includes research to operations planning, wherein the relationships established by NOAA's user engagement community are leveraged in a co-production manner to inform, prioritize, and shape the prototype and final precipitation products developed to meet their information needs, including recognition of the role that our partners may play in serving those needs.

What are the key questions the strategy must address?

Low skill and large-scale systematic errors persist despite extensive research, observations, publications, and workshops. For instance, Fritsch and Carbone initially noted in 2004 that warm-season quantitative precipitation forecasts (QPFs) are particularly poor;[8] Cash and Burls illustrated the large role of atmospheric variability in the erroneous 2015 seasonal precipitation predictions for the western United States during a strong El Niño year;[9] there are interesting hypotheses for how sustained cross polar flow in the 2018-2019 winter contributed to significant prediction challenges for large portions of the northern hemisphere, including California receiving near-record snowfall in the Sierra Mountain Region; and the October 2010 issue of the Bulletin of the American Meteorological Society focused on the research and services needed to accelerate advances in weather, climate, and Earth system prediction.[10]

The original call to the entire research and operational communities, almost a decade ago, was to break down the observation and model barriers —the "stove pipes" — among the global climate, weather and hydrology communities to advance prediction from the short-range weather scales to the longer-range climate scales. While there has been progress on this in the U.S. and in the international community over the past several years, especially within the World Meteorological Organization (WMO) there is much more to accomplish. The "precipitation" prediction challenge raises the bar in that it requires an integrated weather, water, climate and ocean approach.

In order to make significant progress on the *Precipitation Prediction Grand Challenge*, this strategy must build on decades of research, observations, transitions, operations, publications, and engagement workshops to address seven critical questions:

1. What are the major systematic errors in precipitation prediction systems (due to initial conditions and model biases), and what prediction system deficiencies or simplifications are the ultimate cause of these systematic errors?

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8 Fritsch, J. Michael, and R. E. Carbone. 2004. "Improving Quantitative Precipitation Forecasts in the Warm Season: A USWRP Research and Development Strategy." *Bulletin of the American Meteorological Society*, 85, 7: 955–66. https://doi.org/10.1175/bams-85-7-955.

9 Cash, Benjamin A., and Natalie J. Burls. 2019. "Predictable and Unpredictable Aspects of U.S. West Coast Rainfall and El Niño: Understanding the 2015/16 Event." *Journal of Climate*, 32, 10: 2843–68. https://doi.org/10.1175/jcli-d-18-0181.1.

10 Bulletin of the American Meteorological Society 91, no. 10 (2010). https://journals.ametsoc.org/bams/issue/91/10

2. What are the key physical processes that have the strongest imprint on the model biases and precipitation prediction?
3. How can systematic errors in precipitation forecasts be fixed and which errors should be fixed first?
4. What lessons can be learned from previous successes as well as previous mistakes?
5. What major knowledge gaps persist regarding the nature of precipitation processes and prediction?
6. What new capabilities and opportunities offer promise toward reducing the major systematic errors in precipitation prediction systems and measurable improvement in precipitation prediction?
7. How can NOAA best organize activities within the agency itself, and across the federal, academic and private research enterprise, both nationally and internationally, to make significant progress?

What are the major systematic errors in precipitation forecasts?

In order to begin answering the first critical question listed above, the Precipitation Prediction Grand Challenge Working Group documented many of the major systematic errors/model limitations that are believed to limit predictive skill for precipitation across timescales (see Appendix A for a synthesis of historical and prospective sources of improvement in precipitation prediction). These errors are understood to be cumulative, so that forecast skill on longer timescales is negatively impacted by errors on shorter timescales. The best chance for diagnosing and ameliorating the root cause of the following systematic errors lies in following a process-based approach working on the shortest time scale possible:

- Timing, magnitude and location of the diurnal cycle of precipitation
- Mid-latitude warm surface temperature simulation
- Predicted precipitation amount
- Phase speed of mid-latitude troughs
- Propagation errors of convection
- Sub-seasonal tropical variability
- Inability to predict steering flow in winter over the West coast of the United States on sub-seasonal timescales
- Regime transition: Predicting flash drought onset
- Regime transition example: Shift from prolonged record drought to record flood

- Sub-seasonal to seasonal sea surface temperature forecasts
- Time Mean Statistics of Large-Scale Precipitation Forecasts:
- Double ITCZ [intertropical convergence zone]
- El Niño Southern Oscillation (ENSO) false alarms
- Sea ice prediction
- Quasi-Biennial Oscillation (QBO)
- Seasonal-to-decadal variability

How will the Precipitation Prediction Grand Challenge be accomplished?

By leveraging major progress in observations, understanding, and models from the last several decades, and by learning lessons from the past, the Strategy that follows establishes an integrated set of objectives and actions. When implemented, these objectives will advance understanding of predictability, improve process level understanding, and improve prediction systems to address the atmospheric and oceanic variability associated with predictability limits and prediction skill (see Figure 3).

Figure 3. Precipitation Prediction Grand Challenge Strategic Objectives

In order to advance the way NOAA does business, these objectives will be accomplished in partnership with EPIC's drive to develop the world's most accurate and reliable operational modeling system. In particular, the *Precipitation Prediction Grand Challenge* and EPIC will work together to:

- Exploit machine learning and artificial intelligence tools to advance data assimilation, modeling, and precipitation prediction capabilities.
- Leverage testbeds and other fora that bring together communities of practice within NOAA, with other agencies, academia, and the private sector to share ideas, experience, data, technologies, facilities, and progress in a seamless interactive and collaborative environment.
- Accelerate the transition of new precipitation capabilities to operational implementation through development, evaluation and testing in the NOAA

Hydrometeorological Testbed, the Climate Testbed and the Joint Center for Satellite Data Assimilation.
- Design observation and prediction systems with the flexibility to adapt to new technologies and approaches.

In addition to the key partnership with EPIC, these objectives will draw on the NOAA Artificial Intelligence Strategy to reduce the cost of data processing and provide higher quality and more timely scientific products and services for societal benefits[11] and the NOAA Cloud Strategy to provide significant improvements in performance and skill in areas such as satellite data products and services, numerical weather prediction, and ocean models, with expanded benefits, such as integrated research to operations.[12]

The following principles guide the objectives and actions proposed in this strategy:

- Predictability sets the upper limit on prediction skill.
- Prediction skill cannot reach the predictability limit because of error growth in a prediction system.
- Error growth can lead to systematic model biases that ultimately cause the model to deviate far enough from reality to render model output useless for prediction.
- In a fully coupled prediction system, the major sources of error are inaccurate initial conditions, model deficiencies, and unaccounted external forcing (e.g., land use, volcano eruption).
- Inadequate prediction products depreciate values of prediction to its users.

Because these strategic objectives will be pursued in partnership with NOAA's end users and partners to ensure that the products and services derived from the improved data, tools, and information are relevant and accessible, every person and business will benefit from having improved answers to when, where, and how much it will rain.

[11] NOAA. 2020. "Artificial Intelligence Strategy: Analytics for Next Generation Earth Science." https://nrc.noaa.gov/LinkClick.aspx?fileticket=0I2p2-Gu3rA%3D&tabid=91&portalid=0

[12] NOAA. 2020. "Cloud Strategy: Maximizing the Value of NOAA's Cloud Services." https://nrc.noaa.gov/LinkClick.aspx?fileticket=d5uzrl7vPnc%3d&tabid=68&portalid=0

Impact	NOAA's research is aligned across all readiness levels (research, to operations, to services) and timescales (from weather, to S2S, to S2D), resulting in (1) improved process understanding; (2) a significant reduction in systematic errors in NOAA global models; (3) improved operational precipitation prediction skill; and (4) effective engagement, development, and delivery of decision-support tools and services based on this improved skill

2.0 Objectives, Actions, and Impacts

By leveraging major progress from the last several decades (see Appendix A for a a list of specific sources of improvement over the past 20 years), and by learning lessons from the past, the Working Group recommends six ambitious strategic objectives to provide more accurate, reliable, and timely precipitation forecasts across timescales through development and application of NOAA's fully coupled Earth System prediction model. The Working Group recommends taking immediate steps to implement these interdependent objectives to achieve this goal through investment in the supporting actions over the next five years.

Objective 1. Enhance and sustain user engagement

Acknowledging the necessary emphasis on science to improve prediction, a deep and continuous connection to the end user is key to building products and services that are useful, usable, and actually used (see also NWS Strategic Plan, Goal 1, sections 1.1-1.6; NESDIS Reimagined User Engagement Pillar 4 of 5; and NOAA Model for Service Delivery).

> **Action 1.1 Strengthen existing user engagement entities to continuously engage with internal and external end users and partners** to understand user needs, translate their requirements, co-develop products, deliver and train them. Users include forecasters, researchers, observing teams, interagency, international, and also sector-specific, internal and external users.
>
> **Action 1.2 Champion co-production of precipitation applications between user engagement entities and product development teams** to ensure a relevant and usable response to internal and external user needs. Also, examine how existing products can be used or modified.

Action 1.3 Develop and sustain region-specific networks to understand users and their needs and build the capability and capacity to respond to the needs across timescales to inform place-based, sector-based decisions.

Impacts: NOAA has prioritized and strengthened the connection between the user and the development of information, products, and services that are useful, usable, and actually used. NOAA has formalized a framework outlining the specific use of user engagement as central to product and services development and delivery.

Objective 2. Improve precipitation prediction products and applications

Products, services, and applications that mine model information to provide the appropriate visualization and context of the forecast, including confidence and alternative scenarios.

Action 2.1 Revamp precipitation products and services to effectively communicate uncertainty, with particular focus on translating model forecasts into services that are tuned to the impacts decision makers care about.

Action 2.2 Post process raw coupled model precipitation forecasts to calibrate for bias and other deficiencies and to quantify prediction uncertainties.

Action 2.3 Translate precipitation output into actionable visualizations and data that help forecasters more directly make a forecast decision.

Action 2.4 Establish reforecasts and high quality multi-decadal analyses of precipitation to support more statistically advanced precipitation post-processing techniques.

Action 2.5 Design prediction verification metrics based on physical reasoning and user applications.

Impact: NOAA will have a coordinated post-processing effort, with all collaborating groups using common observation and analysis datasets, and community-developed post-processing and verification software tools for calibration and verification. Improvements in precipitation forecasts will be realized by ‘front line’ decision makers (e.g., improved public health and safety by improving emergency planning and actions; improved national security by better assessing likely outcomes) served by NOAA and our partners.

Objective 3. Improve prediction systems for precipitation

These improvements will address large-scale systematic errors in NOAA's Unified Forecast System and guide development and improvement of precipitation prediction capabilities across time-scales.

Action 3.1 Improve Unified Forecast System (UFS) Precipitation Forecasts by addressing errors from initialization. This must go hand in hand with investigation of particular locations and variables in initial conditions that precipitation prediction is most sensitive to. Precipitation challenges due to UFS initialization include:

- Understand and quantify error growth in UFS models and its attribution to the inaccuracy and gaps of initial conditions;
- Use existing observing technologies and innovative new technologies to fill critical observational gaps;
- Develop targeted coupled (e.g. ocean-land-sea-atmosphere) and atmospheric (e.g., radar, all-sky, lightning, etc) data assimilation capabilities that take full advantage of existing and forthcoming observations;
- Develop reanalysis and reforecast capabilities to ensure consistency between initial conditions and models required to maximize hindcast skill and calibrate model output.

Action 3.2 Improve Unified Forecast System (UFS) Precipitation Forecasts by addressing errors from model biases. This must go hand in hand with investigation of particular physical processes critical to precipitation prediction (Action 3.3). Similar to many other models, the UFS precipitation biases include:

- Precipitation distribution, with underestimation of heavy precipitation and overestimation of very light precipitation;
- Diurnal cycle of precipitation, with maxima too early in the day;
- Initiation of convective precipitation, for example due to errors in boundary layer stability;
- Double ITCZ;
- Organized tropical convective precipitation features (such as the Madden–Julian oscillation (MJO)) are poorly represented.

Bias correction will benefit from optimizing the prediction system design, including use of large ensembles, optimal resolution, efficient computing, and innovative coupling/nesting/adaptive configurations.

Action 3.3 Improve physics in coupled air-sea-land-ice models by emphasizing co-development of all model components, focusing on UFS. This requires the following:

- Promote more effective use of process-level diagnostics by operational model developers**;**
- Identify opportunities to remove key deficiencies in UFS models through integrated modeling-observational studies of coupled processes and model studies focusing especially on global, regional, and local hydrological cycles;.
- Implement innovative physics packages (e.g., scale-aware convective parameterizations, sophisticated microphysics and boundary layer schemes) that directly lead to reduction in systematic errors in precipitation prediction;
- Explore new technologies for modeling, including artificial intelligence, machine learning, stochastic perturbation, global and cloud resolving models.
- Identify and experiment in a number of targeted domains to accelerate research and development.

Impacts: NOAA will at least double the rate of improvement of precipitation prediction skill in operations, improve model competencies especially for extremes of drought or flood, and improve ensemble systems to better characterize uncertainty in its forecasts.

Objective 4. Sustain, enhance, and exploit observations

Ensure that all available high-quality observations are utilized and critical observational gaps are identified and bridged. A continuum of activities using observations is required, including initializing and constraining models, deriving data products, and focusing research on testing models and improving prediction capabilities. Continuous, high-quality, scientifically sound, global-scale observations of a number of environmental variables are critical. The Precipitation Prediction Grand Challenge will identify the observations required to improve precipitation prediction and also optimize the use of existing observing systems, recognizing resource, technological, and logistical limitations.

Action 4.1 Extend observations needed to advance understanding of precipitation predictability across space and time scales, and for variables including soil moisture, sea surface temperature/salinity/density (sea-surface properties), vertical profiles of upper-ocean heat and freshwater contents, ocean turbulence, sea ice, snow cover, vegetation, air-sea fluxes, as well as the air surface and air vertical profiles of buoyancy, stability, precipitation, cloud properties, temperature, wind, and moisture content (liquid, ice, vapor). Predictions of precipitation beyond a few weeks also depend on the state of long-term oscillations in the 3-D atmosphere-ocean-land system, which involve changes in precipitation, circulation, and air-sea-land-sea ice interactions.

Action 4.2 Enhance observations needed for advancing understanding of physical processes key to precipitation prediction by exploiting new technologies (such as new satellite sensors and observation strategies, and in situ platforms) and new product development to support prediction model development and improvement.

Action 4.3 Sustain, enhance, and exploit observations for improving initial conditions for precipitation prediction by maintaining, enhancing, and innovating existing and future observational capabilities (including space and ground remote sensing, aircraft, ships, autonomous devices, coastlines, offshore platforms, moorings), and by supporting international observing efforts. The number of surface ocean, surface land, and ocean-profiling observation platforms in operation today does not cover all areas or time windows (i.e. domain and frequency of observations) needed for initializing or validating precipitation prediction models. The current network of observations requires maintenance and also support for expansion and innovations of technology in regions determined to be critical for precipitation predictability. While new remote sensing methods for observing the upper atmosphere must continue to be explored, the current atmospheric sounding observation system also needs reinvestment to meet its critical original goals. An assessment of an optimal space and surface observing architecture for the purposes of this initiative is recommended. This should also consider forthcoming geostationary hyperspectral assets which will provide more frequent and spatially continuous soundings.

Action 4.4 Expand observations needed for calibration, verification, and uncertainty quantification of precipitation prediction products and ensure that these effectively align with the requirements and needs across NOAA and with our partners. An example is satellite radiances, which require continuous calibration and validation against in situ observations, direct interpretation in geophysical terms, and assimilation into reanalysis models. NOAA should ensure that precipitation prediction skill and applications are optimized because of sufficient use of observations, which should include their transformation into Climate Data Records to ensure their long term homogeneity.

Impacts: NOAA ensures that all available high quality observations are utilized in the end-to-end precipitation prediction forecasts and their verification. NOAA tests and employs new observation capabilities in a timely manner within NOAA testbeds, including emerging technologies, to help fill gaps in observations critical to precipitation prediction.

Objective 5. Improve process-level understanding and modeling

These improvements will provide insights into the key processes that have the strongest imprint on model biases and the limits of precipitation predictability and prediction skill.

Action 5.1 Support synthesizing analysis of existing observations (in situ, remote, routine data, UxS and citizen science observations, and field experiments) to ensure that researchers and modelers effectively extract new knowledge from existing datasets to advance process understanding and modeling.

Action 5.2 Identify and fix key model deficiencies and processes that contribute the most to error growth leading to systematic biases and limited precipitation prediction skill, with particular emphasis on reformulating convective parameterizations to work across space and timescales. Other examples include large-scale dynamics versus local-scale processes, coupling of atmosphere, ocean, sea ice and land, physical processes of clouds and boundary layers, and errors in initial conditions.

Action 5.3 Conduct targeted field experiments to obtain intensive observations to better understand the key processes important to precipitation in partnership with the United States and international research communities. While a unified/integrated approach is recommended, specific objectives ought to be targeted at particular areas and lead times with broad impacts.

Action 5.4 Conduct a hierarchy of modeling-observational integrated studies spanning from large-eddy simulations, cloud-resolving models, super-parameterization approaches, and global models having a range of resolutions.

Action 5.5 Focus studies on extremes (flooding and drought on land, as well as precipitation anomalies and events over ocean) via synergistic observational, modeling studies to better understand the physical bounds on precipitation extremes, and how addressing model and observational deficiencies can most effectively improve prediction and preparedness.

Impacts: NOAA has identified and is addressing key model biases that limit precipitation forecasts. NOAA is using process-level model-observation integrated approaches to improve model representation of key processes for prediction (e.g., the diurnal cycle of convection in the tropics) and the leading patterns of variability (including blocking patterns, teleconnections, and the Madden Julian Oscillation) that influence model characterization of precipitation, especially for intense rainfall or sudden-onset drought/flood.

Objective 6. Advance understanding of precipitation predictability

These advances will address what is practically predictable and the theoretical limits of predictability. Addressing what is practicably predictable requires understanding the needs of decision makers and incorporating that understanding into Earth system predictability research.

Action 6.1 Modernize observational and modeling tools for the study of predictability. Identify, improve, and focus coordinated modeling and observations on key sources of error. Explore how observations can be included in predictability studies, and what would be the best way to conduct predictability studies using models with biases. New tools can include AI (artificial intelligence) and ML (machine learning), stochastic perturbations to the entire physical space, global cloud or cloud-resolving models permitting.

Action 6.2 Understand precipitation predictability, its sources and barriers, including dependence on time, locations and scales, and windows of opportunity (temporal high predictability). The focus will be on the sources of predictability that have the strongest influences on precipitation prediction, especially extremes.

Action 6.3 Expand the definition of predictability to be directly applicable to users. For example, include rainfall and other relevant fields critical to applications for the regions and sectors.

Impacts:

- NOAA and the broader community has a better understanding of what is practically predictable and NOAA is using that to guide planning of future investments in process studies and process modeling (Objective 4). NOAA can also set realistic targets for the expectations of researchers, product developers and end users.

- NOAA is applying improved understanding of predictability to improve our interpretation of model errors, such as ENSO false alarm rate, errors in steering flow, or regime transitions.
- NOAA has an improved understanding of the needs of decision makers and is incorporating that understanding into Earth system predictability research. Improved understanding of predictability will also improve our communication of uncertainty to stakeholders.
- NOAA has an improved understanding of the limits of precipitation predictability and is using that to reduce errors in initial conditions.

3.0 The Future

In Two Years

- {Objective 3} NOAA has developed coherent, testable hypotheses for major precipitation systematic errors in partnership with the United States and international communities, and has funded research projects to test these hypotheses and to explore productive algorithmic changes to address them.
- {Objective 1} NOAA is supporting partnerships with the decision-making community to establish precipitation predictability metrics that are of relevance to users and applications.
- {Objective 4} NOAA has supported projects that synthesize existing field observations for more effective applications to prediction model development and improvement.
- {Objective 5} NOAA is working with the broad national and international community to implement multi-disciplinary, multi-agency process studies targeting key deficiencies in forecast systems that limit precipitation prediction skill the most.
- {Objective 4} NOAA is working with the broad national and international community to identify gaps in the global observing system that contribute the most to errors in initial conditions of forecast systems which limit precipitation prediction skill.
- {Objective 3} NOAA will have implemented a global reanalysis/reforecast strategy to support the post processing of convection permitting forecasts using reforecasts and high quality multi-decadal analyses.

- {Objective 4} NOAA will have assessed the feasibility of generating high-resolution precipitation analyses over many years with its Multi-Resolution / Multi-Sensor (MRMS) system and will be prepared for product generation, in support of precipitation post processing, situational awareness, forecast validation, and more.
- {Objective 3} NOAA will have GEFSv12 reforecast-based algorithmic modifications delivered to the Meteorological Development Laboratory to provide improved precipitation forecasts in its National Blend of Models program.
- {Objective 3} NOAA supports community-based UFS coupled global modeling and will apply the Global Energy and Water Exchanges (GEWEX) coupling metrics to investigate how coupling affects precipitation prediction and related diagnostics.
- {Objective 3} NOAA supports development of the UFS regional convection-allowing-ensemble forecast system, capable of improved accuracy and forecast spread.
- {Objective 3} NOAA has invested its research resources in model-observation integrated studies to advance understanding and model improvement.
- {Objective 2} NOAA has established more robust communities of practice and communication between managers, researchers, forecasters, and stakeholders to ensure that the most pressing needs for improved precipitation forecast information are met.
- {Objective 1} New investments are driven by stakeholder needs for information and applications.
- {implicit in the others} NOAA has completed 25% of the actions proposed in this Strategy.

In Five Years

- {implicit in the others} NOAA has successfully allocated substantial resources to support activities of the Precipitation Prediction Grand Challenge.
- {Objective 1} NOAA has further strengthened robust communities of practice and hosted multiple engagements amongst managers, researchers, forecasters, and the broader community to meet the needs for improved precipitation forecast information

- {Objective 1} NOAA is leveraging robust communities of practice to guide the production and application of precipitation products and research results.
- {Objective 2} NOAA has improved products (visualization and product design) to address forecaster's and partners needs, including information on confidence and alternative scenarios.
- {Objective 3} NOAA's UFS data assimilation is able to fully capture the previously untapped information provided from cloudy/precipitating radiances.
- {Objective 4} NOAA will have extended its MRMS high-resolution precipitation analyses back as far as 2013 in support of precipitation post processing.
- {Objective 3} NOAA will have implemented algorithms for use of the GEFSv12 data in its National Blend of Models precipitation post-processing algorithm.
- {Objective 3} NOAA has reduced major systematic biases in UFS models by margins that are statistically significant.
- {Objective 4} NOAA has implemented new observational networks using advanced observing technologies in critical areas that have the highest impact on reductions in initial condition errors for precipitation prediction.
- {Objective 6} NOAA's new investments in research, observations, modeling and research to operations have led to clear advances in understanding of precipitation predictability, improvements in precipitation prediction skill in operations, and effective dissemination of prediction products to their users.
- {Objective 2} NOAA "portals" provide easy access to precipitation forecasts, products, and applications across timescales.
- {Objective 3} NOAA will have applied global ensemble reforecasts and high quality multi-decadal analyses of precipitation in producing regional to local probabilistic precipitation forecasts to inform decision making and risk management across time scales from days to 1 month.
- {Objective 4} NOAA is leveraging past and future investments to make the

underlying observations available.

- {Objective 3} NOAA has increased the rate of improvement of the skill of precipitation forecasts from 15% per decade to 30% per decade (i.e., doubled the rate of improvement per decade).
- {Objective 3} NOAA will have implemented improved convective parameterizations in its global models that provide more realistic propagation of coherent precipitation features such as the Madden-Julian Oscillation and mesoscale convective systems.
- {Objective 3} NOAA will have implemented improvements in its global and regional systems that result in improved representation of the diurnal cycle of convection, developing and dissipating in the forecast model at the same time as in precipitation analyses.
- {implicit in the others} NOAA has accomplished 50% of the actions proposed in this Strategy.

In Ten Years

- {ALL} NOAA has further increased the rate of improvement of the skill of precipitation forecasts from 30% per decade to 50% per decade (i.e., double the skill over two decades).
- {ALL} NOAA provides water resource managers, emergency management, community leaders, managers, researchers, forecasters, and the public improved robust early warnings and longer-term predictions for issues ranging from life-saving actions, such as evacuations and swift-water rescues caused by extreme precipitation events, to water resource management affected floods and droughts and supports broader decision-making applications.
- {implicit in the others} NOAA has completed 80% of the actions proposed in this Strategy.
- {ALL} NOAA's precipitation prediction is viewed as the best worldwide.

Next Steps.

The PPGC Working Group will build the partnerships both nationally and internationally across disciplines, agencies, and organizations that are needed to achieve the goals, actions and objectives recommended in this strategy (see Appendix B for a summary of the role of the community). This includes alignment of resources (both current and new) needed to organize and carry out targeted observations and process studies that lead to advances in process-level understanding and modeling, and which are prerequisites to understanding precipitation predictability limits and advancing prediction skill.

- Continue to work through the NOAA Weather, Water, and Climate Board to complete the strategy and move towards implementation.
- Adopt the Weather, Water, and Climate Board's Service Delivery Framework (Sept 2020) and use it to frame the PPGC actions in the future, in coordination with the Service Delivery entities of NOAA and our partners, outlined in the Service Delivery Implementation Plan, under construction.
- Coordinate and collaborate with interagency partners (e.g., NASA, DOE, NSF, USGS, DoD, USDA, USBR) through USGCRP to leverage capabilities and accelerate progress on the Objectives/Actions herein.
- Respecting the role and processes of NOAA's Science Advisory Board, collaborate with appropriate groups — especially the Environmental Information Services Group and the Climate Working Group — to identify opportunities for coordination in identifying broad user needs and support for decision making applications.
- Leverage the Executive Office of the President's interagency Council for Advancing Meteorological Services, and constituent committees and interagency coordination groups offices, for coordination of multi-model ensembles, physics interoperability, and model architecture to aid transitions.
- Engage with the World Meteorological Organization (WMO), including:
    - World Weather Research Program;
    - World Climate Research Program;
    - Global Climate Observing System;
    - Coordination Group for Meteorological Satellites' International Precipitation Working Group and other relevant Coordination Group for Meteorological Satellites Science Working groups;
    - Committee on Earth Observation Satellite's Precipitation Virtual Constellation;
    - Research Board on Weather, Climate, Water and the Environment; and
    - Scientific Advisory Panel.

Appendix A: Worksheet for Specific Sources of Substantial Improvement

A1. Sources of Substantial Improvement in Precipitation Prediction in the Last 20 Years (Historic)

Timescale of improvement (e.g., daily, subseasonal, seasonal, etc.)	Source of improvement (decision, observation, process, etc.)?	How was the lesson learned (observations, modeling, prediction)?	Qualitative value to precipitation prediction (low, medium, high)?
Instantaneous	GOES-R satellite era	Observations	Medium
Instantaneous	NEXRAD and Dual-Polarization Radar Observations; Multi-Radar /Multi-Sensor (MRMS) algorithms that integrate data streams from multiple radars, surface and upper air observations, lightning detection systems, satellite observations, and forecast models	Observations	High
Instantaneous - hourly	Improved rapid refresh capabilities in data assimilation, inclusion of high density, low-latency observations.	Observations and modeling	High

Instantaneous to daily	JPSS satellite era	Observations	Medium
Instantaneous, monthly, seasonal	TRMM and GPM satellite era	Observations	High
Daily, weekly, monthly	Improved physics and physical process understanding and improved physical parameterizations; Reanalysis and reforecasts to provide the training data necessary for accurate statistical postprocessing Improved methods of postprocessing. Post processing higher resolution, especially convection-allowing grids; Improving ensemble prediction systems	Observations and modeling	High
Daily, subseasonal	Product generation based on ensemble post-processing	Experimental public products transitioned into operations	High
Monthly and seasonal	GPCP data set	Observations	Medium

Monthly, seasonal and longer time scales	Improved understanding of the role of the ocean Improved coupling Increased model resolution Improved physics and physical process understanding; improved physical parameterizations; improved external forcings (GHG, aerosol) to capture trends Improved data assimilation and initial conditions Improved observations (e.g. Argo, scatterometer, ...) Improved coupled ensemble prediction systems, including multi-model ensembles (e.g. NMME) Supporting reforecast data sets spanning multiple decades.	Observations and modeling	

	Improved postprocessing methods		

A2. Sources of Substantial Improvement in Precipitation Prediction in the Next 20 Years (Foresight)

Table entries are meant to apply everywhere, not just over CONUS or over land.

Timescale of improvement (e.g., daily, subseasonal, seasonal, etc.)	Source of improvement (decision, observation, process, etc.)?	How was the lesson learned (observations, modeling, prediction)?
Instantaneous - hourly	Improved rapid refresh capabilities, inclusion of high density, low-latency observations in the data assimilation cycle.	Improved model initialization, nowcasting, very short range forecasts
Hourly to daily	Better utilize existing observations and models via focused data assimilation improvement (particularly coupled, rapid update methods)	Extend improvements from past two decades to improve model initialization, short-range forecasts
Daily	Increase resolution to convection-allowing scales (~3 km)	Extend improvements from last two decades
Daily, Subseasonal	Reformulated moist physics (convective schemes and microphysics)	Extend improvements from last two decades

Daily, subseasonal	Services based on user thresholds and generated based on ensemble post-processing	Experimental public services
Daily, Monthly, Subseasonal, Seasonal	Work with the WMO and GCOS Program at the WMO to fill in critical gaps in the global upper air network of 1300 stations resulting from missing stations particularly in the Pacific Ocean region, South America, and Africa.	Improved model initialization
Daily to medium range to sub-seasonal to seasonal	Regular production and maintenance of supporting data sets (precipitation analyses, reforecasts for production systems)	Through very positive experience with post-processing of global reforecasts for medium-range weather predictions.
Daily to medium range to sub-seasonal to seasonal	Improved post-processing methods, including machine learning.	Recent studies comparing machine learning with simpler approaches
Daily, Monthly, Seasonal	Improved boundary layer schemes from collaborative modelling/obs studies (includes boundary layer interactions such as boundary layer + radiation, boundary layer + clouds, coupled boundary layers [air-land-sea-ice])	Advance incremental improvements from more comprehensive approach
Subseasonal	Increasing observations of identified sources of predictability and their usage in initial conditions	Demonstrations of strong influences on global prediction skills by the sources of predictability, especially their accurate representations in initial conditions

Appendix B: Worksheet for the Role of the Community

Continuous engagement within the entire community is critical to the success of this grand challenge. The delineated roles in the table below are presumed to be part of an agile process for continuous integration and continuous deployment.

ORGANIZATION	PROGRAM OR SUBUNIT	ROLE
NOAA		
NESDIS	Center for Satellite Applications and Research (STAR)	• Adapt ongoing NESDIS satellite data user engagement processes and requirements to fit the emerging needs of the PPGC rather than NOAA Line Office engagement process • Directly engage the PPGC leadership to develop future observation needs that contribute to next generation satellite observing system requirements
NMFS	Science Centers and Regional Offices	Identify key needs and applications for improved precipitation forecasts
NWS	Analyze, Support, and Forecast office (AFS)	Forecast program and funding management. Manages the NWS forecast budget and staff for human-based forecasts
NWS	Climate Prediction Center (CPC)	• Operational forecasts, research on model development and testing • Generate long-term and seasonal national official forecasts of precipitation. R2O for rainfall on the sub-seasonal to seasonal scale
NWS	Environmental Modeling Center (EMC)	Develop and maintain post processing and product generation software for all NCEP environmental modeling systems. Manages NWS model products
NWS	Meteorological Development Laboratory (MDL)	Develop and maintain statistical post processing software. Manages NWS statistical post processed products, such as Model Output Statistics (MOS) and the National Blend of Models (NBM)
NWS	National Centers for Environmental Prediction (NCEP) Central Operations (NCO)	Implement, execute, and maintain NCEP models via 24x7 operations. Disseminate post processed products. Manage NWS model graphics
NWS	River Forecast Centers (RFC) /Service coordination hydrologist and others	Service side, messaging, operational flood forecasting

NWS	Science and Technology Integration office (STI)	Science and technology program and funding management. Manages the NWS modeling program and project milestones
NWS	Surface and Upper Air Observations	NEXRAD, ASOS, COOP, CoCoRAHS, other related State mesonets, and NWS Upper Air Network
NWS	Weather Forecast Offices (WFO)	Generate short-term local forecasts of precipitation
NWS	WFO/service hydrologists and others	Flash flooding, messaging, testing new products, coordinating needs and requirements
NWS	Weather Prediction Center (WPC)	● National operational forecasts, service delivery, national product development, research on model development and testing ● Specialized rainfall/rainrate post processing aligned with Partner impact thresholds. Generate official short-term national forecasts of precipitation. R2O for rainfall on the weather time-scale
OAR	Air Resources Laboratory (ARL)/Boundary Layer Research	In order to improve the predictive capabilities of NOAA's modeling suite a better understanding of the various physical processes and interactions in the PBLis needed. These processes include interactions of PBL with the earth's surface, turbulent mixing by the surface and by clouds, the formation and evolution of clouds within the PBL and into the free-troposphere, the evolution of the thermodynamic and kinematic profiles during the morning and evening transitions, and much more. Detailed observations of thermodynamic, kinematic, cloud, radiation, and surface properties are critical for characterizing the evolution of the PBL and understanding the processes at work that affect the PBL and above. Various modeling frameworks, including large-eddy simulation (LES) and single column models (SCM), can be used together with these observations to gain insight into the various processes at work in the PBL and how to represent them in the various forecast models.. Furthermore, this improved understanding must lead to more accurate model parameterizations of these processes and ultimately to improved

		hydrologic, air quality, wind and solar energy forecasts.
OAR & NESDIS	ARL (OAR) and National Centers for Environmental Information (NCEI, NESDIS) - U.S. Climate Reference Network (USCRN) Program	Leverage surface air temperature differences data (which are affected by soil moisture in the upper layers) from the U.S. Climate Reference Network, with boundary layer indices to support model parameterizations leading to better predictions of precipitation
OAR	ARL/Global Climate Observing System (GCOS)	● Work with the Global Climate Observing System (GCOS) in their efforts to fully operate and maintain 160 GCOS Upper Air Network stations and to look at addressing gaps in the other 1100 or so other global upper air network stations that do not report key upper water vapor data necessary to produce better precipitation forecast results ● Support the efforts of three U.S. GCOS Reference Upper Air Network (GRUAN), as well as water vapor measurements at the GRUAN station in Lauder, New Zealand, in order to provide high-quality climate upper tropospheric and lower stratospheric water vapor data that is a key reference parameter that can be used to assist in eventually producing better precipitation forecast results
OAR	Physical Sciences Laboratory (PSL)	● Development of global ensemble prediction systems, including production of ensemble reanalysis/reforecast data sets, and advanced methods of postprocessing. Portfolio includes collaborations with university scientists and government lab scientists to understand the basic research developments, and collaborations with NWS scientists to incorporate improvements into operational products ● Development of global ensemble prediction systems, including coupled data assimilation methods, ensemble prediction methods including the treatment of model uncertainty in ensemble predictions, and the production of supporting data sets such

		as reanalyses and reforecasts
OTHER FEDERAL ENTITIES		
Bureau of Reclamation	Reservoir operations	End-user, daily forecasts users, decisions on releases
DOD	Strategic Environmental Research and Development Program (SERDP)	Development and then application of high-resolution deterministic precipitation forecasts and downscaled probabilistic ensemble forecasts as input to forecast streamflow/flooding events impacting critical infrastructure.
DOE		Weather/climate modeling
EPA		Drinking water, wastewater, water quality
NASA		Precipitation observations from remote sensing, modeling, field campaigns
USACE	Flood control operations (dams); in-river transportation	End-user of the improved forecast, flood briefings from NWS/RFC
USDA		Forecast for producers to inform crop planning
USDA	Natural Resources Conservation Service (NRCS)	Snow Telemetry (SNOTEL) system - https://www.wcc.nrcs.usda.gov/snow/ Soil Climate Analysis Network (SCAN) - https://www.wcc.nrcs.usda.gov/scan/
USGS		Tri-agency
INTERAGENCY, INTERSTATE, INTERNATIONAL		
	USGCRP, WMO, interstate water, Western governors	Coordination, process research
NON-FEDERAL ENTITIES		
Academia		Innovative post-processing approaches - such as Machine Learning. Engaged via NOAA testbeds

Academia	Climate modelers	Advertise role of end-users, remind their communities on why PPGC is working on this, CPC workshops, incorporation of observations
Academia	Geographers, natural resource scientists	Secondary impact assessment, on animals, diff species, habitats
Academia	Meteorologists	Testing experimental products, helping ID needs from their community, convey messages, understanding the impact of the decision, or the confidence in the prediction
Academia	Oceanographic modelers	Precipitation is the result of air-sea interaction and ocean processes, precipitation is also an important force acting on the ocean in terms of freshening, stabilizing, and cooling. This structures the ocean heat content, freshwater content, momentum, and coupled earth-system processes that feedback to the atmosphere. This happens in the upper ocean and also deep ocean. Advances in ocean modeling will advance precipitation modeling, and advances in precipitation modeling will lead to advances in ocean modeling, and therefore coupled earth-system modeling in general.
Academia	Social scientists	Perception, risk, behaviors
Private Sector		Innovative post-processing approaches - such as Machine Learning. Engaged via NOAA testbeds.
Private Sector		Value-added products, after initial output-- sector-specific applications, visualizations
Private Sector	Insurance	Annual rate setting on precip forecasts, risk assessment, flood potential, hail, property reimbursement based on t-storm tracks, precip form (e.g. hail) and damage
Private Sector	Public/private partnerships	Mesonet obs on trucks and cars, obs where there aren't obs, sensored vehicles
Private Sector	Sector- specific decision-supporters	Transportation and road salt, forecast applications-- precip amount and form
Private Sector	Software/App developers	Transforming complex model output and PPGC output to digestible info for the public, Internet of Things

Private Sector	Visualization companies	Sector-specific value-added visuals, GIS overlays for asset management, real-time info and long-term scenarios
Private Sector	Water utilities	End-user, impact submissions, obs of precip and runoff to supplement obs
States		End-users, water managers, state hydrologists
States	Drought task forces	Monitor drought, set state level declarations and restrictions
States	Emergency management	Flood forecasts, evacuations
States	Environmental managers (DEP, DEM)	species and habitat management
States	Local governments	End-users, decisions on local water supply
States	Public health departments	Water quality, end-user
States	State hydrologists	Messaging, media, info distribution
States	Water control board	End-user of flood forecasts, releases for drinking water, turbidity issues
States	Wildfire management	Allocation of resources, prescribed burns
Other	Citizen science	Improving observations, feedback on experimental products
Other	Indigenous communities	Traditional ecological knowledge, impact observations and reporting,
Other	International	Lessons learned across borders, info exchange, best practices
Other	Professional Organizations (AMS, etc.)	Convening multiple sectors, exchanging info on end-user needs, case studies by geography and use of information

Appendix C: Methodology

In November 2019, the Weather, Water, and Climate Board convened the cross-Line Office Precipitation Prediction Grand Challenge Working Group and charged the members with developing NOAA's strategy for accelerating improvements to global models that will lead to increases in precipitation prediction skill and that will translate these improvements into more effective decision support. The Working Group was co-chaired by Wayne Higgins (as chair of the NOAA Climate Team), John Murphy (as chair of the NOAA Weather Team), and Tom Graziano (as chair of the NOAA Water Team).

The Working Group began meeting in December 2019, with an initial mandate to write the detailed outline. Based on that outline, six writing teams were identified (see Appendix D for writing team membership):

- **User Needs.** Identifying the tools, data, and information required by decision makers under changing environmental conditions.
- **Model Limitations.** Identifying the current model limitations and prioritizing the systematic errors in the models that should be addressed first
- **Research Questions.** Identifying and prioritizing the focused research questions that need to be addressed
- **Transitions.** Articulating how to accelerate R2O2R [research-to-operations-to-research]
- **Observations.** Identifying current observation systems that could be better leveraged and those that need to be implemented
- **Post Processing.** Identifying post-processing approaches to ensure that model output is transformed into actionable decision support services

The writing teams reported on progress and sticking points at the bi-monthly Working Group meetings that were held from January through July 2020 and each writing team developed a stand-alone paper on their topic:

- User Needs
- Model Limitations
- Research Questions
- Transitions
- Observations
- Post Processing

Based on these writing team drafts, the Working Group agreed to develop a Strategy with the following structure:

- **Objectives.** The Objectives that would inform each of these Actions.
- **Actions.** The Actions that the PPGC Working Group recommends as the best path forward for meeting its goal of accelerating improvements to global models that will lead to increases in precipitation prediction skill and that will translate these improvements into more effective decision support. The Actions identified by the Research Questions Team served as the starting point.
- **Impacts.** The beneficial Impacts to the nation of taking these Actions.

The Working Group conducted a Workshop on June 15-16, 2020 to ensure alignment on the contents across the full membership. Additionally, the Weather, Water, and Climate Board received updates on the progress of the Working Group throughout the process, with a special Board meeting dedicated to reviewing and discussing the Strategy in its entirety on June 18, 2020. The Working Group finalized the original draft in July 2020.

Appendix D: Membership

NAME	AGENCY OR NOAA LINE OFFICE	WRITING TEAM
Trevor Alcott	OAR	Team 6: Post-processing
Monique Baskin	OAR	Team 1: User Needs Team 3: Research Questions
Stan Benjamin	OAR	Team 2 Model Limitations
Lisa Bengtsson	OAR	Team 2 Model Limitations
Brooke Bingaman	NWS	Member
DaNa Carlis	OAR	Team 4: R2O2S
Jessie Carman	OAR	Team 2 Model Limitations Team 3: Research Questions Team 4: R2O2S
Adam Clark	OAR	Team 2: Model Limitations
Shanna Combley	NWS	Team 3: Research Questions Team 4: R2O2S
Tom Delworth	OAR	Member
David DeWitt	NWS	Team 2: Model Limitations Team 3: Research Questions
Howard Diamond	OAR	Team 5: Observations
Juliana Dias	OAR	
Ralph Ferraro	NESDIS	Team 5: Observations
Gary Geernaert	DOE	Members
J.J. Gourley	OAR	Team 5: Observations
Thomas Graziano	NWS	Co-lead
Roger Griffis	NMFS	Team 1: User Needs
Tom Hamill	OAR	Team 6: Post-processing
Katherine Hawley	NESDIS	Team 1: User Needs
Wayne Higgins	OAR	Co-lead
Jin Huang	OAR	Team 2 Model Limitations Team 3: Research Questions
Margaret Hurwitz	NWS	Team 1: User Needs Team 3: Research Questions

Renu Joseph	DOE	Team 3: Research Questions
Jack Kaye	NASA	Member
Young-Joon Kim	NWS	Team 4: R2O2S
Mark Klein	NWS	
Dorothy Koch	NWS	Team 3: Research Questions
Chandra Kondragunta	OAR	Team 4: R2O2S
Michael Kuperberg	USGCRP	Member
Jason Levit	NWS	Team 6: Post-processing
Sandy Lucas	OAR	Team 3: Research Questions
Kelly Mahoney	OAR	Team 3: Research Questions
Nate Mantua	NMFS	Team 1: User Needs
David McCarren	ESPC	Team 4: R2O2S
Ellen Mecray	NESDIS	Team 1: User Needs
Tilden Meyers	OAR	Team 5: Observations
John Murphy	NWS	Co-lead
Meredith Muth	OAR	Team 1: User Needs
James A. Nelson	NWS	
David Novak	NWS	Team 2 Model Limitations Team 6: Post-processing
Sarah Perfater	NWS	Team 4: R2O2S
V Ramaswamy	OAR	Member
Andrea Ray	OAR	Team 1: User Needs
Russell Schneider	NWS	Member
Gail Skofronick Jackson	NASA	Team 5: Observations
Cheyenne Stienbarger	OAR	Team 5: Observations
Elizabeth Thompson	OAR	Team 5: Observations
Sidney Thurston	OAR	Team 5: Observations
Danielle Tillman	OAR	Team 4: R2O2S
Robert Webb	OAR	Team 3: Research Questions Team 4: R2O2S Team 6: Post-processing
Ernie Wells	NWS	Team 1: User Needs Team 2 Model Limitations Team 3: Research Questions
Kevin Werner	NMFS	Team 1: User Needs

Andrew Wittenberg	OAR	Team 2: Model Limitations
Chidong Zhang	OAR	Team 2: Model Limitations Team 3: Research Questions Team 5: Observations
Ming Zhao	OAR	Team 2: Model Limitations

■ Writing Team Lead

Appendix E: Version Control (in reverse chronological order)

VERSION	NUMBER	DATE
NOAA Weather, Water, and Climate Board concurrence version	V.3	October 30, 2020
Review draft	V.2	September 14, 2020
Review draft	V.1	July 23, 2020
Original draft	V.0	May 18, 2020

WEATHER, WATER, AND CLIMATE BOARD