Building an Interannual to Decadal Prediction and Projection Capability for Decision Support

NOAA Center for Weather and Climate Prediction (NCWCP)
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Executive Summary

Background

Changes in climate, demography, technology, and subsequent environmental, economic, and geopolitical responses are driving efforts to modernize long-term planning strategies. Moving forward, extended range Earth system predictions/projections[1] will be incorporated into strategic decisions over the 2 to 30-year time range in order to mitigate cost and vulnerability of national security, economic vitality, infrastructure, and natural resources.

Users are proactively seeking guidance to inform multimillion dollar decisions with long-term scope. Under present conditions, there is considerable risk of misuse, misunderstanding, or inappropriate use of the information found. Limited resources do not permit any individual agency to address these issues comprehensively, nor do all the decisions fall within any one agency's individual mission. However, the commonality of the physical problem creates an opportunity to pursue a coordinated capability across agencies for building a more unified response for decadal prediction decision support, rather than ad hoc reactions representing short-term, potentially divergent, or resource-expensive solutions.

This exploratory workshop is a preliminary discussion of the need for coordinated updating of physical Earth system predictions to support a wide range of long-term decisions drawing on multi-agency expertise and existing or emerging capabilities. The workshop focused on the challenges of providing and maintaining an updating, but non-operational capability, including the potential dual use of ongoing research efforts supporting coordinated capability/knowledge improvement as well as informing decision support. Discussions emphasized collaborative efforts to create a path forward and facilitate interagency efficiency.

The workshop served as a foundation for continuing information exchange leading to a unified, reliable, and actionable prediction capability, and built on the prior work of agencies involved in the U.S. Global Change Research Program (USGCRP)[2] and the U.S. Climate Variability and Predictability program (USCLIVAR)[3]. Attendance consisted primarily of representatives from all

[1] There are important differences between climate predictions and climate projections. A *climate projection* is a climate simulation extending into the future that is based on a *scenario* of possible future external forcing (e.g., volcanic eruptions, anthropogenic atmospheric changes to atmospheric composition, and land use changes, among others). These external forcings are also called *boundary conditions* or *boundary forcing*. A *climate prediction* or *climate forecast* is a statement about the future evolution of the climate system, and can encompass both internally generated (e.g. naturally occurring processes and interactions within the climate system, such as ENSO, PDO, etc.) and externally forced components. *Decadal climate predictions* lie in the interface between seasonal to interannual predictions (initial value problems) and long-term climate projections (boundary condition problems). See Fig. 1, p. 2.

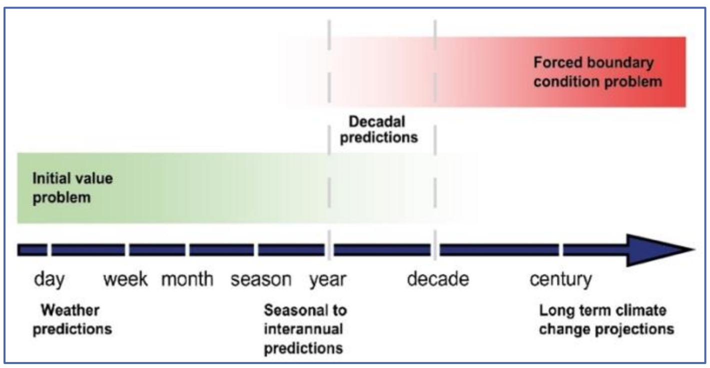
[2] Department of Agriculture; Department of Commerce; Department of Defense; Department of Energy; Department of Health and Human Services; Department of the Interior; Department of State; Department of Transportation; Environmental Protection Agency; National Aeronautics and Space Administration; National Science Foundation; Smithsonian Institution; U.S. Agency for International Development.

[3] The US CLIVAR Inter-Agency Group (IAG) includes program managers from the National Aeronautics and Space Administration (NASA), the National Science Foundation (NSF), the National Oceanic and Atmospheric Administration (NOAA), the Department

Federal agencies participating in the Federal Committee for Meteorological Services and Supporting Research (FCMSSR), providing long-range predictions/projections, and using or potentially using long-range predictions/projections of the Earth system in their decision support.

The workshop was organized to inform participants of identified *user needs*; provide overviews of *present capability and research efforts*; fully understand the *complexities and challenges surrounding decadal prediction*; understand the range of *emerging capabilities and research efforts;* and begin to develop an initial unified US strategy for *fulfilling user needs*. In each of these main categories of information, presenters outlined the scope of their work, and responded to questions from the participants.

The discussions identified key challenges and possible initial steps towards cross-agency coordination for interannual to decadal prediction (2-30 years). Discussions identified primary challenges and categories of need, and suggested avenues, mechanisms, or best approaches to achieving a framework for a unified decadal prediction capability going forward.



Schematic illustrating the progression from an initial-value based prediction at short time scales to the forced boundary-value problem of climate projection at long time scales. Decadal prediction occupies the middle ground between the two.

Challenges

- A primary challenge to building an interannual[4] to decadal capability for decision support is the *lack of mission and mandate for operational (or experimental) predictions or projections on this time-scale*. There is no mandate in the U.S. to provide for this kind of "climate service." While there are existing efforts focused on subseasonal to seasonal (S2S) and multi-year projection, these efforts generally have mandated operational capabilities and experimental frameworks—the interannual to decadal timescale does

of Energy (DOE), and the Office of Naval Research (ONR). Additional partners include the U.S. Global Change Research Program (USGCRP); U.S. Carbon Cycle Science Program; U.S. Carbon and Biogeochemistry Program (OCB); Study of Environmental Arctic Change (SEARCH); and International CLIVAR.

4 *Interannual* refers to something measured or evaluated on a yearly basis or from one year to the next.

not currently have a similar framework. This emphasizes the need for improved and sustained coordination among agencies.

- Delivery of a useful, regularly updated, reliable decadal product with contributions from both the research and operational communities will require redefining our concept of "operational." National ESPC has been encouraging the community to move toward more integration between the research community and the operational community, with measurable progress over the past few years. Decadal prediction (2 to 30 years) not only requires significantly more integration between these communities, the workshop clearly demonstrated that it also requires inclusion of the private sector and the user community in order to be successful.
- Because the interannual to decadal (I2D) timescale lies in a transition zone between subseasonal to seasonal (S2S) prediction on one end of the scale, and climate assessments on the other, there are open questions concerning the predictability of commonly requested variables such as precipitation, sea-surface temperature, and land temperatures, and understanding of the physical processes that control or impact these variables (e.g. sunspots, volcanic eruptions); and their interactions with the global climate system must be ultimately included in global climate models. This modeling and research challenge necessitates advances in high performance computing (HPC) resources.
- There is existing diversity in the current configurations of operational systems for long-range forecasting across different centers. Additional issues and factors that surround the advance of operational infrastructure include design configuration factors of operational prediction systems; development of products and communication of probabilistic outlooks; and variation of forecasts based on sample sizes and skill variation.
- Potential future observations needed or to be assessed for improving decadal prediction include: sea ice thickness; permafrost; soil moisture; methane; deep Argo[5] floats.
- Agency and organizational partnerships, and effective methodologies on how to encourage and nurture them with open lines of communication are critical to understanding and meeting the needs of users.
- Communications challenges exist with users and with climate data and decision-makers. Determining how feasibility and user needs discussions should occur between researchers, developers, and end-users is needed, focusing on what is predictable.

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[5] Argo is an international program deploying a global array (up to 3000) of free drifting profiling floats, distributed over the global oceans, that measure the temperature and salinity in the upper 2,000m of the ocean, providing 100,000 T/S profiles and reference velocity measurements per year. The first Argo floats were deployed in late 1999.

Needs

- *Effective coordination* of such an expansive national cross-agency effort for decadal prediction, assessment of capabilities, and coordination with the international community.
- Mechanisms for sustained *user engagement* and *input into climate community development* of decadal prediction.
- Identification of key *initial steps* to build and sustain the effort.

Coordination

In discussions on how best to coordinate and collaborate in developing a decadal prediction endeavor, the following organizations were deemed to be primary resources to leverage, as existing cross-agency organizations and initiatives.

1. National ESPC - Earth System Prediction Capability is a cross-agency collaboration across federally sponsored (NOAA, DOD, NASA, DOE, NSF) environmental research and operational Earth system prediction communities, and sponsor of this workshop for exploring issues related to decadal prediction.
2. The U.S. Global Change Research Program (USGCRP) offers both expertise and existing networks of communication and collaboration to utilize as the producer of the Fourth National Climate Assessment report (2018).
3. The World Meteorological Organization (WMO) progress in decadal prediction and products, including user interactions, can be leveraged. WMO programs might include the S2S (Subseasonal to Seasonal) Prediction Project; the Working Group on Subseasonal to Interdecadal Prediction (WGSIP); the Working Group on Coupled Modeling (WGCM); the World Climate Research Program (WCRP) Coupled Model Intercomparison Project (CMIP); and the WMO Near-Term Climate Prediction (NTCP) project. Utilize WMO networks of communication and dissemination as options.
4. The Office of the Federal Coordinator for Meteorology (OFCM) and its Committee for Climate Services Coordination are responsible for continuing coordination of current climate-related services provided by Federal agencies to national, regional, and local levels two weeks and beyond; and for identifying cross-cutting issues. OFCM's Interagency Weather Research Coordination Committee (IWRCC) will also be a resource, as it coordinates basic and applied U.S. research activities aimed at better fundamental understanding and improved prediction of high impact weather with a potential for future socioeconomic and environmental benefits.
5. National Oceanic and Atmospheric Administration (NOAA) offices include the Climate Program Office (CPO), including the Regional Integrated Sciences and Assessments Program (RISA); the National Integrated Drought Information System (NIDIS); and the NOAA Climate Prediction Center (CPC).

6. The North American Multi-Model Ensemble (NMME) project of the National Centers for Environmental Information (NCEI) is a large network of climate science, prediction, and modeling expertise that may be utilized as collaboration and dissemination of decadal prediction communications.
7. U.S. Department of Agriculture (USDA) Regional Climate Hubs focus on risk adaptation and mitigation, in addition to state Climatological Offices; these entities can provide key input on user groups and needs.
8. Utilize regional and state capabilities while pursuing the national effort. Engaging with these levels of effort can increase both interest, participation, and advocacy.

User Engagement

During the workshop it became clear that many in the research community (both federal and academic) had not necessarily met with various user communities and were not accustomed to each other's needs or concerns. This workshop, then, became an initial, non-comprehensive forum for those discussions and will require amplifying follow-up.

User impacts in presentations and discussions appeared to be focused on drought/flood and other forms of severe weather considered to be seasonal to subseasonal (S2S) phenomena. The value of improving both I2D and S2S prediction will be to allow users to make infrastructure investments to improve planning processes and conduct mitigation to avert various S2S crises, e.g. installing drainage systems; changing crops (and, therefore, required equipment); altering facility design to accommodate expected water levels, and more.

Discussions emphasized the need to involve users from the outset in coordinating a decadal prediction capability. Fully understanding the range and scope of user needs will be necessary to inform technical development and modeling capability, and is a paramount consideration. Involving social scientists would be beneficial to engage users. The private sector role in grooming answers for different user needs and in providing input into climate community development of decadal prediction should be defined.

Specific recommendations included leveraging the following existing organizations to establish mechanisms for sustained user engagement and feedback on decadal prediction and/or user needs:

1. An interannual to decadal case study or pilot program involving a key user group, such as agriculture, and determination of the needs of this sector, compared to 1 to 5 year current capabilities, was proposed.
2. An ombudsman of climate data, or a skilled translator of climate data with the ability to explain climate

> *"How services will be delivered and engagement with users achieved has been much discussed—it will likely be a range of answers, with a complex landscape going forward. But we must make the connections with a range of user communities to be sure the climate-relevant decision points are factored in to our research agenda. Break down the problem to manageable sectors. Start with a sector, a region of the country, various services."*
>
> *Workshop participant (panel discussion)*

prediction phenomena to varied audiences, as well as to the needs of researchers and agencies, was suggested as a key component.

3. USGCRP: Fourth National Climate Assessment report. The NCA4, as well as NOAA's Climate.gov website, can serve as initial resources to recommend to users, whether organizational or individual.

4. Organize and convene Town Hall sessions at the December 2019 American Geophysical Union (AGU) annual meeting and the January 2020 American Meteorological Society (AMS) annual meeting to inform and engage with various user communities.

5. Utilize National ESPC/USGCRP agency-to-user interactions as forms of user engagement.

Initial Steps and Key Actions

1. Arrange a meeting with the Office of the Federal Coordinator for Meteorology (OFCM) and its Committee for Climate Services Coordination (CCSC) for collaboration on decadal prediction/projection; provide them a copy of this report; specifically discuss access and use of the CCSC database of existing cross-agency capabilities and services as a starting point for assessing current climate services capabilities and how they can meet the needs of users.

2. Engage in discussions with USGCRP to leverage their expertise and experience in strategies utilized for the NCA4 report, particularly in user engagement mechanisms and agency networks that have "trickle-down power," as well as cross-agency facilitation.

3. Convene future events or workshop(s) to explore in greater depth how feasibility (what is predictable) and user needs discussions should or could occur between researchers, developers, and end-users.

4. Convene future workshops or other mechanisms to identify the following expected additional goals for decadal prediction capability:

   a. Identify user data, product needs, and decision needs.
   b. Identify current agency sources and decision-support capabilities
   c. Determine/scope gaps between current capabilities and needs.
   d. Establish recommendations for methods, frequency, reliability, and implementation of a decadal prediction capability.

End Executive Summary

Day 1

Opening Session – Welcome and Purpose

Jessie Carman – National Earth System Prediction Capability (ESPC) NOAA Coordinator and National ESPC Associate Project Manager for Research

Michael Bonadonna – Office of the Federal Coordinator for Meteorology (OFCM)

Carman and Bonadonna provided opening remarks regarding the National ESPC and OFCM multi-agency responsibility for coordinating prediction across the wide array of interest sectors: aviation planning; emergency management; agriculture; energy, water resources; defense; maritime planning, and more. The increasing interest in and trend toward better understanding for longer time-scale planning and impacts is illustrated in *Figure 1: Forecast Lead Time/Decision Timescale.* While progress and success have been gained on short-range planning and forecasting, much remains to be done on decadal forecasting ability. Yet, long-timescale decisions are currently being made across many sectors, emphasizing the need for coordinated approaches and actionable suggestions on how best to move forward. Sectoral effects are evident in emergency management; evacuation planning; and humanitarian assistance; management of future markets; DoD deployments, Arctic access, and implementation of climate-driven and situational awareness training for forecasters.

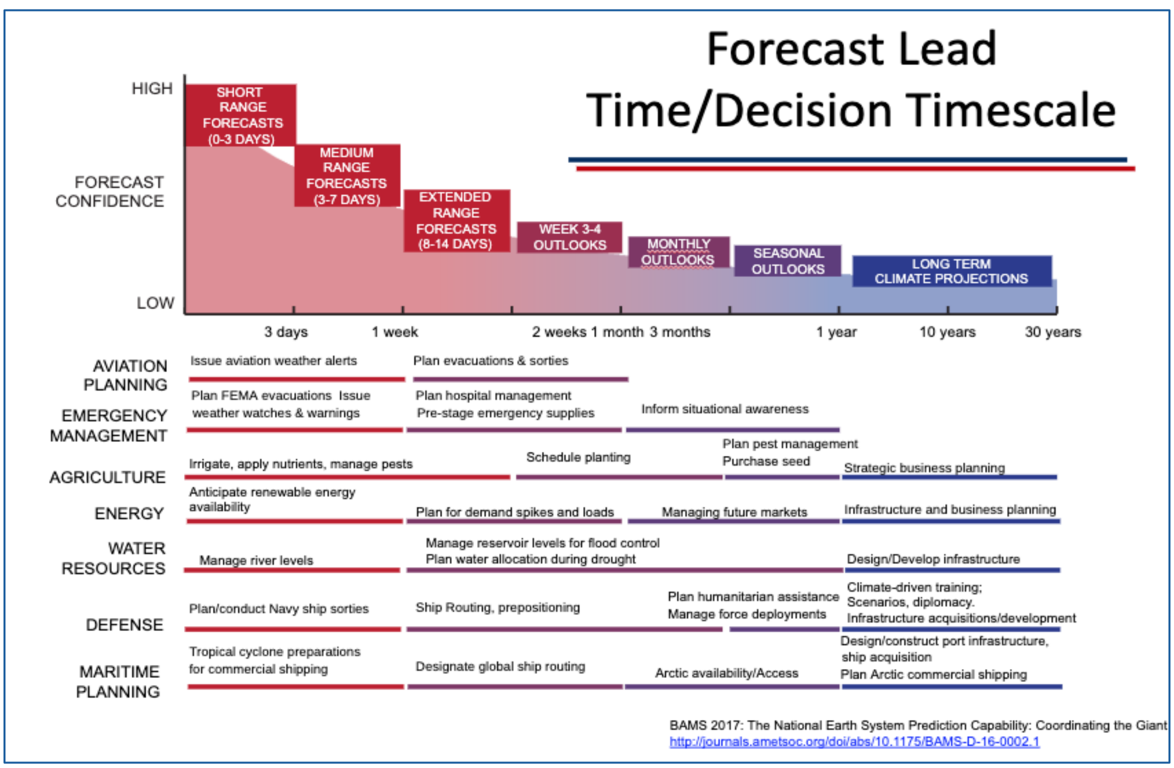

Figure 2: Bonadonna: Forecast Lead Time/Decision Timescale

This workshop gathers experts to assess current status in extended range prediction capabilities; surface decision points not already known; and to identify action points for OFCM tracking. Issues include effective use of ensemble modeling (oceanographic, cryosphere, atmosphere); and the execution of those models in operations. An *exascale* level of computing capability (a billion billion calculations per second) may open up possibilities for long-range prediction/projection.

Scott Sandgathe – University of Washington Applied Physics Laboratory

Sandgathe provided an overview of relevant National Academy of Science (NAS) reports and studies on decadal prediction issued over a 40 year period, from 1975-2016. Early 70s reports considered decadal prediction to be roughly 2-70 years and strongly suggested decadal prediction was necessary to address pending resource shortages. A 1998 report on *Decade-to-Century Climate Variability and Change*, for which the U.S Climate Variability and Predictability Program (US CLIVAR) played a role, was the first to assess anthropogenic change.

From 2000 on, reports emphasize the need to provide user feedback into the development process to create effective information for decision makers across multiple sectors. From 2010 on, the emphasis is on collaboration to achieve better mechanistic understanding and improve capability. In 2016, a report on subseasonal to seasonal (S2S) forecasting noted that achieving comparable 36 hour forecast skill at 72 hours required approximately 15 years and an additional 15 years to achieve that skill at five days. Incremental improvement is essential to predictability capability.

Conclusions from the survey of all reports include:

- There are clear climate variations/signals on 2 to 70 year time scales.
- Not all signals or interactions are completely understood, but we need to move forward incrementally to achieve progress.
- Involvement of researchers, developers, operations, and users in the process is essential. User trust builds from having a clear understanding of the information provided.

Question and Answer (Q&A)

1. Are longer time scales in modeling likely to include forcings from seasonal to annual/internannual?
2. Is more study needed around large-scale oscillations and features, e.g. phenomena in the Southern hemisphere that are completely different from the Northern hemisphere. How do cross-equatorial processes play in?

Sandgathe responded that our understanding of which processes have effects on the longer term is incomplete. Models can include some phenomena, but not all; we can get the right answer for the wrong reason and not know it. Reports examined never identified prioritization of processes, in the sense of prioritizing particular areas of study or additional research. He also noted that reports identified a critical need for high performance computing to achieve successful decadal prediction.

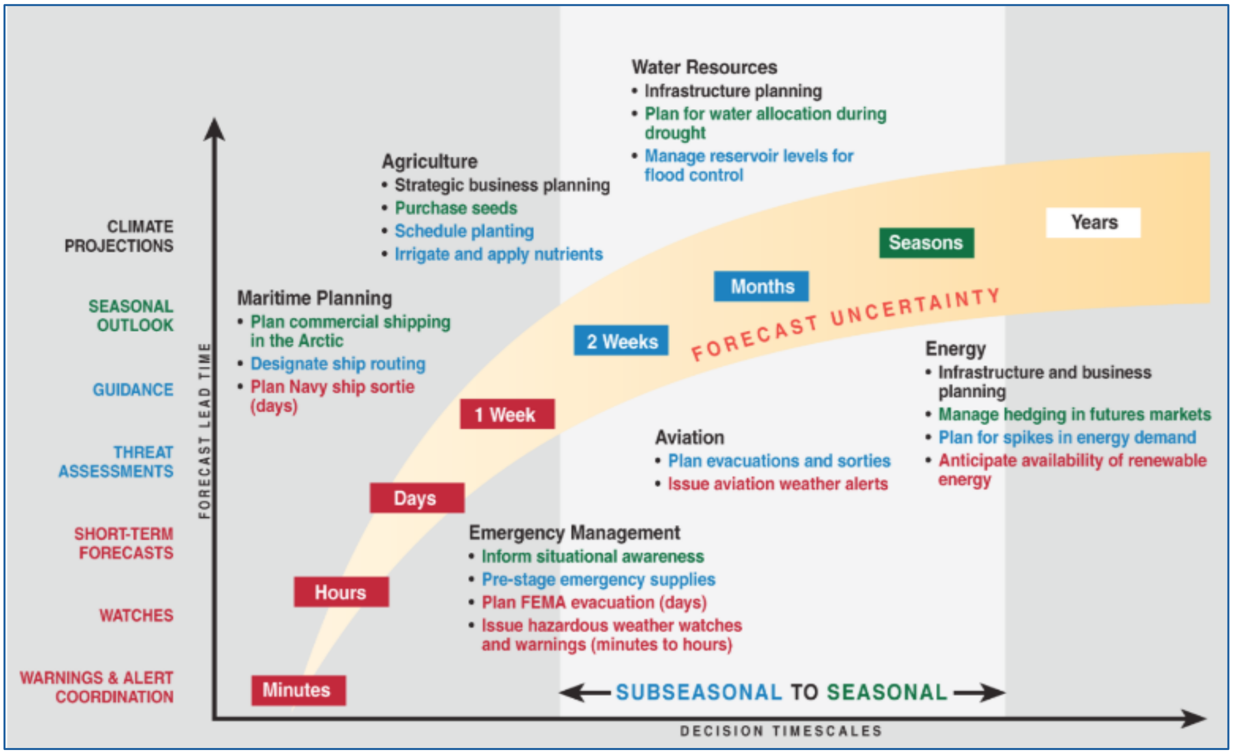

Figure 3 Sandgathe: S2S forecasts, sectors, and timescale
(Modified by National Earth System Prediction)

Figure 3 provides a representation of forecast impacts: S2S forecasts (shown in blue and green) fill a gap between short-term weather and ocean forecasts (shown in red) and longer-term Earth system projections (shown in black). Critical decisions across many different sectors (blue and green) are informed by S2S forecasts since they give information about likely conditions in between more established prediction times.

User Needs

Fernando Echavarria – U.S. Dept. of State

Echavarria provided an informative overview of how the U.S. Dept. of State's Bureau of Oceans and International Environmental & Scientific Affairs (OES) contributes to and enhances scientific research and observational capability as part of its overall mission to *advance America's security and prosperity through international leadership on oceans, environment, science, space, and health.* He appreciates the opportunity to build bridges between federal agencies and welcomes consideration and exploration of how and where international linkages can serve U.S. agency goals.

Examples of pay-off in diplomacy efforts:

- 2015 Euro Commission – lead and fund Galileo (Euro GNSS); Copernicus – 17 terabytes of data; technical collaboration.
- Share with State, if you can identify new uses of Copernicus[6] observations (free, full, and open data policy).
- Land, oceans, climate, emergency management services – provide information products to managers/decision-makers to augment what other agencies are already providing.
- Strengthening Disaster Risk Reduction Across Americas – a 2017 regional summit on contributions of Earth observations. 400 participants from 20 countries.
- Regional environmental hubs emerged and utilized.

Within its strategic goal of advancing American space leadership, OES promotes and supports: *enhanced civil use of space for science, Earth observation, civil positioning, navigation, and timing, and other space-based applications* by pursuing bilateral and multilateral engagements to enable space science and exploration, resilient space services, and burden sharing. The Earth has had 17+ continuous years of space presence via the International Space Station (ISS) since Nov 2000. 107 nations are parties to the Outer Space Treaty, developed in 1967 and updated regularly since. Space-based satellite operations have increased 49% since 2013: entities from 62 countries operate 1738 satellites; almost half of which (803) are operated by the U.S. There are a dozen existing venues and agreement vehicles that can complement the work of U.S. agencies in advancing climate science and observational goals. The US - EU Cooperation Arrangement on Copernicus Earth Observation Data formalizes collaboration between experts from NASA, NOAA, the U.S. Geological Survey (USGS), the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT), and the European Space Agency (ESA) to realize the full value of Earth observation satellites for research and operations. He encouraged sharing further with State if you can identify new uses of Copernicus observations (free, full, and open data policy). Echavarria encouraged the utilization of OES in support of expanding international cooperation, and improving space-based Earth and solar observation**,** especially in monitoring/remote sensing. He would welcome further partnerships and collaboration in decadal prediction and/or other coordinating efforts.

Q&A

- Have there been any discussions about aerosols within the negotiations for treaties and agreements? *Response:* This topic likely falls under the Office of Climate Change and/or space-based applications under international processes. He is happy to explore with National ESPC the proper expertise at State to clarify that issue, as well as any others.

Hendrik Tolman – National Weather Service, NOAA

Tolman is the Senior Advisor for the Advanced Modeling System in the Office of Science and Technology Integration (STI). NWS interests and responsibilities in longer time scale predictability range from:

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[6] Copernicus is the European Union's Earth Observation Programme

- *Seasonal to subseasonal (S2S) scale* products that include provision of precipitation and temperature products from the Climate Prediction Center (CPC); the Global Ensemble Forecast System (GEFS) provided by the Environmental Modeling Center (EMC) (up to 35 days), and the Subseasonal Prediction Experiment (SubX).
- *Seasonal scale* interests include the Climate Prediction Center (CPC) seasonal outlooks and the EMC Climate Forecast System (CFS) model 9-month projection.
- NWS maintains additional responsibilities for an *up to 2-year outlook,* currently.

Improvements and systematic streamlining of all NOAA Production Suite products is an ongoing priority building toward a Unified Forecast System (UFS): a community-based, coupled, comprehensive weather and climate modeling system for operations and research. Dedicated funding leverages existing efforts and a recent agreement between the National Center for Atmospheric Research (NCAR) and NOAA for research and operational infrastructure includes unification of inter- and intra-component coupling; common workflow development; unified testing and model validation; GitHub-based repositories[7]; and modeling support, in the UFS. Dedicated hurricane supplemental funding is also a part of the overall picture moving forward.

Tolman noted that users need certain forecasts at certain data-update cadences (specifically scheduled delivery times or repeat cycles). Past practice has evolved into a "quilt" of implemented solutions in various areas as opposed to systematically addressing requirements. The streamlining of the NOAA Production Suite remedies this, while gaining a better understanding of user needs and communication of forecast accuracy and efficacy. NOAA is moving strongly toward the community modeling concept as evidenced in the projected *Earth Prediction Innovation Center (EPIC)*—a virtual center made possible by recent reauthorization of the Weather and Research Forecasting Innovation Act of 2017, that instructs NOAA to *establish EPIC to accelerate community-developed scientific technological enhancements into operational applications for numerical weather prediction* (NWP). The proposed center will enable the research community to develop new and emerging model technology for transition to forecast operations; and will enable availability of new operational Earth system models to the research community. Use of Multi-Model Ensembles (MMEs) will diminish in the transition to the community-based Unified Forecast System; and be utilized as a tool of opportunity as appropriate. Tolman noted in the following Q&A session that currently NWS is only required to serve its partners out to two years; core partners for NWS are the National ESPC partners.

Mark Brusberg – U.S. Department of Agriculture (USDA)

Brusberg summarized the range of effects on the agricultural sector by seasonal variations in weather, and how these affect a complex range of decisions:

- Precipitation: seasonal accumulation (excess/deficit); frequency; timeliness. Frequency vs. timeliness of rainfall helps with mitigation strategies. If/when insurance doesn't

[7] GitHub is a hosting service and software development version control system and repository, enabling tracking of changes in source code during software development. It provides access control and collaborative features.

handle losses incurred, the community wants to make decisions that helps mitigate problems.

- Temperature: accumulated heating units; heat stress; freezes; seasonal length is important (time between last spring freeze/first of autumn). Statewide temperatures on yearly basis show much above normal and record warm temperatures.
- Potentially damaging extreme events: flash flooding; hail; high winds; lightning (forest fires). Frequency and disease vector progression.
- Potential hazards resulting from weather include disease and insects; over the long-term, overwintering of pests in soil can occur and migration patterns are affected.

USDA adapts and creates weather assessments in partnership with the NWS Climate Prediction Center for its community, including Fire Weather; Western Water Supply Forecasting; Global Monitoring and Assessment; Ground Truth for Remote Sensing; Research, and Crop Insurance Programs publications. These products educate, inform, and explain complex problems within the agricultural community. USDA also produces products to inform about the benefits of improved weather prediction capabilities around seasonal forecasting and frequency of dependable forecasts. USDA conducts frequent outreach to the agricultural community via its ten regional climate hubs, holding regional and state information sessions and forecast outlooks and utilizing agricultural extension services resources.

> *"We need to give users information they can trust and this takes communication and partnerships."*
>
> *Mark Brusberg – U.S. Dept of Agriculture*

USDA issues regular weather assessment advisories on likely impacts of weather to assist the agricultural community at difficult decision points, including daily U.S Agricultural Weather Highlights; Weekly Weather and Crop Bulletin and weekly International Weather and Crop Highlights; monthly International Weather and Crop Highlights; and Major World Crop Areas and Climatic Profiles (periodic updates). Impacts can include:

- Freezes – affect wheat growth; apple and other fruit tree blooms; home gardens and landscaping.
- Cold and Rain – affect corn planting and seed germination; livestock health, especially calves; soil compaction and nutrient loss; inaccessible fields.
- Soil impacts: *temperature* – continuous cold, wet soil and cloud cover keep soils very cool; *moisture* – flooded fields/slow field access; contribute to nutrient loss; increased crop disease issues; impact root growth; *risk:* likely delay in additional planting; heaviest rain expected southern/eastern corn belt; most plains and Midwest.
- Crop impacts – detail which crops are most likely affected by freezing conditions and cold conditions.
- Livestock impacts – cold, rain, wind, and snow accumulations all negatively affect young livestock, requiring monitoring.

Brusberg encouraged participants to reach out to him in the future for collaboration and planning, and encouraged further discussion about forecasting collaboration opportunities for improvement in service to the agricultural community over longer timescales. Users want to avoid future risk; forecast improvement for periods several years out can help them to better plan for lowering risk by implementing infrastructure changes; changes in crops, and other strategies.

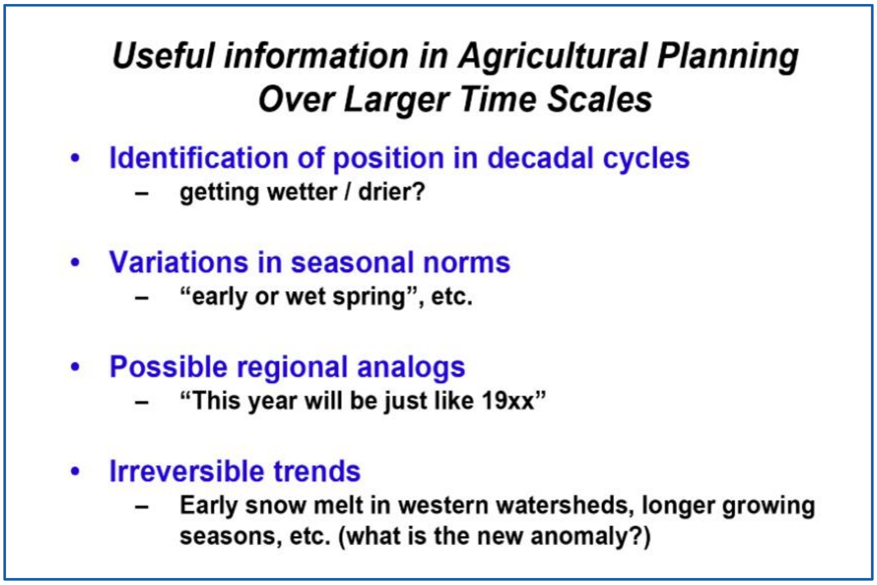


Fig. 4 Brusberg: USDA – Agricultural Planning

Q&A

- From your experience what types of uses for this industry would be helpful on a 5-to-10 year scale? *Response:* one opportunity would be if we could know if it is getting wetter or dryer on a likely ongoing basis. There are risk decisions for infrastructure this information would enable; if a situation is long-term it likely would generate major changes to avoid risks at seasonal time range (tile drainage; culling of herds; making changes in land distribution).
- How is it going in terms of research questions and needs identified by regional climate hubs and extension services? Are agriculture-related weather and climate questions making their way into the NOAA research agenda; is it ad hoc? How could we improve this? *Response:* Inroads have been made with both NOAA and NASA in creating the National Integrated Drought Information System (NIDIS). This is a two-way conversational street: better forecasts are great; relevant forecasts are more important. We need to reach out to ask for specific applications. It is not NOAA's job to tailor to everyone, but showing what we can and can't do can help us find something that works. Establishing communication lines and/or partnerships is important and useful.

Mike Farrar – Headquarters U.S. Air Force – 14th Weather Squadron

Farrar provided a summary of climate services from the U.S. Air Force (USAF), spanning historical, current, and projected response and service to supply the demand for *environmental intelligence* (S2S to decadal), and to help implement DOD's developing Climate Adaptation and Resiliency (CAR) initiative. Current work includes core climatology; monitoring; analysis; prediction (growth space); projection. Increasingly, there are decadal needs in these areas and in guidance and policy development, planning, and mission sustainability.

Climate as a layer into geospatial intelligence (GEOINT) refers to fusing authoritative climate information and data disseminated to support the Intelligence Community (IC) on classified networks; and recognizing the local/political/economic contexts in which a particular climate state occurs:

- Authoritative climate data is used for forensic analysis to understand how and why events happen.
- Delivering S2S forecasting products will be helpful to support the IC shift to the Anticipatory Intelligence (AI) paradigm.
- AI is about delivering models and modeling capabilities in order to provide strategic warning, mission forecasting, and global humanitarian relief preparations.

Air Force Weather (AFW) is coordinating with NOAA and NASA for modernized climate prediction modeling. On-the-horizon aspects include:

- Climate relevancy focus – impacts garnering senior leader visibility; recognition of environmental threats to DOD;
- S2S prediction – not only temperature and precipitation, but also military-relevant variables; improvement of drought and hydrology-related impacts; meeting increased training need across Air Force Weather; and leveraging modeling strategy concepts;
- Decadal prediction – the 14th Weather Squadron has limited capacity and seeks to develop partnerships with other agencies to incorporate tools and information; provide modeling capability to meet gaps, and leverage the Intergovernmental Panel on Climate Change (IPCC) and the Fourth National Climate Assessment (USGCRP, 2018) reports and available tools.

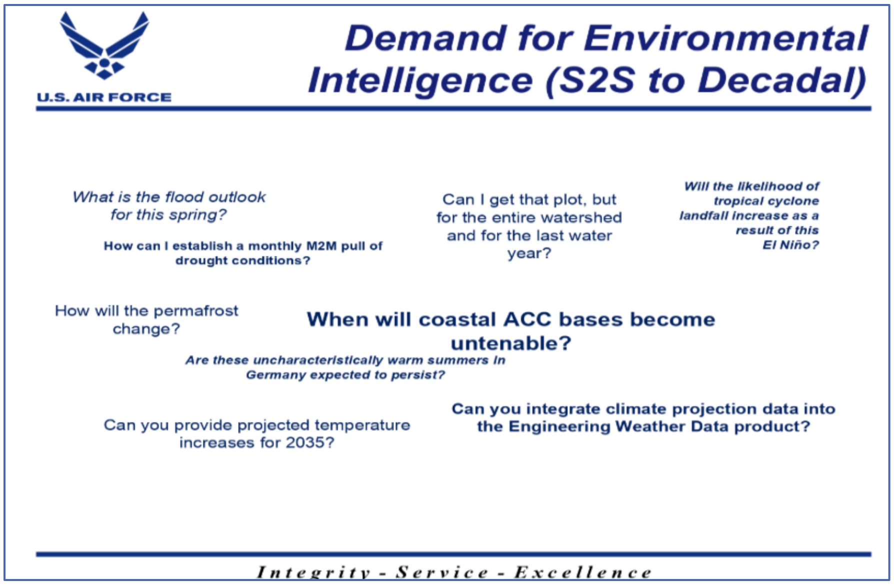


Fig. 5 Farrar: U.S.A.F. Environmental Intelligence

The future challenge of near-peer conflict and the needs of future weapons systems to compete in that conflict will not be met by the current AFW modeling approach. Objectives are to improve/evolve/sustain existing capability to fully meet current user needs; provide modeling capability to meet gaps; and add resilience to AFW modeling system. Major decision points include: model operations; model configuration; distributed computing; hydrology; unclassified/classified processing; sub-seasonal to seasonal forecasting; cloud modeling.

Model needs include: global numerical weather prediction (NWP) model; regional NWP model; cloud model—pursuing explicit cloud forecast capabilities; land modeling; dust/volcanic ash model; stochastic modeling approaches; post-processing: machine-to-machine applications and stochastic post-processing; verification.

Additional objectives are to provide modeling capability to meet gaps in these areas: polar regional model; global/regional hydrology model; subseasonal to seasonal model; high altitude NWP model; surrogate models; machine learning/artificial intelligence; aerosol and chemistry modeling. These additional lines of effort would add resilience to the current modeling system: modular hardware and software; distributed computing; non-traditional data sources; modeling operations with limited data sets; operational back-up; multiple model ingest for model blending; and multiple data sources.

Q&A

- The examples shown in the presentation were mostly in the continental U.S. Can you comment on the importance to DOD of global predictions? *Response:* For DOD, there are both domestic and international impacts; we have global installations, with diplomatic and broader national security implications. We have to think long-term. The longer the lead time, the better.

- Regarding global impacts: for the Dept. of State, NATO readiness action plans and regional climate summaries are very important and are current national issues. The European Commission will invest substantially in climate services and programs similar to Copernicus and Galileo in the future. The U.S. will need to collaborate with Europe on such new missions and efforts. How can we fully harness international partnerships for the benefit of U.S. taxpayers? *Response:* On a practical level, how we collaborate, interact, and partner will enable us to gain the most benefit for the U.S.
- Is security clearance for scientific researchers a hindrance, with AFW? *Response:* There are potentially classified usages of information, but the science itself is unclassified. The biggest barrier now is lack of network and lack of climate scientist availability.

Rob Galbraith – AF Group, Director of Innovation *(GoToMeeting remote participation)*

Galbraith provided a view from the insurance industry on the impacts of climate and weather and how they reverberate throughout the industry and economy. Insurance agencies can inform people they live in a high-risk area, but it is difficult for the public to understand the implications of that due to lack of expertise. When information is unavailable, there is not a proper understanding of risk. People may better understand the impacts of weather and climate from an economic standpoint—a pricing point of view. Private insurance can serve as a safety net, and can lessen the burden of the necessity for disaster aid.

Categories of insurance user needs:

- *Projection of future loss trends* – historically, trend loss data was used to set appropriate prices and reserves. Current process is to examine a wide range of internal and external factors and use "actuarial judgement" to select a trend factor, driving insurance premiums. (The insurance industry sells a product before they know what it will cost). *50% of property losses are due to weather*; there is currently no good information to help with trend selection.
- *Input to catastrophe models* – catastrophe models became widespread following Hurricane Andrew (1992). These models provide probabilities of ruin that assist insurance carriers, regulators, and rating agencies in determining capital reserve requirements (the greater the capital reserve required, the higher the premium). There is no implicit representation of future weather/climate impacts today. Models are adjusted by insurance companies; they have stress-testing, but there is not a comprehensive way to adjust the processes.
- *Pricing of reinsurance and insurance-linked securities* (catastrophe bonds) – reinsurance is insurance for insurance companies (e.g. Lloyds of London and Bermuda markets). The pricing of reinsurance signals risk to primary carriers; pricing fluctuates with risk assessment or perceived risk. Insurance-linked securities provide alternative capital driven by Wall Street banks and investors. *Parametric insurance* does not indemnify the

full loss for the buyer seeking protection; a party is buying a pre-defined amount of protection which will pay out on pre-defined terms: e.g. when a low-frequency but high-intensity loss event (such as hurricanes) occurs. Loss adjusters are not required; the pre-defined event triggers the pay-out.

- *Underwriting risk selection and market stability* – pricing is driven by historical losses + catastrophe models + reinsurance risks. Underwriting amounts to risk selection for a company, i.e. which policies to insure or decline.

Q&A

- With risk of flooding and increasing flooding frequency: is there any appetite in the U.S. to take away the artificial barrier between regular homeowner's insurance vs. flood insurance? *Response:* the U.S has a flood insurance program through FEMA; companies like USAA serve as agents for the flood insurance program. Private carriers do not have an incentive to write the national flood insurance program. We don't effectively educate homeowners about the need or advisability of flood insurance. There is some regional activity around private flood insurance; and advocacy to see those efforts as equal to a national flood insurance program. It may be likely to see more of a push towards this over the next 10 years.
- There are many climate change projections in climate modeling. How do you evaluate your catastrophe models at 10-20 years without incorporating climate models? *Response*: Most of the insurance industry works on time scales of 1-3 years, rather than 25, which is what I would work toward (Galbraith). In property and casualty, the term is annual. Events that may have been considered very extreme in the past may become more commonplace; this can change the appetite of insurers. There is an opportunity here for insurance companies to widen this scope, and extend insurance. This could be a public/private conversation.

David McCarren (National ESPC) – Group Discussion: Definition of Needed Capabilities

The intent of the discussion session is to identify the next steps. *The National ESPC serves a federal coordinator role, which places us in the interagency arena.* We have mechanisms to encourage take-up via the Office of the Federal Coordinator of Meteorology (OFCM) to address common needs. Observations and commentary on the morning sessions included:

Policy, organizational challenges

- No U.S. agency has the mission or mandate to perform long-term climate prediction (i.e. decadal scale); the U.S. does not have a comprehensive climate services office. Various groups work in this arena to support different mission goals, but general support or overarching coordination is not specifically or formally assigned. Such decadal-related efforts as there are in the U.S. are different from the use of current operational models that deal with prediction from 1-10 days. Tasks in the direction of extended range prediction are currently accomplished as one-off research and development (R&D) projects.

- A 2-to-30 year span is a very research-rich area for prediction, production, attribution, and understanding. *Should there be some kind of formal operational prediction capability in the US going forward, including an informed or synthesized research agenda?*
- *What does an operational timeline look like*? Consumers of this information are also policy makers. There is an annual budget cycle (fiscal years); a single congressional cycle (2 years), or an administration cycle (4 years). The 1-4 year timeframe is thus essential for consumers, but user input is necessary for success.

Socio-economic factors; communications

- USGCRP has taken strides to better incorporate regional science centers as hubs for user engagement, and current activities are more focused on seasonal prediction rather than decadal. *There is potential for USGCRP to integrate social sciences to better inform collaboration and communications with users.*
- Mary Glackin, representing the Science to Climate Action Network (SCAN) (and president-elect of the American Meteorological Society), applauded any and all interagency efforts. She commented that decision-makers do not consider climate information alone; socio-economic factors, international treaties, and more are considered as well.
- The discussion is about time scales: creating products and applying them to longer-term time scales. The insurance presentation was very useful in noting the human and economic impacts of improved long-range prediction. *Interest in long-term climatology is changing, and impacts projected trajectories.* That involves understanding the low-probability/high-risk "long tails" of probability distributions. What crisis events may be falling in the tail?
- Sea level rise is a current impact. The Netherlands government prioritized reassessment of all former risk assessment due to the threat of sea level rise but the U.S. has not had a similar reassessment. Methods linking research to impacts and the meaning of operational in this context is critical, but we do not have policies in place for these applications. *Science that considers an end-to-end approach places human and economic impacts at the forefront, and this socio-economic linkage may push toward an operational definition for this time-scale.*

> *"For prediction and projection, we need to emphasize the underlying assumptions. We have not yet mentioned projections (predictions made in the context of various assumptions about future greenhouse gas levels). How we engage and communicate is extremely important. This is not 'done' science. We should never separate research from operations. These efforts have to be done in concert."*
> *Mary Glackin, Science to Climate Action Network (SCAN)*

- Insurance companies are changing costs of policies due to changes in the frequency of phenomena. In the direct discussions of risk and pricing with consumers, there may be a way to weave in awareness and communication about longer term climate impacts. Catastrophes and their frequency are changing; but in addition, event-specific risks are changing. For example, in the DC area, given an increase in hail events, what was formerly a $50 premium cost for hail insurance actually rose to a $250 premium cost. *These direct* *impacts on the cost of insurance may seem mundane, but they have direct impacts on the industry and on users.*

- The Department of State session summarized observing system arrangements and agreements, the international spectrum, and touched on how climate will change globally (sea-level rise; infrastructure impacts; Arctic impacts), *causing serious socio-economic impacts.*

- The USDA session revealed a 2-5 year focus in agriculture, with serious impacts on individual livelihood. Decisions made around these impacts may project to the decadal range, and can determine whether a farm stays in a family, especially for lower-tier water rights holders. Decisions are often based on seasonal phenomena, but if it becomes evident that extreme events are increasing in frequency, farmers may take advantage of longer-range information via a change of crop. *Farmers want to see evidence that they are being given good information and that they can count on the reliability of forecasts*.

Technical, operational, and research challenges

- For predictions of less than two years, the term "operational" means the results are created at a recognized, funded production center, with formal requirements on availability, reliability, and skill. For products extending past two years, there is no such production center designated; however, some research products may be appropriate for decision support. Designating appropriate research products opens a conversation of whether they are "operational" or not. Research products may be appropriate if they have reliable funding, established skill, and are provided on a periodic, predictable basis.

- Downscaling climate models—taking information known at large scales to make predictions at local scales—is done independently to inform climate assessments for specific locations or industries. *A more unified or coordinated activity for extended range forecasting might offer the opportunity to apply or generate greater accountability across the practice of downscaling.*

- Many of the reviewed NAS reports state that improvement in forecasts will be attained incrementally as research is performed, and products will improve as users engage with them. *Extended range prediction products must be made available to users, and a communication feedback structure between researchers and users in place for improvements to occur.*

- The Coupled Model Intercomparison Project (CMIP), as the principal data source for the IPCC assessments, include a wealth of data that has not been mined. *These data can be analyzed further and utilized to help inform our knowledge on questions such as the skill necessary for specific users, what data are, or are not, currently available, the most useful timing and frequency, and needed capabilities.*

Potential organizing roles

- We need some sort of decision support structure to push the effort forward. An *operational* product is defined as something from a designated source that comes out on a schedule, and has a reliability attached to it, and it is attached to a user. There is a loop of certification, validation, and reliability, with formal interaction with users for improvements.

- USGCRP is another important body coordinating research across agencies and international connections, involving its 13 agencies (footnote pg. 1).

Present Capability and Research Efforts

Joshua Cossuth – U.S. Navy's Earth System Prediction Capability Effort

The Navy's interests in extended range prediction are critical in Department of Defense (DOD)/Navy planning and policy development for: mission planning (e.g. typhoon risk assessment, ship routing) and long-term infrastructure installation and replacement planning. The *U.S. Navy Arctic Roadmap 2014-2030* takes a long term approach, given its long history of Arctic Ocean operations and explorations. Reduced summer sea ice will make the Arctic Ocean viable for international shipping and resource explorations, and is critical for national security concerns. Estimates for economic potential of hydrocarbon resources exceed $1 trillion in the U.S. Arctic. The Navy's strategic plan seeks to match environmental predictive capabilities to tactical planning requirements: fully coupled (ocean-atmosphere-wave-ice) global, regional, and local modeling and prediction capabilities for operational planning at tactical, strategic, and subseasonal to seasonal scales.

Navy Earth System Prediction Capability (ESPC) Model Overview

- Developed to meet Navy needs for global Earth system forecasts on timescales from days to months: initial operational implementation and transition in FY19.
- Earth System Modeling Framework (ESMF) and the National Unified Operational Prediction Capability (NUOPC) are used to facilitate upgrades.
- Participate in NOAA Modeling, Analysis, Predictions and Projections (MAPP) SubX (multi-model subseasonal prediction experiment). Seven global models have produced seventeen years of retrospective (re-) forecasts and more than a year of weekly real-time forecasts. SubX is now housed in the Office of Weather and Air Quality (OWAQ).

Initial Operational Capability: 2019

- Can do deterministic short-term forecast at 0-16 days, daily.
- Probabilistic long-term: 0-45 days, 16 members, weekly.
- Final operational capability: FY22 – seasonal (90-day) ensemble forecasts; coupled data assimilation; inline aerosols, middle atmosphere; interactive ocean surface waves.

Uniqueness of Navy ESPC: High resolution ocean and sea ice

- Navy needs high fidelity simulations in atmosphere, ocean, and sea ice; emphasis on high-resolution ocean and tropical precipitation.

SubX Pacific North American (PNA) Oscillation and North Atlantic Oscillation (NAO)

- Navy ESPC is competitive with other SubX models for PNA and NAO forecasts in deterministic mode.
- Navy ESPC is better than the NCEP coupled forecast system model (CFSv2), for Madden Julian Oscillation (MJO) skill, but not quite as good as the European Centre for Medium-Range Weather Forecasts (ECMWF) products.

SubX Real-time Forecasts used by National Ice Center (NIC)

- Navy ESPC real-time forecasts were leveraged to provide NIC with 45-day forecasts of sea ice concentration, thickness, and drift for long-range planning guidance for 2018 Operation Deep Freeze (McMurdo re-supply mission) and ICEX (Beaufort Sea) field campaign support.

The Navy ESPC operational transition is scheduled for FY19. Relatively high resolution ocean ice models are promising: SubX runs are being used by NIC for resupply missions and field campaigns. Future work includes optimizing ensemble design and configuration, including model uncertainty; continuing model development to address biases; developing new extended-range and probabilistic forecast products; final operational implementation (2022) will include coupled data assimilation and coupled ocean surface waves.

Renu Joseph, Corinne Hartin – Department of Energy (DOE) Modeling Capability

Modeling in DOE is performed by the Climate and Environmental Sciences Division and its three divisions:

- Atmospheric Science
  - atmospheric radiation measurement climate research facility
  - atmospheric system research
- Earth and Environmental Systems Modeling (integrator of all work across the Division)
  - Earth system model development
  - regional and global model analysis
  - multisector dynamics
- Environmental Systems Science
  - terrestrial ecosystem science
  - subsurface biogeochemical research
  - Environmental Molecular Sciences Laboratory

Key DOE themes determining all projects are: modes of variability and change; cloud processes; high latitude feedbacks; water cycle; extremes; and biogeochemical feedbacks.

The primary model of DOE focus is *E3SM: Energy Exascale Earth System Model*, along with multi-model approaches and use of a hierarchy of models of varying complexity to address relevant science questions. DOE model work looks to improve computational efficiency, model biases, internal variability, and change. They seek to improve initialization methods and sources of prediction skill, and attribution of extremes. They are examining model biases, extending into the coupled model framework.

Joseph gave examples of several DOE/university collaborations across those themes that are advancing capabilities:

- *Arctic Decadal Prediction and Predictability* is a case study using the Regional Arctic System Model (RASM) to focus on dynamical downscaling of the CESM on decadal timescales, including sensitivity of predictability for critical processes and coupling channels governing Arctic climate variability and trends; and whether there are measurable gains in long-term Arctic prediction from dynamical downscaling for regional Arctic predictability in Earth system models.
- *Dynamical downscaling of the Climate Forecast System Reanalysis (CFSR)* using RASM produces more realistic sea ice thickness distribution. A focus on producing realistic sea ice thickness distribution is critical as thicker/thinner sea ice takes longer/shorter time to melt in summer. No data assimilation is used but instead the emphasis is on improving model physics by focusing on the specific region and use of high spatial and temporal resolution for more realistic process-level simulations.
- *CESM2/E3SMv1 collaboration on Decadal Climate Prediction*; DOE and NCAR are addressing initialization, drift, model error, prediction skill, processes, and mechanisms.
- Within DOE individual university projects interact with the larger laboratory projects and coordination across agencies and with NCAR.

Corrine Hartin summarized DOE work with its E3SM**,** conducting simulations, predictions, and projections to support the energy mission. The U.S. energy sector is vulnerable to decreasing water availability; more intense storm events and floods; increasing temperatures; and sea level rise. The focus on high resolution can significantly improve simulation quality and spatial specificity for more useful information to provide for energy decisions. Quantifying uncertainty is important for providing actionable predictions for decision-making.

- Version 1 was released April 2018; includes code, output and analysis tools; developed for DOE science including water cycle, biogeochemistry, and ocean-cryosphere.
- Version 2 release is scheduled for 2021 – it will focus on improving computational aspects of the project; regionally refined North America; moisture transport to the Arctic; effects of Arctic changes on lower latitude extremes; vegetation changes; effects of surface heterogeneity, and effects of freshwater shifts on the AMOC.
- Version 3 release is scheduled for 2024, to include carbon cycle and coastal hydrology; terrestrial-aquatic interfaces; groundwater; coastal processes.

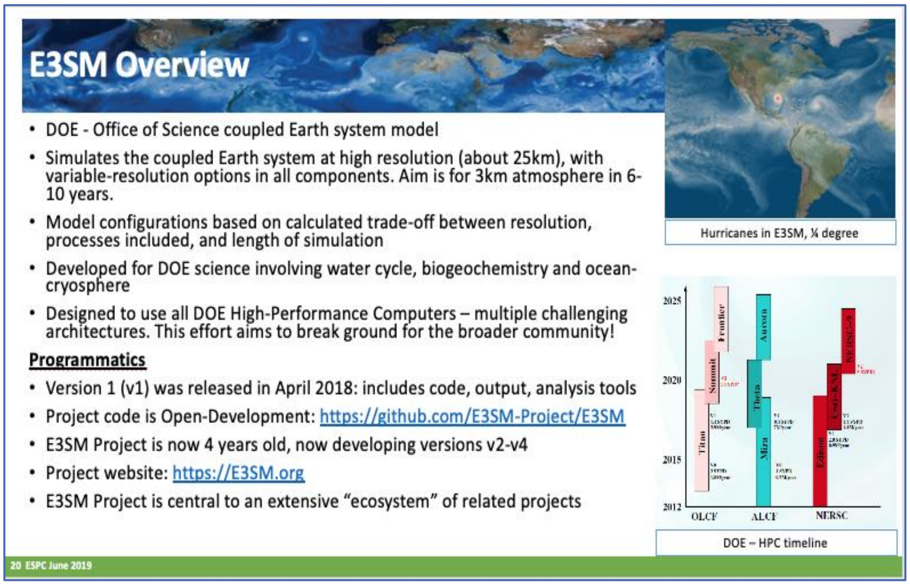


Fig. 6 Hartin: DoE E3SM Model Overview

Q&A

- DOE work related to groundwater is a very complex issue. How does DOE gain feedback, deliver products to customers? *Response:* We are primarily focused on research and connecting with other projects that use E3SM and that connect with customers; and via other departments within DOE, interactions via advisory committees, and via open source code provision. We have found it is a slow process to gain feedback from water managers.
- General discussion included commentary about existing decadal efforts, including DOE's. There is a robust international decadal prediction activity: the UK Met Office is the WMO-designated Lead Centre for Annual-to-Decadal Climate Prediction for 15 organizations contributing to decadal prediction.

David Reidmiller – USGCRP - Director, National Climate Assessment

USGCRP is a federal program mandated by Congress in 1990 to coordinate federal research and investments in understanding the global environment, human and natural, and impacts on society. Thirteen agencies[8] participate in USGCRP. Every four years USGCRP produces the National Climate Assessment report, analyzing the effects of global climate change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity.

The *Fourth National Climate Assessment (NCA4), Vol. 1* was released Nov. 3, 2017 detailing physical changes in global climate change; detection and attribution; extreme events; downscaled information (taking information known at large scales to make predictions at local scales); potential surprises; and climate model weighting. NCA4 Vol. 2 was released Nov. 23, 2018. Its conclusions are policy relevant, but not policy prescriptive. It places strong emphasis on regional information; quantifies impacts in economic terms; integrates international considerations; and assesses a range of potential impacts to help decision makers better identify risks that could be avoided or reduced. It uses case studies to provide context and to showcase community success stories. It seeks to build community resilience, and incorporates public engagement as a cornerstone of the report process, undergoing eight rounds of review and decision. A *"risk-based framing"* approach was used to ensure focus on issues of importance to decision-making and to help with communicating assessment outcomes. Key messages addressed:

> *"Sub-national mitigation-related activities are growing across all sectors of the economy. The magnitude and rate of these activities (both domestically and abroad) do not yet approach the scale needed to avoid the worst impacts."*
> David Reidmiller, USGCRP

- What do stakeholders value/what is at risk in a given sector or region?
- What outcomes do we wish to avoid with respect to these valued things?
- What do we expect to happen in the absence of adaptive action and/or mitigation?
- How bad could things plausibly get; are there important thresholds or tipping points in the unique context of a given region or sector?

The impacts of NCA3 and NCA4 are not yet clear; there is no formal feedback process on report content. We know that adaptation is happening, but much of the action is at sub-national and regional levels.

The current and future risk to economies and infrastructure, natural environments and ecosystem services, human health and well-being, food quality/supply disruptions, mental health issues generated by dislocation, relocation, lifestyle changes—these are interconnected and interdependent systems with cascading impacts through physical, social, institutional, and

[8] Department of Agriculture; Department of Commerce; Department of Defense; Department of Energy; Department of Health and Human Services; Department of the Interior; Department of State; Department of Transportation; Environmental Protection Agency; National Aeronautics and Space Administration; National Science Foundation; Smithsonian Institution; U.S. Agency for International Development.

economic linkages. *Sectoral interactions across energy, water, land, ecosystems, human health, transportation, urban systems are all affected by an array of climate-related and non-climate related influences.*

Renu Joseph – USGCRP Interagency Group on Integrative Modeling (IGIM)

As an interagency program the USGCRP enables its thirteen agencies to coordinate global change research and science across the U.S. government; produce results to inform decisions; produce

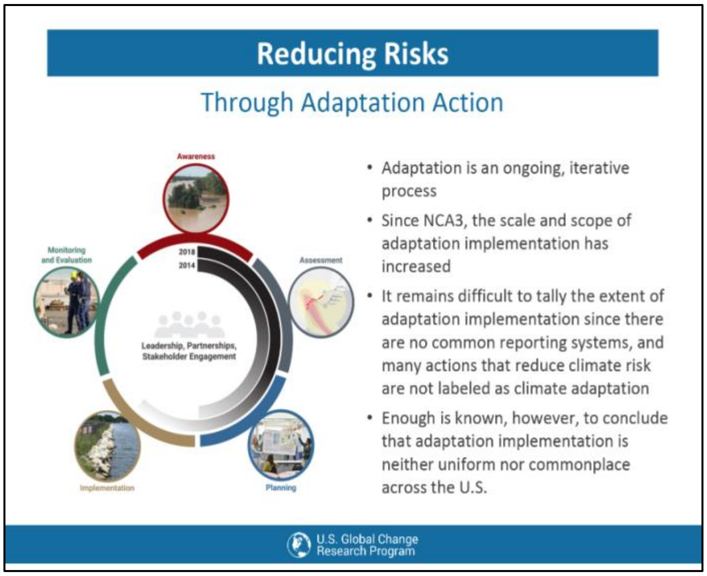


Fig.7 Reidmiller: USGCRP – National Climate Assessment

products such as the quadrennial NCA; and promote international cooperation and coordination of U.S. activities with programs of other nations. One of the interagency groups within USGCRP is the *Interagency Group on Integrative Modeling* (IGIM). IGIM consists of representatives from DOE, NASA, Navy, NOAA, NSF, and USDA. It meets monthly to improve coordination of federal climate and Earth system modeling activities, provide guidance on modeling priorities, and actively coordinates USGCRP federal research and development for modeling and prediction for S2S to centennial time scales. It encompasses atmospheric, oceanic, cryospheric, and terrestrial domains; human systems are treated as an integral component of each domain. One of IGIM's major activities is the convening of the U.S. Climate Modeling Summit (USCMS) encompassing the major national climate Earth system model development groups:

- DOE – Energy Exascale Earth System Model (E3SM)
- NASA – Global Modeling and Assimilation Office (GMAO)
- NASA– Goddard Institute for Space Studies (GISS)
- NOAA – Global Fluid Dynamics Laboratory (GFDL)
- NOAA – Climate Forecast System (CFS)
- NSF – Community Earth System Model (CESM)

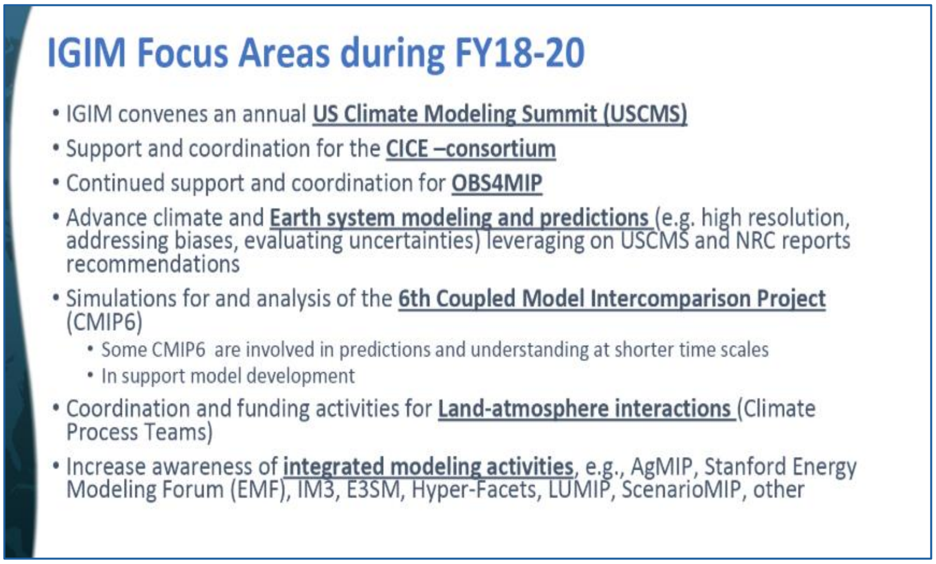


Fig. 8 Joseph: Interagency Group on Integrative Modeling

Jessie Carman – ESPC: Discussion – Needs vs. Capabilities

Primary observations from the group about the information received thus far and related current activities center on these two main areas:

- *User/stakeholder needs identification* and methods of communication/interaction
- *Capabilities* – identifying current capabilities, and applying assessment, which must be based on and informed by user needs.

User/stakeholder needs identification and communication

Participants agreed that user/stakeholder input is essential to developing any kind of effective interannual/decadal prediction capability, and aligns with recommendations from multiple prior NAS reports. *Researchers, developers, operational personnel, and users* all need to be part of the process. The *value* of *decadal scale information* is that it allows people to take actions that might mitigate or avoid seasonal impacts, and better serve key societal risk areas.

The Day 1 sessions revealed much about the range of sectoral users and the variable nature of the information they need. It is correct to focus on communication with and to users, and assessment of whether we can provide those answers to those needs, to develop a national plan to implement climate services, as a nation.

- Creating *links to user communities* to have a better understanding of their needs would help to determine priorities coming out of any assessment of the existing tools or information we have.
- What kinds of decision-support do we need? *Every decision by a user contains an implicit context that cannot be overlooked or lost*. What is the science that is needed by the user?
- An *assessment of existing platforms for user engagement is called for.* Discussion included:
    - USGCRP provides the NCA; as part of the development of that report – as well as through their other interagency coordination activities – the Program engages with providers and users of climate information.
    - The *framework* of the National Climate Assessment was postulated as a good starting point for five years and beyond, but it may not necessarily be adept at answering questions and addressing issues that users have.
    - *Case studies* were suggested as having potential for providing more sense of the range and depth of user needs.
    - The notion of *utilizing regional science organizations, or state climatology offices* may possibly produce a better capability to address some aspects of user communication—both as to feedback from, and communications to users—given their expertise within their localities and regions, and potential existing networks of user engagement. *Intermediate group(s)* that can serve a purpose to user groups, when allied with authoritative analysis, would be beneficial—someone or some service, *with expertise who can then effectively translate/communicate* complex scientific concepts, dependencies, and interactions.
    - An online participant affiliated with the Midwest Climate Hub (a former state climatologist) contributed that "climate services" entails a whole suite of entities and products. We can move ahead in climate services by helping people using existing tools and explaining how they can use model output to make decisions. For agriculture, state climatologists help to interpret Climate Prediction Center information for users. *This has to be done at a regional basis, and has to be done with the information we have*. He encouraged state and regional entities to deal with these issues, interacting with the people making the decisions; while larger national entities deal with the bigger, broader problems, such as modeling. At extended time scales, the model data needs to be tailored for the specific use (dynamic/statistical downscaling).
    - *European approaches to climate services* for users can serve as a good template; they have successfully bridged science with users of climate services, utilizing both climate scientists and social scientists (e.g., Blue Action, a major European research project bringing together experts from 40 organizations in 17 countries).

This is an important piece of communication and engagement that is missing in the U.S.

- *Methods for sustained community engagement are needed.*

Capabilities

- Earlier discussion touched on standing up a *national capability* to meet end-user needs; determining next steps for that is key.
- The OFCM Committee for Climate Coordination Services has developed an initial database assembling *information on cross-agency capabilities*, that might be leveraged. The first step is to do a *capabilities-available assessment*.
- *A sustained assessment ecosystem is needed*. Communication is necessary between user and researcher/developer, in order to know the nature of the user need. *What would users like to see as services coming out of the range of tools now available?*
- Understanding user needs is key, but more importantly, *what do users need that is predictable*?
- Consulting the NCA report is unlikely to be helpful for answering specific questions, for example, whether one can pump water out of the Ogallala aquifer in 20 years. A useful *smart search method* is needed and would be a valuable service to provide.
- *What you will use a model for defines the requirements*. One needs to know the intended purpose to properly design the model and post-processing. We need a better understanding of what we want the models to do, and a better understanding of what data we have now. At decadal scales, one develops directly to the use or user. Identifying who we produce data for—i.e. the end user—is needed in order to translate the data in a way that is usable and appropriate.
- Unlike the National Weather Service (NWS), which has a mission for protecting life and property; there is no mandate to provide this kind of "climate service." *Translating this issue into terms of economic impact and/or human impact* (land use, water use, extreme weather) *would help to create a mandate* to get the resources for such a service.
- Traditional weather models work on shorter time scales; *we don't know whether existing tools have the skill* to do what we want.
- *What does operational mean past the 2 year time-scale?* Predictability and understanding of physical processes may lead to increased skill, but processes such as large-scale variability, sunspots, and their interactions with the climate system must be further studied and included in global models.

Day 2

The Decadal Prediction Grand Challenge

David Titley - Professor of Meteorology, Pennsylvania State University; Rear Admiral, U.S. Navy, Chief Oceanographer, retired

Professor Titley utilized the anniversary of WWII D-Day landing as an analog to our current need for 10-30 year prediction. Using primarily statistical and analog methods, and a 40 year collection of northern hemisphere charts, Allied forecasters spent six months analyzing the weather thresholds (visibility, ocean state, surf, soil trafficability) for D-Day for various Allied forces, in order to extend decision support beyond the typical range.

Titley spoke to the origins of the National Earth System Prediction Capability (ESPC), over ten years ago, when there was a desire in the Navy to prepare for climate change and Arctic conditions. How, in a federated sense, could we take world-class components of excellence to have a conceptually seamless unified model, 0 hours to 30 years? This served as the impetus for developing an inter-agency collaboration. If agencies together can figure out collaboration/cooperation/coherence, in substance, you may be able to use this window of opportunity. The more you show a bottom-up approach, the less opportunity for top-down directives. *Societal requirements for seasonal to subseasonal to decadal prediction have only grown. Put this science in terms people can understand, to develop increased resiliency*.

Q&A

- There were hurdles and challenges of bureaucracy in the formation of ESPC; what are the hurdles we face? *Response:* a committee would be a good way, where there are a variety of views and perspectives. There should be an assessment; is A or B useful or beneficial to the goal? Communicate with your agencies; you are not trying to take away topics or resources, but discover/enable the optimum and best approach for the problem. Define what the enterprise is.
- Much data has been generated (e.g. SubX); data are available but not used well. Would a good project for inter-agency cooperation be machine-learning/AI data mining for this data? *Response:* if ESPC/USGCRP does not do it, someone else will. Many universities and groups are focused on ML/AI. Can you extract more value by doing so?
- This meeting is exploring the ability to develop capability for a long-range, federal coordinated strategy. Yesterday we talked about the lack of a federal office of climate services. We want strategies that help us get to the user. Is there any private sector gap-

filling that can be done? *Response:* The more the federal agencies can coordinate together, the more you can make a case for private sector involvement.

Overview of Day 1

Johnna Infanti, ESPC; NOAA Office of Weather and Air Quality

Infanti provided a comprehensive overview of discussions from Day 1 of the meeting and the scientific challenges of decadal prediction.

Scientific challenges

- Predictability and understanding of physical processes may lead to increased skill, but processes such as large-scale variability, sunspots, etc. and their interactions with the climate system must be further studied and included in global models. Be wary of getting the right answer for the wrong reason.

Collaborative and overall challenges

- *Lack of mission or mandate in the U.S*. in extended range or long-term climate prediction creates an ad-hoc structure for prediction on this timescale.
- International partnerships and a global view of climate prediction is necessary. Explore how we can best harness existing efforts for the benefit of US taxpayers.
- Earth system models are increasingly complex and predictions on longer or extended range time-scales are becoming more commonplace, necessitating increases in high performance computing (HPC) and computational efficiency.
- We must leverage the value of existing partnerships and of existing collaborative vehicles. (USGCRP, ESPC, OFCM and Committee for Climate Coordination Services; NOAA Climate Program Office (CPO) and the potential for Climate.gov as a platform).

User Communication and engagements challenges

- Communication – *skilled translators of climate science information* (with authoritative analysis) are necessary to improve user trust in data and predictions. This role may best be filled at an intermediate level, as by regional and/or state offices and services.
  - A challenge to such authoritative analysis is lack of network and lack of available climate scientists.
  - The human and economic impact needs to be central to decision support; these social impacts are important to consider at the forefront. Sustained user engagement is needful.

> *Let's get the federal act together to speak with a coherent voice to be able to engage the three pillars: government, private industry, academia.*
>
> *David Titley*
> *Penn State University*

- USGCRP – the NCA4 reports (Vol 1 and 2) can be a potential first stop for satisfying user needs.
- We should pursue *defining the end product, from user perspectives, to be purpose-built, rather than taking an ad-hoc development approach*.

Next Steps

- Strengthen ties between USGCRP and ESPC as cross-agency coordinators.
- Determine what capabilities we currently have, and if these will meet the needs of users (is the science reliable, credible and salient?). Utilize the OFCM CCCS and its cross-agency capabilities database for initial assessment of cross-agency capabilities.
- Determine strategies for how feasibility and user needs discussions should occur between researcher/developer and end-user; conversations need to be had about *what is predictable*.
- Encourage the capability at regional and state levels while pursuing the national effort. State level support is key. Increase interest and advocacy; utilize existing networks and services: USDA Climate Hubs, RISAs, NCA as the potential first stop for users; Blue Action as frameworks for understanding, leading toward a mandate.
    - Framing the importance of meeting user needs for decadal prediction in economic and human terms is an avenue toward gaining attention and advocacy.

Emerging Capability and Research Efforts

Shanna Pitter Combley – NWS International Activities Office
International Challenges: 2yr – Decadal Predictions

Pitter Combley focused on relevant World Meteorological Organization (WMO) activities; existing World Climate Research Program (WCRP) groups; and the WCRP Strategic Plan 2019 – 2018. The WMO is currently rescoping procedures to eliminate stovepiping via its strategic plan, with the goal of breaking down barriers between weather, climate, and ocean, and to improve its research program. They are in the process of approving two new bodies for science, for better coordination and better service; are looking at a research board and structure for research conduct and are engaging with new partners, including economists, social scientists, food sector, agriculture and meteorology.

WCRP working groups include:

- The Working Group on Coupled Modeling (WGCM) fosters the development and review of coupled climate models.
- The Working Group on Subseasonal to Interdecadal Prediction (WGSIP) conducts numerical experimentation for subseasonal to interdecadal variability and predictability, with emphasis on assessing and improving predictions.

- WCRP Coupled Model Intercomparison Project (CMIP) works on better understanding of past, present, and future climate changes arising from natural, unforced variability or in response to changes in radiative forcing in a multi-modal context.
- The Working Group on Numerical Experimentation (WGNE) fosters development of atmospheric circulation models for use in weather and climate.

WCRP grand challenge: *Near-term Climate Prediction (NTCP)* – the primary goal is to produce skillful and reliable forecasts that improve the quality of initialized decadal climate information and prediction; that synthesize and tailor information toward services that address stakeholder needs; and that develop processes to assess and communicate degree of confidence and uncertainty in predictions.

NTCP key activities include: promoting international collaboration and comparison studies; and establishment of internationally agreed mechanisms to provide decadal predictions. These include standards for WMO Global Producing Centers (GPCs) of annual to decadal prediction; designating a WMO lead center for annual to decadal climate prediction, which is the UK Met Office; and production of a WMO-produced Global Seasonal Climate Update. They will also initiate and issue yearly, real-time Global Annual to Decadal Climate Updates.

Mary Glackin – Commercial Sector/Non-profit Sector (Science to Climate Action Network) President-elect, American Meteorological Society (AMS)

Glackin spoke on *Evaluation Knowledge for Applications: A Framework for Sustained Assessment*. Private sector applications of climate science and services are mitigation efforts; it is a mature area; much is going on, and evaluation will be increasingly important. Adaptation efforts are a large growth area, occurring across communities, businesses, regions, nations—all are actors. Adaptation must recognize the limitations of science (*prediction vs. projection*); we should be thinking not just of making decisions, but of encouraging *pathways for decision-making*, and how that process can evolve over time.

In business consumption, Wall Street recognizes that mitigation saves money, but there has not been much focus on adaptation. In some places, there are policies enforcing actions:

- Australian governing policies – some business opportunities are emerging there.
- Confidence in services is a factor – how do I know this is as good as you say?
- Favorable cost/loss equation – the cost of (in)action is favorable to doing nothing.
- The context of other factors – *nobody makes decisions just on climate information alone*; there is a context around decision-making. Finding out how particular businesses are involved could be helpful.

Glackin spoke to sustained assessment and the supporting environment needed to advance that:

- Per USGCRP and the Fourth National Climate Assessment a key recommendation was for "…*an inclusive, broad-based, and sustained process for assessing and communicating scientific knowledge of the vulnerabilities, impacts, risks, and opportunities associated* *with a changing global climate…"* Communities need sustained communication, among users and experts. A *community-of-practice approach* around impacts (e.g.; storm water) would be helpful. This can change community goals to be more actionable, creates impact-driven goals.

- Motivating insights for sustained communication include usability and the desire to improve efficiency.
- Four critical elements to enable such communication are *enduring partnerships, scientific foundations; a process infrastructure, and priorities and a broad resource base*.
- Status: from the independent Advisory Committee on Applied Climate Assessment: a condensed version appears in the May 2019 *Bulletin of the American Meteorological Society (BAMS)*: A Framework for Sustained Climate Assessment in the United States (Moss, 2019b)*;* the full report is available in *Weather, Climate, and Society* (Moss, 2019a). Recommendations include the establishment of *a civil society component* of assessment process; assessment of applications; and advanced methods for user-driven climate data evaluation; benefit-cost analysis; artificial intelligence (AI); citizen science; indicators; and geospatial analysis.

The *on-the-ground situation*: perspectives of cities, states, tribes, NGOs, and business—some institutions and jurisdictions are adapting and mitigating; many more need basic facts and support; even where action plans are completed, implementation can falter. Support needed includes how to use information to guide implementation: engaging; designing options; analyzing benefits/costs; updating codes and policies; monitoring results. Identifying what constitutes best practice involves determining what data and information are appropriate for given entities and sectors. Practitioner requests include how to integrate adaptation, mitigation, and other goals; assess equity implications; sustain partnerships; *provide authoritative guidance and information* (*tested practices*); and then provide feedback to the research community on information needs.

Glackin presented examples of topics for assessment within various communities including impact-driven goals: managing catastrophic wildfire risk; reducing inland flooding; managing coastal risk; safeguarding public health in extreme heat. Traditional goals affected by climate include promotion of economic vitality; modernizing infrastructure; siting public or private facilities; sustaining safe water supply; conserving ecosystems.

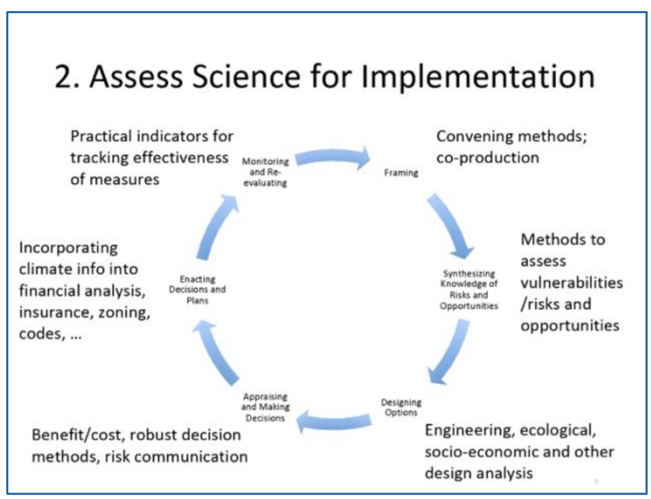


Fig. 9 Glackin: Assess Science for Implementation

Building a *community-of-practice approach* to a sustained and applied national climate assessment process relies on enduring efforts, composed of user communities, for building and sustaining partnerships. A typical problem-specific scenario would be to identify objectives for a specific location; determine the shared information needs; and the topics for technical assessment. This approach sustains interactions, identifies shared information needs, and evaluates approaches to identify "*practice-tested applications*." Glackin described the Science for Climate Action Network *(SCAN)* and its efforts to develop a sustained and applied national climate assessment process, currently in development. The effort is seeking funding, and seeks to balance federal leadership with civil society leadership.

Q&A

A participant noted Glackin's former position as undersecretary for NOAA and inquired about the challenges across federal agency engagement and collaboration. Have things changed, are collaborations more possible than before? *Response:* Glackin cited lessons learned: when NOAA tried to establish a national climate service ten or more years ago, there was a significant gap between science and decision-makers. The time is not right for it now (to do an organizational change as was then proposed), but there is an increased need to provide information in these realms. She recommended a different, interagency approach; this requires grass-roots involvement and common-sense framing in terms of both economic and human impacts.

Sandgathe: Even if anthropogenesis is removed from climate change discussions, there are still a lot of processes; you have specified a non-operational approach—what would be an appropriate timeframe for that? *Response:* That remains unclear; with the variety of assessment activities required, it is time to look at that again. What does it mean to be "operational"? The National Academy of Sciences did an assessment of assessments in 2004; it is likely time to repeat that. How computing resources are used, and the requirements for same, are very different from 2 years to 30 years. Long-term decisions are never made on climate factors alone.

Other comments:

- The business and investment communities have a high tolerance for uncertainty. In some cases, our scientific information is already good enough for some users.
- In the climate science community, we have underinvested in assuring our information is good, but we are not communicating it well. We must put more resources into leveraging what we do. Federal agencies *are* involved in making and supporting decision-making.

Tom Delworth – NOAA Geophysical Fluid Dynamics Laboratory (GFDL)

Delworth presented on GFDL and collaborators' work on the development of a seamless seasonal to multi-decadal prediction and projection capability. Delworth discussed physical phenomena and their relative timescales, and the components of the system: observation systems; assimilation systems, models—these are all *initial value* problems in seasonal to decadal prediction; whereas changing radiative forcing is a *boundary value* problem, in decadal to multidecadal projection.

The benefits of a seamless system for predictions and projections include: interactions among various scales, and high relevance for understanding, and for attribution. The desired capability was for a modeling system that can produce large ensembles of initialized predictions and projections for time scales ranging from one season to multiple decades in advance. *The desired product is probabilistic predictions and projections of climate variations and change that have utility for planning across a range of time and space scales, 2-30 years*.

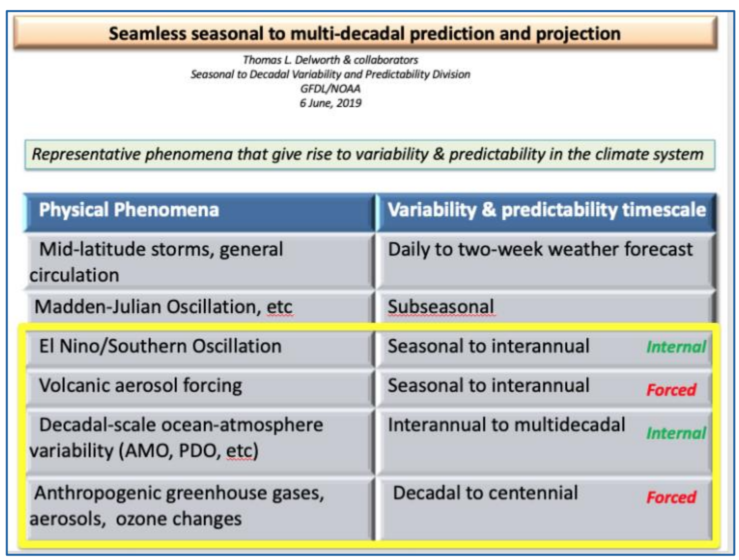
An example problem to pose might be to find out how predictable changes in ocean temperature influence tropical storm activity, and the likelihood that such phenomena like the AMOC would change phase, altering Atlantic hurricanes and other climate features; or that the Pacific Decadal Oscillation (PDO) would change phase and impact the North American hydroclimate. How will anthropogenic climate change alter the probability of extreme events over the U.S. for the next decade, including rainfall, flooding, and heat waves?

The GFDL seamless system approach started with a first generation of global coupled ocean-atmosphere climate models, 10 years ago: CM2.1 (coupled model 2.1) and FLOR (Forecast-oriented low ocean resolution)—both are run as part of the North American Multi-Model Ensemble (NMME). They provide output to the National Center for Environmental Prediction (NCEP) and others in informing seasonal outlooks, analyzing the El Nino Southern Oscillation (ENSO), hurricanes, precipitation, temperature, sea ice and more.

They perform decadal predictions as part of the international coordinated program through the UK MET Office (WMO). Large ensembles of multi-decadal climate projections are utilized in response to radiative forcing changes. The key point is that these prediction and projection systems are made possible through harvesting the fruits of decades-long research effort on both initialization systems, and model development—two of the key components of the seamless system.

Delworth elaborated further on example possibilities for seamless prediction, including facilitation of the attribution of observed events (retrospective predictions); and decadal predictive skill from internal variability, including:

- Atlantic ocean surface and subsurface temperature (AMOC, ocean circulation)
- Pacific Decadal Oscillation – is less predictable than North Atlantic phenomena
- Southern Ocean – potentially predictable on long-time scales



Seamless seasonal to multi-decadal prediction and projection

Thomas L. Delworth & collaborators
Seasonal to Decadal Variability and Predictability Division
GFDL/NOAA
6 June, 2019

Representative phenomena that give rise to variability & predictability in the climate system

Physical Phenomena	Variability & predictability timescale	
Mid-latitude storms, general circulation	Daily to two-week weather forecast	
Madden-Julian Oscillation, etc	Subseasonal	
El Nino/Southern Oscillation	Seasonal to interannual	Internal
Volcanic aerosol forcing	Seasonal to interannual	Forced
Decadal-scale ocean-atmosphere variability (AMO, PDO, etc)	Interannual to multidecadal	Internal
Anthropogenic greenhouse gases, aerosols, ozone changes	Decadal to centennial	Forced

Figure 10 Delworth: Phenomena

Seamless systems may provide advance warning of emerging threats; projected changes in sea surface temperature (SST) and atmosphere lead to new threats of tropical storms in the Arabian Sea where previously there were none—an identification of new threat. It is a powerful statement to say that decadally, we will have cyclonic storms where none occurred before. We are able to gain useful measures for decadal prediction.

GFDL is using next generation component models to build the next generation seamless prediction system. Drivers of this work include advances in scientific understanding, physics, and numerics; and user needs for improved predictions and projections on seasonal to multi-decadal time scales, especially for extremes and regional scales. Two versions are completed (Spear_Lo (100 km atmos resolution; reforecasts underway) and Spear_Med (50 km resolution; reforecasts are planned over the next six months). Spear_HI (25 km) is in development; a very limited set of reforecasts are planned due to computational costs. This next generation Spear has emerging capabilities for prediction aspects of ocean biogeochemistry. Delworth summarized possible actions for a broader U.S. perspective on 2-30 year predictions and projections (Figure 11).

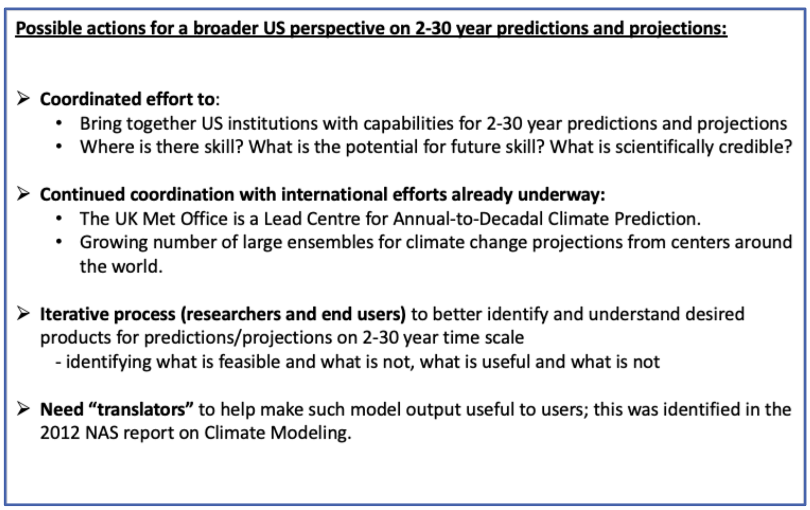


Figure 11 Delworth: Concrete Steps

Steve Yeager – NCAR Climate and Global Dynamics Laboratory (CGD) – Emerging capabilities

Yeager elaborated on the contributions NCAR can offer for a national ESPC effort, covering Interannual to Decadal (I2D) prediction system design developed at NCAR; example results from initialized predictions using the Community Earth System Model (CESM); and reviewed outstanding challenges and future plans. Key strengths of NCAR relevant to ESPC:

- NCAR is an international leader in coupled climate and Earth system model development (CESM), with multi-disciplinary scientific expertise in-house.
- NCAR has strong synergistic ties to the university geoscience community.
- Multi-agency support for prediction research.

- Emphasis is on process understanding (providing well-founded predictions).
- Strong ocean modeling expertise: and extensive research experience in I2D ocean variability and historical ocean state reconstruction (generating relevant initial conditions).
- Growing expertise in coupled data assimilation (DA).
- Promising results from preliminary explorations, since 2011.

Shared infrastructure – open collaboration

The National Unified Operational Prediction Capability (NUOPC) is a consortium of Navy, NOAA, and Air Force modelers and their research partners working toward a common model architecture – a standard way of building models. The collaboration has built the NUOPC Layer defining conventions and templates for using the Earth System Modeling Framework (ESMF). The next major release of the Community Earth System Model (CESM) will include all NUOPC compliant components, and new process workflows.

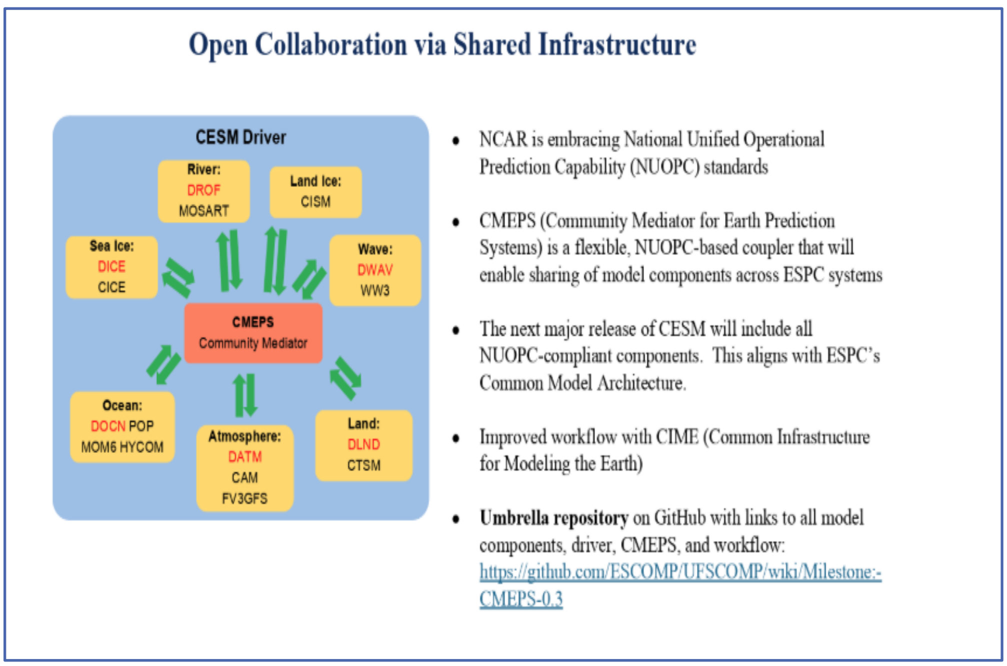


Figure 12 Yeager: NCAR CMEPS

Yeager described Interannual to Decadal (I2D) Prediction System Design and NCAR's contribution to the Decadal Climate Prediction Project (DCPP) of the WMO Coupled Model Intercomparison Project (CMIP6):

- 40-member CESM 20th century Large Ensemble of uninitialized runs provided a benchmark for evaluating the impacts of initialization.

- Forcing – initialized the fully coupled model in various ways (ocean and sea ice first) and conducted reanalysis of ocean/sea-ice simulations and 40 member ensemble hindcasts from 1954-2017.
- BAMS article September 2018: *Predicting Near-term Changes in the Earth System* (Yeager, 2018): a 26K sim-year experiment; provided prognostic ocean biogeochemistry; unprecedented statistical power for quantifying the impacts of initialization and ensemble size. Made possible by multi-agency support from NOAA, NSF, and DOE.
- I2D is gaining impactful skill in climate scale over land; and enhanced skill from the large ensemble:
    - High N. Atlantic upper ocean skill enabling predictions of 10-year trends in Arctic winter sea ice extent.
    - Predicting ocean biogeochemistry: have multi-year skill in predicting air-sea CO_2 flux; ongoing work is exploring predictability of other components of Earth's carbon cycle and other ocean biogeochemistry fields.
    - Predicting changes in weather extremes: I2D has gained unprecedented skill in predicting decadal variations in the frequency of winter blocking over Greenland (recent paper: 2019 Smith, D. et al, Clim Atm Sci) (Smith, 2019). Skill vs. ensemble size curve hints at potential for even greater predictability (with larger ensembles and/or improved models).
    - Combined dynamical-statistical predictions can be used to overcome poor representation of some processes in the coarse model.

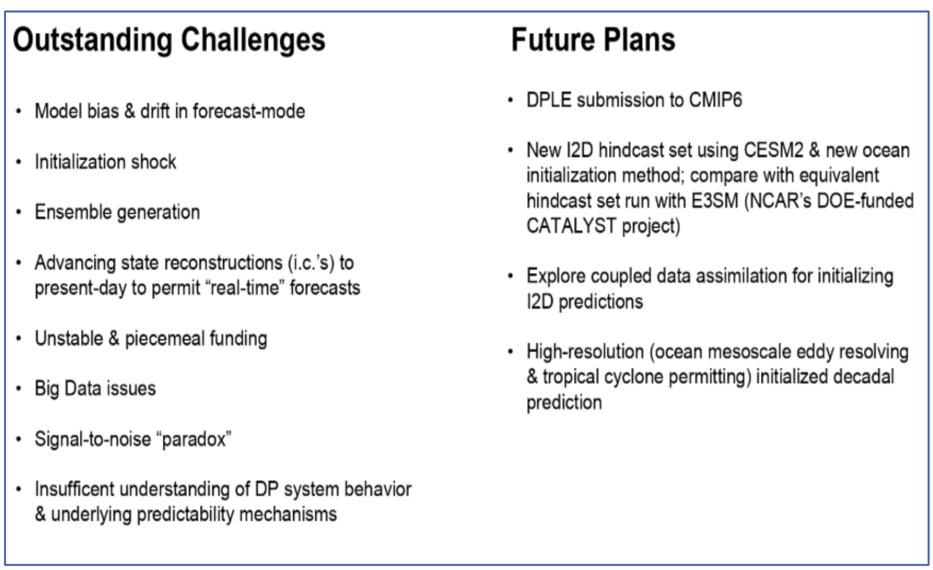


Figure 13 Yeager: Outstanding Challenges

Q&A

Coarse resolution models may not resolve deep water formation. Does the system pick up deep water formation, and what is the necessary resolution? Yes, we believe we are picking that up; it is not supported by many observations—there is not a lot to benchmark, but some extending back to the mid-1950s, and the coarse resolution model is able to capture low frequency variability in deep water formation. We don't have good observations for abyssal data. Other participant comment: deep water is formed by large-scale atmospheric processes; even if the real small-scale details are not modeled, the models have analogous representation.

Andrea Molod - NASA Global Fluid Dynamics Laboratory – Global Modeling and Assimilation Office (GMAO) - Emerging Capabilities

NASA has no direct mandate to provide forecasts on any timescale, but has interests in maintaining state-of-art forecasting systems. Participation in model intercomparisons is a way to ensure that expertise. NASA modeling efforts are "observation-driven" – the direction of modeling/assimilation work is guided by available and anticipated observations with the goal of extracting as much value as possible from observations, and determining the impact of observations on prediction skill. While the impact of observations on weather and seasonal forecasts has been clearly demonstrated, the impacts of present and future observations on decadal prediction skill has not yet been demonstrated. NASA's modeling and assimilation capabilities will be extended to assess these impacts. Potential future observations needed or to be assessed for improving decadal prediction include: sea ice thickness; permafrost; soil moisture; methane; deep Argo floats.

Sources of decadal predictability; motivation for observation/modeling strategy:

- Responses to a big event that impacts forcing long-term (e.g. volcanic eruption such as Pinatubo) – the signal in the stratosphere remains for years and may impact ENSO.
- Long time scale memory in the ocean – ventilation time scales at depths below 500m in some ocean basins are longer than 10 years.
- Long term variability: phase of the Pacific Decadal Oscillation (PDO), for example
- Longer time scale memory in the land/carbon cycle
- Climate time scale trends (e.g. sea level)

The longer the lead time, the longer the period of time-averaging needed, which increases the signal-to-noise ratio enough to obtain reliable forecasts. It is not clear what length of time-averaging is required at longer lead times.

NASA Predictability Studies

- Table of Community seasonal prediction system characteristics
- Working towards atmosphere-ocean-land coupled DA. Coupled data assimilation is critical for initialization of decadal prediction.

GEOS-ECCO is a new prototype modeling tool for decadal prediction—an ocean-ice-atmosphere coupled data assimilation system that can offer advantages:

- 4D-Var ocean DA with long data window. The entire 20-year model trajectory is adjusted simultaneously, with the potential to capture the longer time scale for better initialization of decadal forecasts.

- Configurations with high vertical resolution have potential for better resolution at ocean depths below available observations.

> *"None of these agencies (GFDL, NCAR, NASA) have the mandate, per se, for decadal prediction, but each of these three organizations are doing work and developing tools that are critical to the National Weather Service for where we want to go for seamless prediction—all the things taking place in decadal weather prediction."*
>
> *Brian Gross, Environmental Modeling Center,*
> *National Centers for Environmental Prediction*
>
> *"All prior and current work on all scales from these labs are essential for progress on effective decadal prediction."*
>
> *Hendrik Tolman, National Weather Service*

Fulfilling User Needs

Arun Kumar - Principal Scientist, Climate Prediction Center (CPC); Chair, WMO Inter-Programme Expert Team on Operational Predictions from Subseasonal to Longer Time Scales (IPET-OPSLS) – Advancing Operational Infrastructure

- WMO sets standards and enables collaboration globally, coordinating operational infrastructure and data exchange between different centers engaged in long-range forecasting (subseasonal, seasonal, decadal).
- IPET-OPSLS provides oversight on operational infrastructure on decadal time scales for prediction capabilities, communication technology, and how research needs to advance operational infrastructure, and develops data exchange requirements based on evolving user needs and technological advancements.

Kumar's presentation outlined the current WMO operational infrastructure for S2D predictions; operational issues and research requirements; and status in advancing operational infrastructure.

- Global Producing Centers and Regional Climate Centers provide information and support on a global scale. Regional Climate Outlook Forums are groupings of countries that have similar interests, producing user-relevant outlook products in real time, to reduce climate-related risks.
- 13 Global Producing Centers – these have operational status as well as meeting long-range forecasting requirements. On a monthly basis, seasonal forecasts are provided to the WMO Lead Center for Long Range Forecast, then they disseminate final forecasts to members. Products are available online.
- Annual to Decadal Climate Predictions (ADCP) – the lead office is the UK Met Office; outlooks are updated once a year; outlooks for year 1 and years 2-5 averaged.
- There are plans to release a *Global Annual to Decadal Climate Update (GA2DCU)* – it will mimic similar WMO updates for ENSO – an executive summary; current state of climate,

including potential drivers for low-frequency variability; multi-model based annual-to-decadal outlooks. The publication will be released once a year.

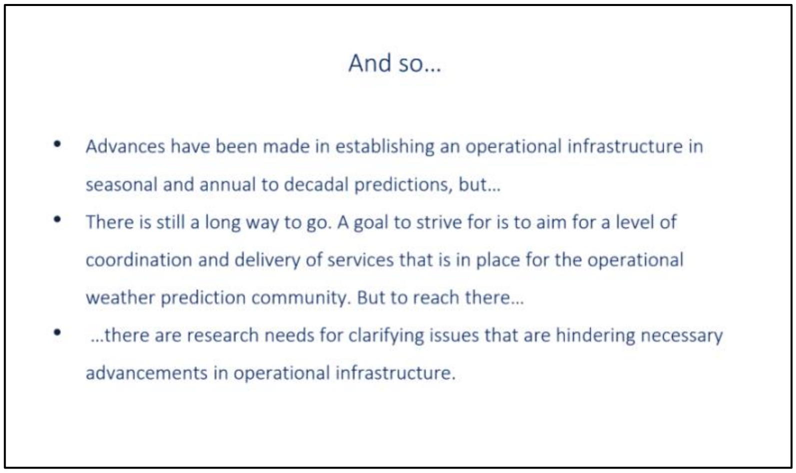


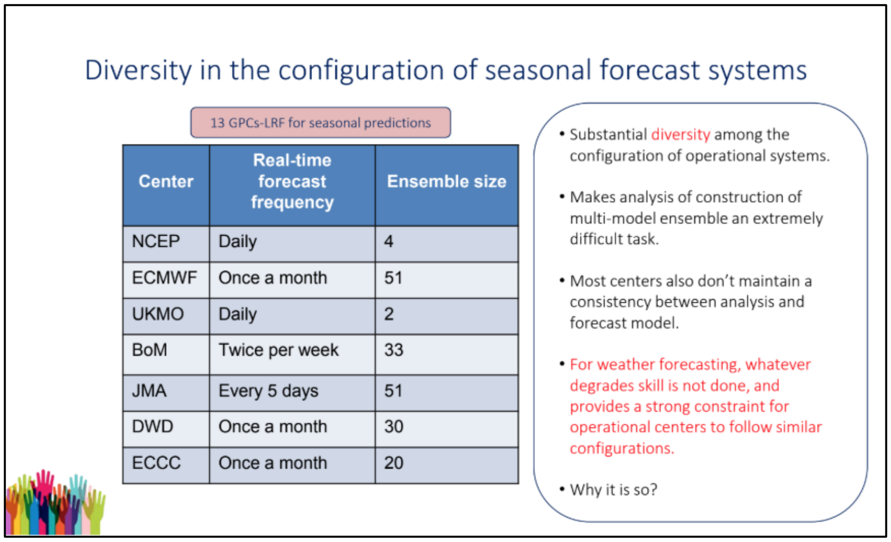
Figure 15 Kumar: Issues

Issues surrounding the advance of operational infrastructure include:

- Design of the configuration of operational prediction systems (and the science that provides the rationale for the design decisions): hindcast period, ensemble size, consistency of analysis across reforecasts and real-time forecasts; perturbation generation.
- Development of products and communication of probabilistic outlooks: bias correction, calibration, multi-model construction; communicating probability and reliability.
- Variation of forecasts: small sample size; intuitive vs. rigorous scores, conditional vs. unconditional skill, understanding past variations in skill.

There is large diversity in the current configurations of operational systems for long-range forecasting across different centers. Factors responsible for such diversity are equally numerous: operational schedules; length of hindcasts; ensemble size; assimilation methods and initialization; perturbation strategies; consistency of analysis across hindcasts and real-time forecasts. There are clear research needs to establish guides to what matters for realizing predictive skill to guide the design of operational systems. What model resolution is required? Which components of the Earth system are essential to include? What observations are critical for forecast initialization? The basic science question still is: what are the sources of predictability that can be realized? And pursuing answers to this question should continue.

Advancing operational infrastructure
A multi-model approach with reliance on an international infrastructure is going to be absolutely essential. A mechanism for periodic assessment in operational prediction systems and improvements in prediction skill is also needed.



Center	Real-time forecast frequency	Ensemble size
NCEP	Daily	4
ECMWF	Once a month	51
UKMO	Daily	2
BoM	Twice per week	33
JMA	Every 5 days	51
DWD	Once a month	30
ECCC	Once a month	20

Figure 16: Kumar – Diversity in configuration

Thoughts for panel discussion

- Developing strategies for international development across operational centers.
- Based on the current state of knowledge, a mechanism for developing recommendations for the design of operational systems.
- Understanding to what extent the current operational infrastructure is being utilized and what may be impediments to the utilization of information? Mechanisms for user feedback.
- Building and sustaining an observing system for the components that are key sources of predictability.
- How will services be delivered?

Q&A

- Regarding reliability/credibility/usability – there have been several stakeholder meetings between the NOAA Climate Program Office (CPO) and the Climate Prediction Center (CPC) – is there a documented set of stakeholder/user-requested products and an assessment of how these forecasts are being done? *Response:* There is some effort in CPC and in the Office of Weather and Air Quality (OWAQ/CPO) for stakeholder information in subseasonal; there is greater scale in what users expect. How are forecasts being used and how are these forecasts integrated? We have to have user needs/expectations, and need to find common ground.
- Is there any mechanism to track the users of operational decadal forecasts, to somehow assemble metrics of these uses? *Response:* We are hoping the UK Met Office will be able to provide some answers here.

Panel and Group Discussion: Andrea Molod – NASA GMAO; Jin Huang – NOAA CPO; John Cortinas, NOAA OWAQ

Molod:
Regarding traction with users: go back to predictability; look at what you are being shown: five year averages of a 40 member ensemble. *The interactions between developers and users is key to all of this.* Until we have a more formalized structure, a *simple user response desk* would give some guidance about how information is to be used, or not used.

Huang:
With increased capability from modeling centers, there are some opportunities for the U.S. to do more: organize efforts to use modeling activity to evaluate uses; involve users in requirements setting; gain feedback; an analog for an experimental prediction system. ESPC has been around for almost 10 years, and grew from the weather community. With increased interest and demand for timescales beyond seasonal, we need a formal way to have a *climate community*. Decadal prediction is a research-rich area. Experimental decadal prediction can set research goals.

Cortinas:
There are more pieces in place today than five years ago; the description of ESPC's origin is helpful. Agencies and organizations will continue to work toward their missions; we should bring their areas of expertise to ultimately configure some kind of operational capability. ESPC has the focus, and interagency engagement; there is already some framework in place (WMO; NMME); these could be starting points. It will take some group to organize a viable approach.

Group Discussion on starting points
The group engaged in a discussion about existing resources to utilize and leverage for coordination for long-term prediction/projection. These included ESPC; USGCRP and any of their agency-to user trickle-down avenues; OFCM Committee for Climate Services Coordination (CCSC); the Fourth National Climate Assessment Report; WMO frameworks: World Climate Research Programme (WCRP) and Near Term Climate Prediction (NTCP) initiative; NOAA Climate.gov; North American Multi-Model Ensemble (NMME) project. Resources with existing engagement and user needs avenues include: NOAA Regional Integrated Sciences & Assessments (RISA) program; NOAA Fisheries; USDA Climate Hubs; and DOI's Climate Adaptation Science Centers.

> *"Social sciences are a missing piece; we need the human element in every part of the process."*
>
> John Cortinas, NOAA Office of Weather and Air Quality

Comments on the panel discussion centered primarily on the importance of engagement with various user communities around needs vs. possibilities; defining further what is predictable; and facilitating movement toward coherent voicing and development for climate services needs.

User engagement

- The advantage of groups like the Regional Integrated Sciences and Assessments (RISA) teams is their regional nature and focus, which is key; and they involve both physical and social scientists, though they are limited to US regions.
- The projected report from this meeting should be discussed at the federal coordinators meeting: OFCM-CCCS – Committee for Climate Services Coordination. Arrange an ESPC/OFCM conversation.
- User engagement is key – we need a way to get the users to bubble up; we need to know what people are doing now. Town Halls at AMS and AGU were suggested.
- Break down the user engagement problem to manageable sectors. Start with a sector, a region of the country, various service agencies. Develop pilots. Engage users, but not all users at once: pick segments; start with AMS/AGU meetings.
- Creation of an ombudsman-like position within NOAA was suggested; it would require both a climatologist and a social scientist, to be effective.
- ESPC should have a way for the climate research community to engage.
- Federal agencies themselves are also the users – AG, DOD etc. There is need for the federal government to get consistent information.
- There is room for the private sector to be grooming answers for different user needs. Coordinate federal and research output, plans, and strategies; with the first goal of providing to federal agencies, and growing beyond that.
- Putting together a database for climate services information is a good place to start. Leverage the OFCM initial database; find out the key players and ensure they are informed.
- Ultimately, an updating capability is necessary for the extended range timescale. Due to its intermediary position between sub-seasonal to seasonal predictions (an initial value problem) and long-term projections (a boundary condition problem), this capability must be suitable to add in boundary problems such as sudden volcanic events.

Data use as avenue:

- The National Environmental Satellite, Data, and Information Service (NESDIS) is a data warehouse that holds much climate data, and might be a beginning point for how services can be delivered: using data delivery approaches. NESDIS is hosting primarily observational data, but they also have forecast data; the ocean data observation group should be involved.
- Data use as a starting point is somewhat problematic in that it would require translators, for effective usage. Climate data is big data, with lots of opportunity for problems to arise. Users People want the analysis done before they get the data. Intermediaries need to provide a summary of what the data is providing, and that in turn increases confidence in the data, by providing the analysis.

Path Forward - Possible Actions

The intent of this exploratory *Workshop on Building an Interannual to Decadal (2 to 30 year) Prediction/Projection Capability for Decision Support* was to form a basis for an emerging strategy and coordinated approach to extended range prediction/projection capabilities, based on user needs. Decadal prediction is a challenge scientifically, as it represents a transitionary period between seasonal predictions and long-term climate projections. Building a capability for decision support is a substantive collaborative and communications challenge organizationally as well. These collaborative and communicative challenges exist between scientists, decision-makers, users, but also between agencies. Additional challenges identified include:

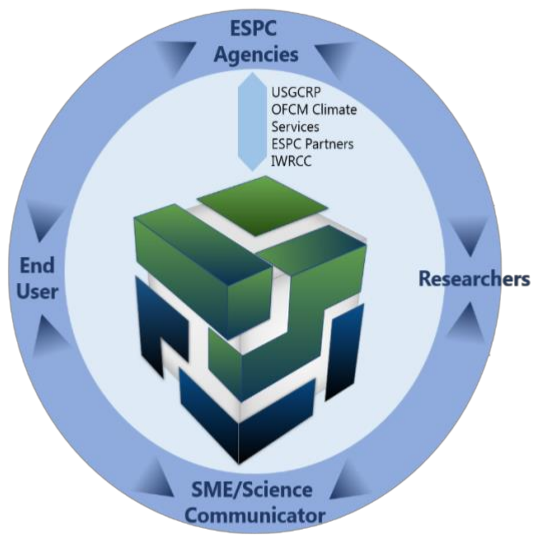
- Because the interannual to decadal time-scale lies in a transition zone between subseasonal to seasonal predictions (2 weeks to 2 years) and decadal projections, there are open questions concerning the predictability of commonly requested variables such as precipitation, sea-surface temperature, and land temperatures. Understanding of the physical processes that control or impact these variables, such as large-scale variability and climate modes, sunspots, volcanic eruptions, and their interactions with the global climate system, must be further studied and included in global climate models, with the assumption and ability to modify climate models as knowledge is gained, or with natural boundary processes such as volcanic eruptions. This modeling and research challenge necessitates high performance computing (HPC) advances.
- A primary challenge to building an interannual to decadal capability for decision support is the *lack of mission and mandate for operational (or experimental) predictions or projections on this time-scale*. While the subseasonal to seasonal and multi-year projection fields have mandated operational capabilities and experimental frameworks, the interannual to decadal timescale does not currently have a similar framework. This emphasizes the need for improved and sustained coordination among agencies. The available data and experimental frameworks employed to date make these data and results difficult to understand and ingest by users. With greater uptake of these predictions by users and increased interest and understanding, a mandate or mission to meet the needs of users could emerge.
- *Agency and organizational partnerships, and effective methodologies on how to encourage and nurture them with open lines of communication, are critical to understanding and meeting the needs of users*. The following organizations should be leveraged to form a cohesive capability, and further discussion should focus on currently available products versus user needs and gaps:
    - National ESPC (interagency)
    - Interagency Weather Research Coordination Committee (IWRCC/Office of the Federal Coordinator for Meteorology - OFCM)
    - U.S. Global Change Research Program (USGCRP)
    - Regional Integrated Sciences and Assessments Program (RISA/NOAA)
    - National Climate Assessment (NCA/USGCRP)

- National Integrated Drought Information System (NIDIS/NOAA)
- Climate Program Office (CPO/NOAA)
- NOAA Climate Prediction Center (CPC)
- U.S. Department of Agriculture (USDA) regional climate hubs
- Department of the Interior (DOI) Climate Adaptation Science Centers
- State climatological offices
- International organizations: the European Centre for Medium-Range Weather Forecasting (ECMWF) and its and World Meteorological Organization (WMO) regional centers and/or committees as appropriate

- Strong recommendations were made to determine the nature of current capabilities across these groups and agencies. *Conduct of an assessment of such capabilities, and how they will meet the needs of users (i.e. is the science reliable, credible, and salient?) was proposed, utilizing the OFCM Committee for Climate Coordination Services and its cross-agency capabilities database as a starting point.*
- Communication challenges also exist with users of climate data and decision-makers. A number of participants in the workshop noted that user engagement is a key step in this process. *To determine user needs and facilitate user engagement, several paths forward were discussed*:
  - An *ombudsman* of climate data, or a skilled translator of climate data with the ability to explain climate prediction/phenomena to a varied audience, as well as their needs to researchers and agencies, is a key component.
  - *Town halls and discussions* on interannual to decadal scale climate services at large meetings such as the American Meteorological Society (AMS) Meeting and the American Geophysical Union (AGU) Meeting were discussed as initial steps.
  - *An interannual to decadal (S2D) case study or pilot program* involving a key user group, such as agriculture, and determination of the needs in this sector compared to 1 to 5 year current capabilities was proposed. Pathways from the user to the research entity and agency, possibly involving a science communicator, must be determined. Once these pathways are determined, other users may be considered.
- Determine strategies for how *feasibility and user needs* discussions should occur between researchers, developers, and end-users; conversations need to be had about *what is predictable*.
- Unlike the National Weather Service (NWS), which has a mission for protecting life and property, there is no mandate in the U.S. to provide this kind of "climate service." *Framing the importance of meeting user needs for decadal prediction in economic impact and human impact terms* (land use, water use, extreme weather) is an avenue toward gaining advocacy, and *would help to create a mandate that could support development of such a service.*

- *Encourage capability at regional and state levels while pursuing the national effort*. State level support is key. Increase interest and advocacy; utilize existing networks and services: USDA Climate Hubs, RISAs, NCA as the potential first stop for users; Blue Action (ECMWF) as frameworks for understanding, leading toward a mandate.

The National ESPC is positioned to facilitate interagency efforts leading toward an interannual to decadal capability for decision support. Through collaborations and discussions with some of the organizations noted previously, namely the OFCM Climate Services Committee, USGCRP, IWRCC, and more, ESPC may be able to bring these interannual to decadal decision support ideas to their respective agencies. Again, user needs, researchers, and the science communicator must be included from the onset, optimistically leading to an iterative process that incorporates user needs in research questions and agency missions/mandates. An example of this process is shown in Figure 17.



The challenges and path forward are initial steps toward facilitating an interannual to decadal decision support capability. We envision further engagement and workshops that include other organizations working in the climate services sector; ESPC agency engagement with researchers; and roles for science communicators, end users, and social sciences experts.

Addendum 1 – Defining Prediction vs. Projection

Though they may sound similar, there are important differences between climate predictions and climate projections—both in process (i.e. how these data are simulated) and in interpretation. First, we must define "externally forced" variations in climate, those such as volcanic eruptions, anthropogenic atmospheric changes to atmospheric composition, and land use changes (among others). "Internally generated" climate variations are naturally occurring processes and interactions within the climate system (ENSO, PDO, etc.). Climate variables are characterized as a combination of internally generated and externally forced components. When simulating climate with a climate model, the temporal behavior of the climate system is represented under specified external forcing and boundary conditions. These simulations can form climate predictions or climate projections, discussed below.

A *climate projection* is a climate simulation extending into the future that is based on a *scenario* of possible future external forcing. These external forcings are also called *boundary conditions* or *boundary forcing*. A *climate prediction* or *climate forecast* is a statement about the future evolution of the climate system, and can encompass both internally generated and externally forced components. Climate predictions forecast the evolution of weekly to decadal averages or extremes, and are simulated using some of the same models as climate projections. Weather predictions and seasonal to interannual climate predictions are an *initial value* problem, and the governing equations are integrated forward in time based on observed initial conditions (see Figure). *Decadal climate predictions* lie in the interface between seasonal to interannual predictions (those that are initial value problems) and long-term climate projections (those that are boundary condition problems). Decadal predictions differ from seasonal to interannual predictions and long-term climate projections in that they are based in an observed initial state (as in seasonal to interannual predictions) *as well as* boundary conditions (as in long term climate projections) (see Figure 1).

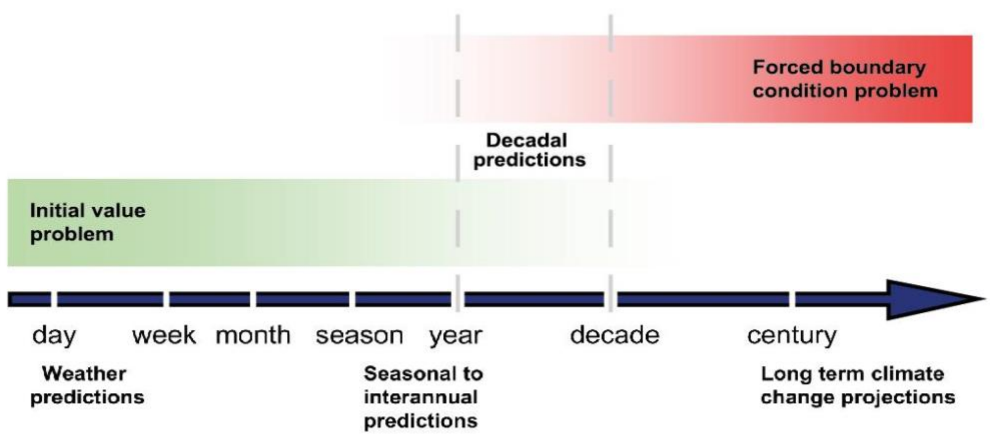


Figure 1: A schematic illustrating the progression from an initial-value based prediction at short time scales to the forced boundary-value problem of climate projection at long time scales. Decadal prediction occupies the middle ground between the two. (Chapter 11) (Meehl, et al., 2009b)

Addendum 2 – Acronyms

Acronym	Title
ADCP	Annual to Decadal Climate Predictions (WMO)
AFW	Air Force Weather
AGU	American Geophysical Union
AI	Artificial intelligence
AMOC	Atlantic Meridional Overturning Circulation
AMS	American Meteorological Society
CAR	Climate Adaptation and Resiliency (DOD)
CCSC	Committee for Climate Services Coordination (OFCM)
CESM	Community Earth System Model (NSF)
CFS	NOAA Climate Forecast System
CFSR	Climate Forecast System Reanalysis (NCAR)
CICE	Sea ice modeling consortium – development repository for the CICE sea-ice model (on GitHub)
CMIP	Coupled Model Intercomparison Project (WCRP)
CPC	Climate Prediction Center (NOAA)
CPC	Climate Prediction Center (NOAA)
CPO	Climate Program Office (NOAA)
DA	Data assimilation
DC	District of Columbia
DCPP	Decadal Climate Prediction Project (WCRP)
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
E3SM	Energy Exascale Earth System Model (DOE)
ECMWF	European Centre for Medium-Range Weather Forecasts
EMC	Environmental Modeling Center (NOAA)
ENSO	El Niño Southern Oscillation
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
ESA	European Space Agency
ESMF	Earth System Modeling Framework (NUOPC)
ESPC	Earth System Prediction Capability (Navy)
Euro GNSS	European Global Navigation Satellite Systems Agency
FCMSSR	Federal Committee for Meteorological Services and Supporting Research (interagency)
FEMA	Federal Emergency Management Administration
FLOR	Forecast oriented low ocean resolution
GEFS	Global Ensemble Forecast System
GEOINT	Geospatial intelligence (DOD/USAF)
GEOS-ECCO	NASA prototype modeling tool
GFDL	Global Fluid Dynamics Laboratory (NOAA)
GISS	Goddard Institute for Space Studies (NASA)
GMAO	Global Modeling and Assimilation Office (NASA)
GPC	Global Producing Center (WMO)
HPC	High performance computing

I2D	Interannual to decadal
IC	Intelligence community
ICEX	Ice exercise (U.S. Navy)
IGIM	Interagency Group on Integrative Modeling (USGCRP)
IPCC	Intergovernmental Panel on Climate Change
IPET-OPSLS	Inter-Programme Expert Team – Operational Predictions from Subseasonal to Longer Time Scales (WMO)
ISS	International Space Station
IWRCC	Interagency Weather Research Coordination Committee (OFCM)
MAPP	Modeling, Analysis, Predictions and Projections program (NOAA)
MJO	Madden Julian Oscillation
MME	Multi Model Ensemble
NAO	North Atlantic Oscillation
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NCA4	Fourth National Climate Assessment report
NCAR	National Center for Atmospheric Research
NCEP	National Center for Environmental Prediction (NOAA)
National ESPC	National Earth System Prediction Capability (interagency)
NESDIS	National Environmental Satellite, Data, and Information Service (NOAA)
NIC	National Ice Center
NIDIS	National Integrated Drought Information System (NOAA)
NMME	North American Multi-Model Ensemble
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
NTCP	Near-Term Climate Prediction (WCRP)
NUOPC	National Unified Operational Prediction Capability
NWP	Numerical weather prediction
NWS	National Weather Service (NOAA)
OES	Bureau of Oceans and International Environmental and Scientific Affairs (U.S. Dept. of State)
OCB	U.S. Carbon and Biogeochemistry Program
OES	Bureau of Oceans and International Environmental & Scientific Affairs (U.S. Dept. of State)
OFCM	Office of the Federal Coordinator for Meteorology
ONR	Office of Naval Research
OWAC	Office of Weather and Air Quality (NOAA)
PDO	Pacific Decadal Oscillation
PNA	Pacific/North American pattern
R&D	Research and development
RASM	Regional Arctic System Model (DOE)
RISA	Regional Integrated Sciences & Assessments Program (NOAA CPO)
S2D	Seasonal to decadal
S2S	Subseasonal to seasonal
SEARCH	Study of Environmental Arctic Change
SST	Sea surface temperature

STI	Office of Science and Technology Integration (NWS)
SubX	Subseasonal Prediction Experiment (NOAA)
US CLIVAR	U.S. Climate Variability and Predictability Program
US CLIVAR IAG	U.S. CLIVAR Inter-Agency Group
USDA	U.S. Department of Agriculture
UFS	Unified Forecast System (NOAA)
USN	U.S. Navy
USAA	United Services Automobile Association
USAF	United States Air Force
USCMS	U.S. Climate Modeling Summit (USGCRP)
USGCRP	U.S. Global Change Research Program (interagency)
USGS	United States Geological Survey
WCRP	World Climate Research Programme
WGCM	Working Group on Coupled Modeling (WCRP)
WGNE	Working Group on Numerical Experimentation (WCRP)
WGSIP	Working Group on Subseasonal to Interdecadal Prediction (WCRP)
WMO	World Meteorological Association

Addendum 3 - References

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