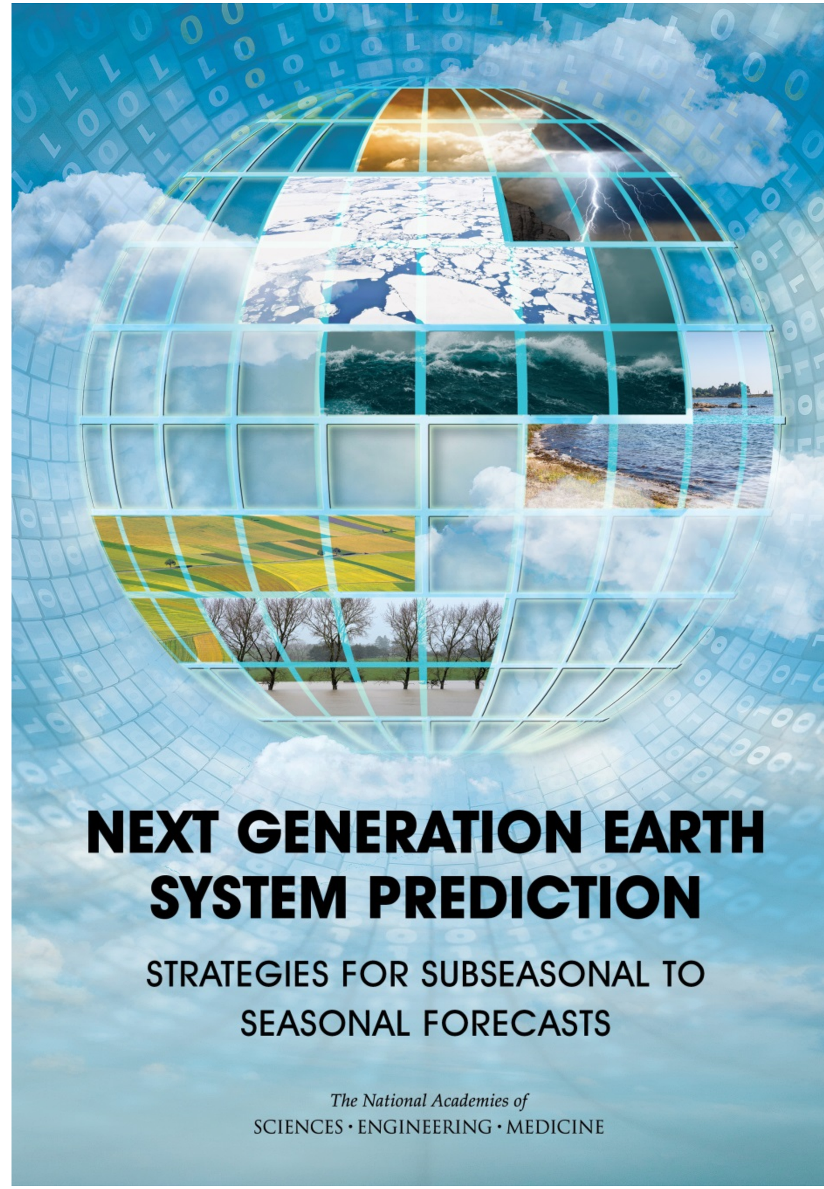
Next Generation Earth System Prediction:

Strategies for Subseasonal to Seasonal Forecasts



Presented by
Duane Waliser
JPL/Caltech/NASA

On Behalf of the S2S Study Committee

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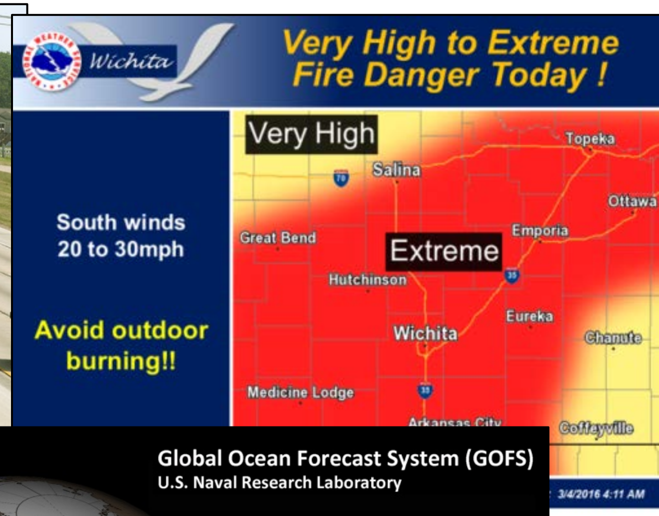
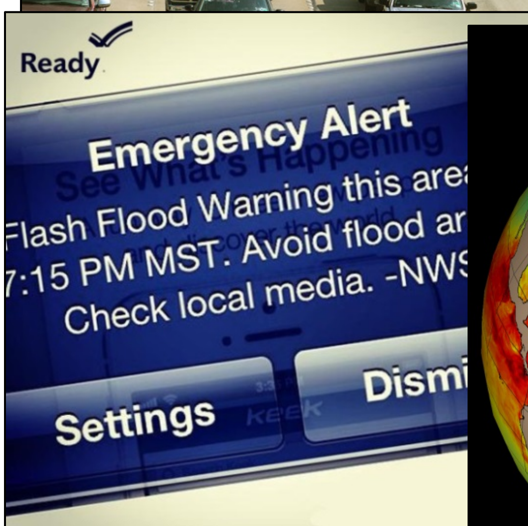
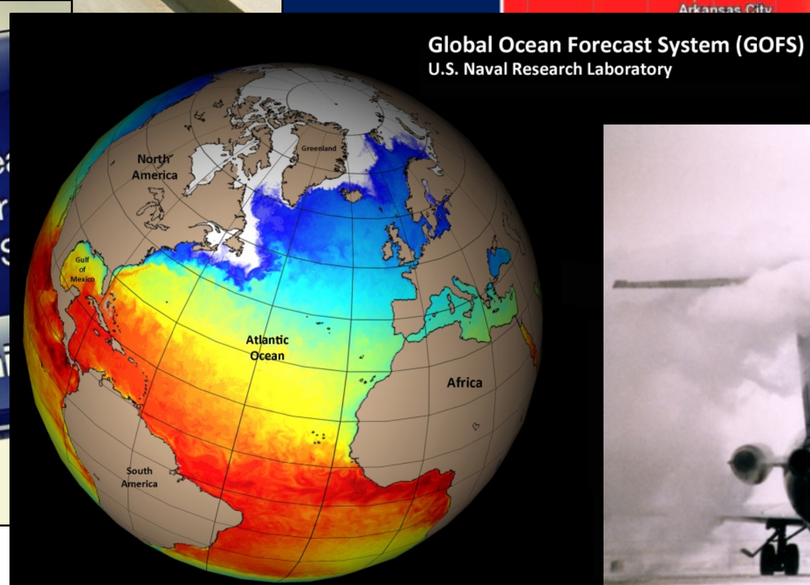
Weather, Water, and Climate Forecasts are Vital to Decision Making

Businesses Governments Individuals







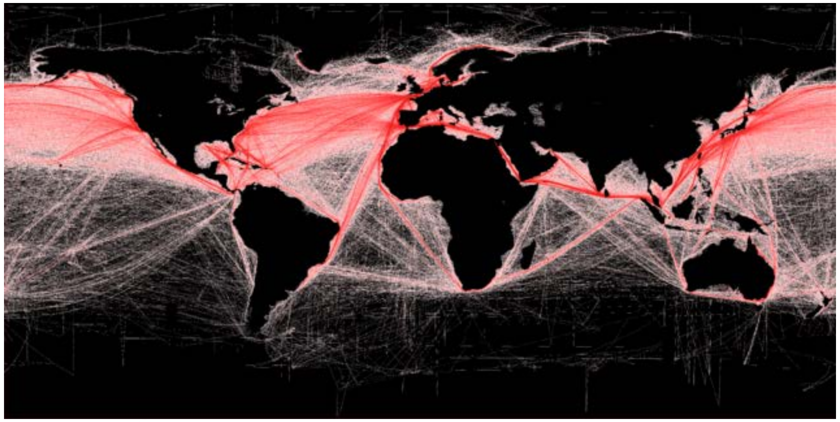
Forecast Timescales

- Weather 0-14 Days
- **Subseasonal 2-12 Weeks**
- **Seasonal 3-12 Months**
- Interannual 1 year - Decade
- Climate Decades - Centuries

Subseasonal to Seasonal (S2S)
2 weeks -12 months

What if Longer-Range Forecasts Were More Skillful and Widely Used?

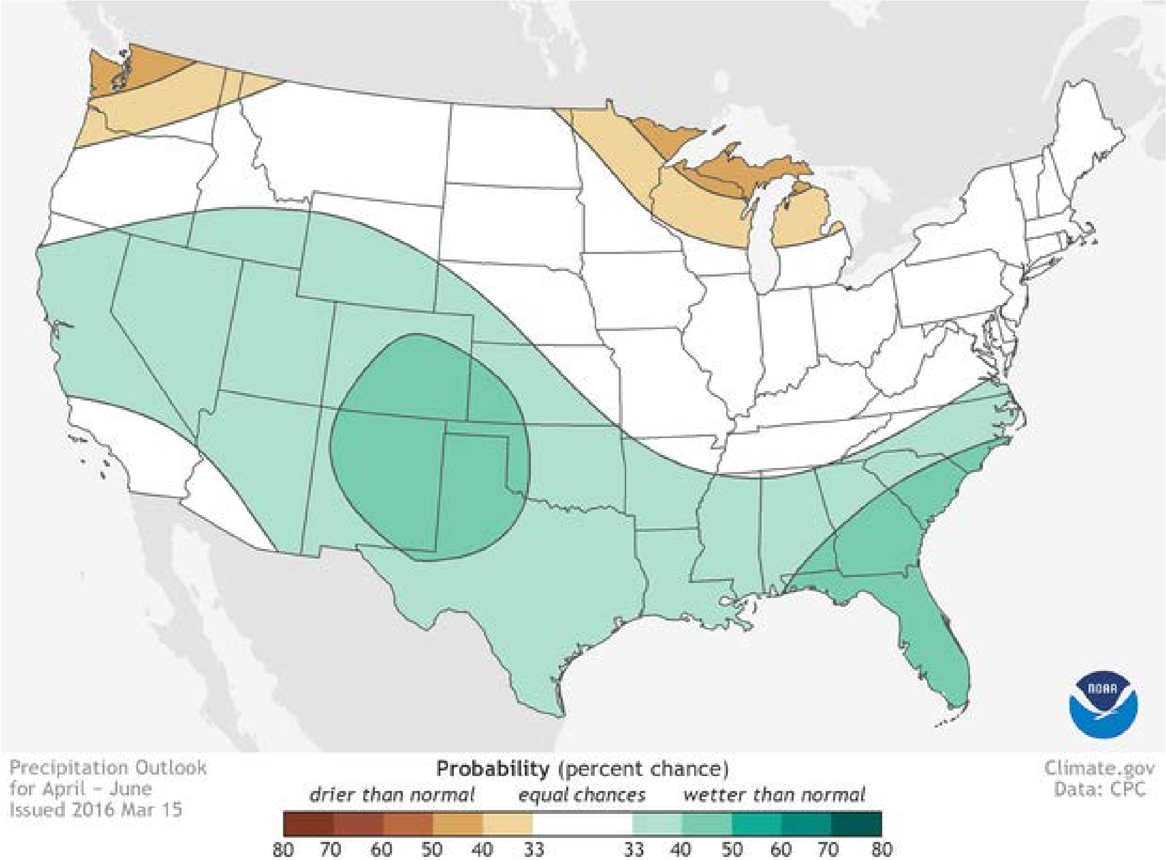
- Many decisions must be made in the space between weather forecasts and climate projections
- Improving S2S forecasts would benefit many sectors of society
- Will improve planning and preparation to help save lives, protect property, increase economic vitality



Current State of S2S Forecasting

- S2S forecasts are increasingly used in agriculture, energy, and water resource management—but more engagement with users in other sectors will increase use

Precipitation Outlook for April–June 2016
Issued March 15, 2016



Current State of S2S Forecasting

- Scientific knowledge gap, gaps in observations and modeling, and limited computational capacity currently limit accuracy of S2S forecasts

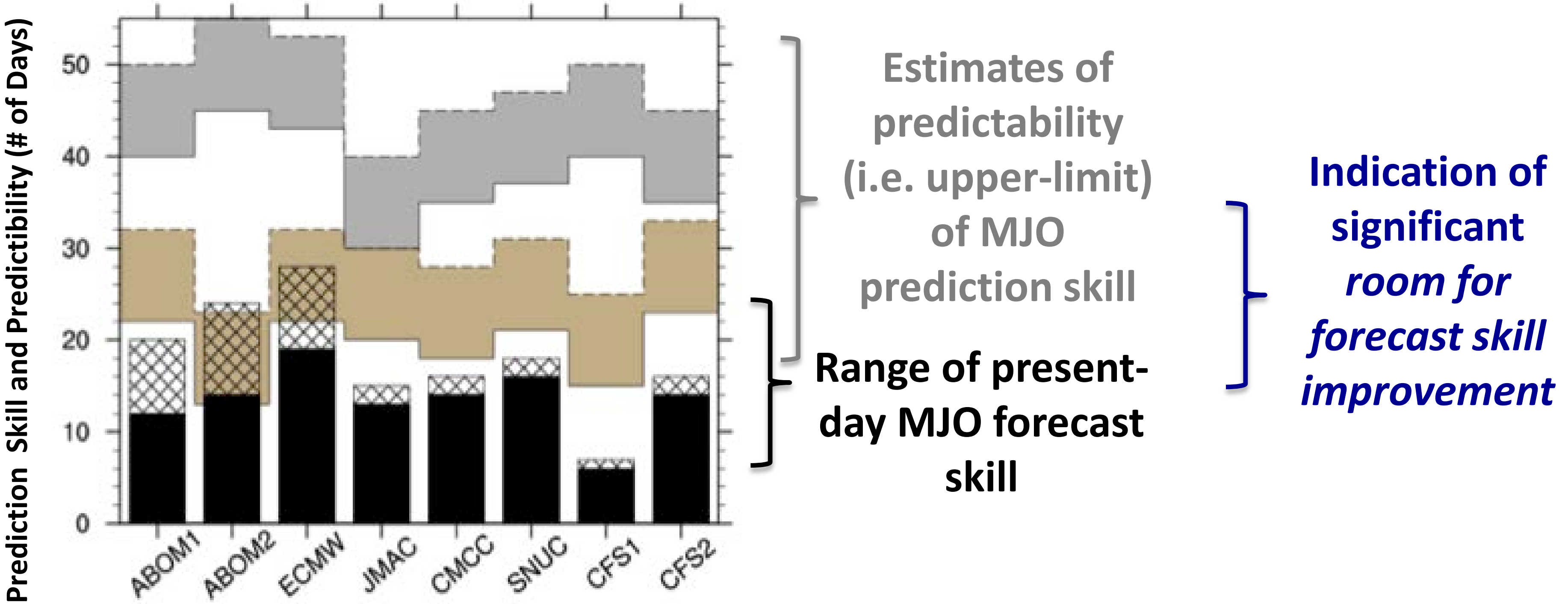


Figure 4.2
Neena et al., J. Climate, 2014

Why This Study?

- Sponsored by Office of Naval Research, Heising-Simons Foundation, NASA, and NAS Arthur L. Day Fund

Task:

- To describe a strategy to increase the nation's capacity for S2S forecasting
- To develop a 10 year scientific research agenda to accelerate progress

Committee Roster

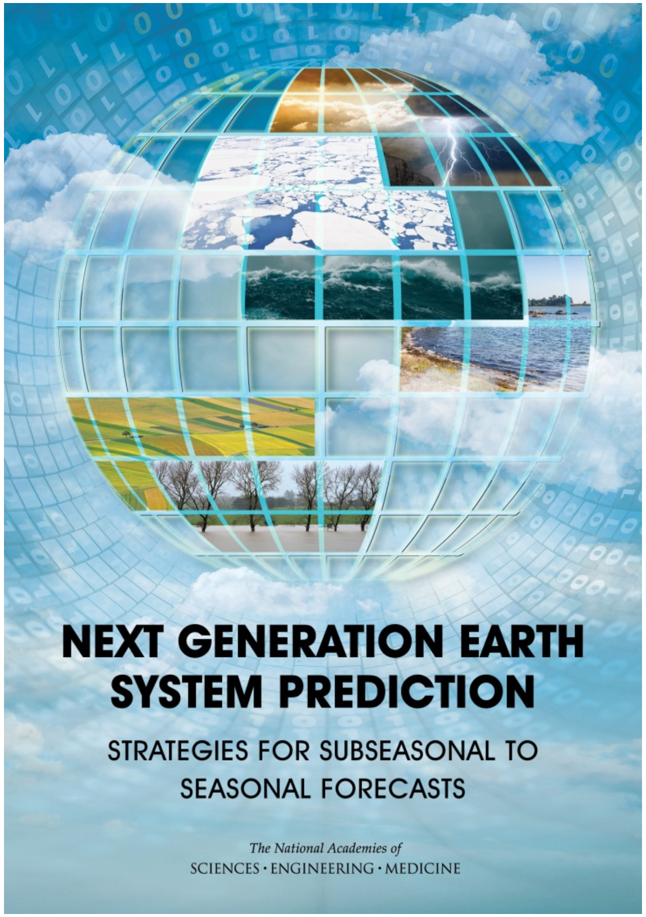
- **Raymond J. Ban (Chair),** Ban and Associates, LLC
- **Cecilia Bitz,** University of Washington
- **Andy Brown,** UK Met Office
- **Eric Chassignet,** Florida State University
- **John A. Dutton,** Prescient Weather, Ltd.
- **Robert Hallberg**, NOAA Geophysical Fluid Dynamics Laboratory
- **Anke Kamrath**, National Center for Atmospheric Research
- **Daryl Kleist,** University of Maryland, College Park
- **Pierre F.J. Lermusiaux,** Massachusetts Institute of Technology
- **Hai Lin,** Environment Canada
- **Laura Myers,** University of Alabama
- **Julie Pullen,** Stevens Institute of Technology
- **Scott Sandgathe,** University of Washington
- **Mark Shafer,** The University of Oklahoma
- **Duane Waliser,** Jet Propulsion Laboratory
- **Chidong Zhang,** University of Miami

Committee held five in-person meetings, spoke with dozens of researchers and users
Report reviewed by 12 outside experts

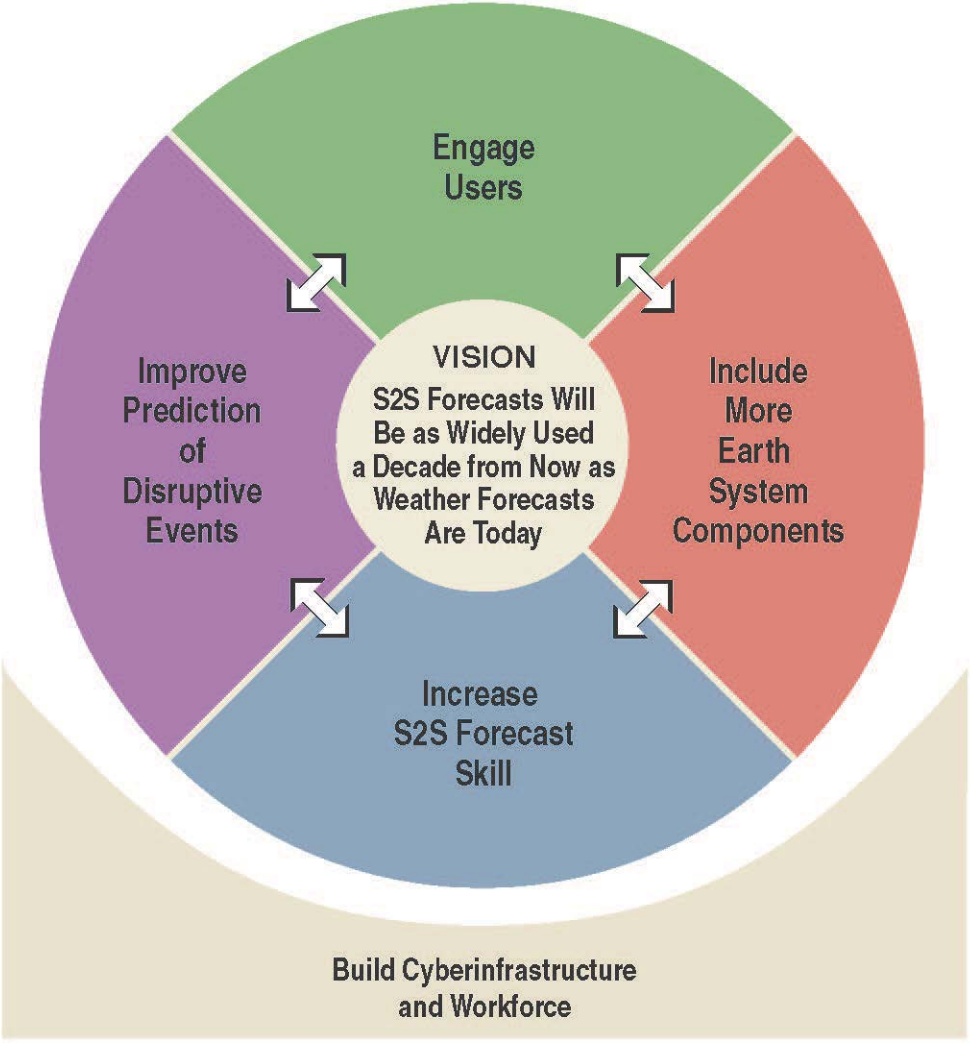
The Committee's Vision

S2S forecasts will be as widely used a decade from now as weather forecasts are today

- Fulfilling this vision will take sustained effort and investment



Fulfilling the Vision: Research Strategies



1. Engage Users
2. Increase S2S Forecast Skill
3. Improve Prediction of Disruptive Events
4. Include More Earth System Components

Research Strategy 1 – Engage Users

- Currently, there is a mismatch between available S2S forecasts and many end users' needs

Recommendation A: Develop a body of social science research that leads to more comprehensive and systematic understanding of the use and barriers to use of seasonal and subseasonal Earth system predictions.

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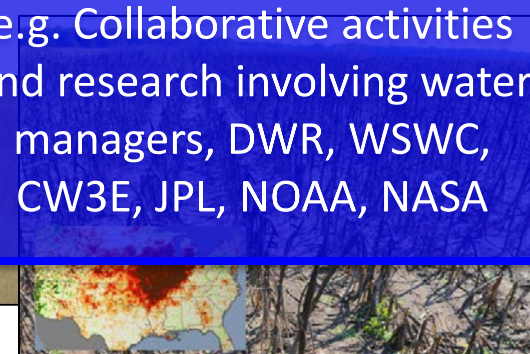
Research Strategy 1 – Engage Users

- More dialogue between researchers, forecasters and users will:
  - Accelerate application of S2S forecasts to decision making
  - Guide development of forecast verification metrics and products
- Government, academia, and private sector should all play a role

Recommendation B: Establish an ongoing and iterative process in which stakeholders, social and behavioral scientists, and physical scientists co-design S2S forecast products, verification metrics, and decision-making tools

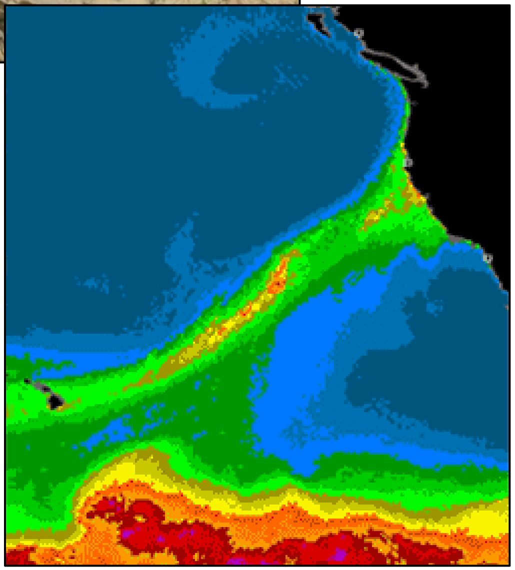
e.g. Collaborative activities and research involving water managers, DWR, WSWC, CW3E, JPL, NOAA, NASA



Example: Water Resource Management

Improved S2S predictions of drought and the probability of atmospheric river events will:

- Support improved management of reservoirs, including drought management, flood control, and planning for hydropower
- Need engagement to understand critical decisions and to produce forecast information that fits water project/agency location and timing needs

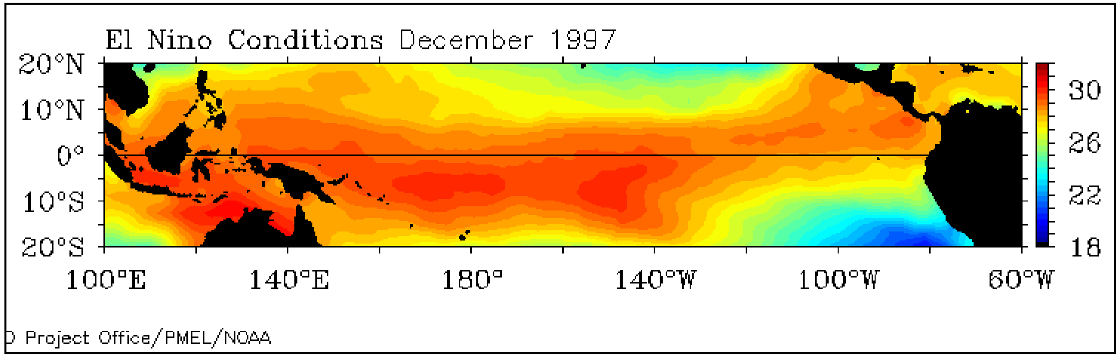


Research Strategy 2 – Increase S2S Forecast Skill

- Sources of predictability--natural processes in the atmosphere, ocean, or land surface that influence climate in predictable ways on S2S timescales
- Building blocks of S2S prediction

Recommendation C: Identify and characterize sources of S2S predictability, including natural modes of variability (e.g., ENSO, MJO, QBO), slowly varying processes (e.g., sea ice, soil moisture, and ocean eddies), and external forcing (e.g., aerosols), and correctly represent these sources of predictability, including their interactions, in S2S forecast systems.

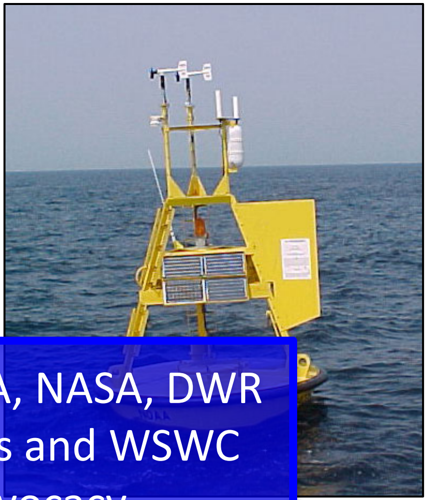
e.g. NASA, NOAA, NSF funded S2S research activities



Research Strategy 2 – Increase S2S Forecast Skill

- Observations are key to studying sources of S2S predictability
- Real-time observations are key for initializing forecast models

Recommendation E: Maintain continuity of critical observations, and expand the temporal and spatial coverage of in situ and remotely-sensed observations for Earth system variables that are beneficial for operational S2S prediction and for discovering and modeling new sources of S2S predictability



e.g. NOAA, NASA, DWR w/ states and WSWC advocacy

Research Strategy 2 – Increase S2S Forecast Skill

- Observations – cost and logistics will demand that scientists prioritize the most critical observations

Recommendation F: Determine priorities for observational systems and networks by developing and implementing OSSEs, OSEs, and other sensitivity studies using S2S forecast systems

Sorely needed national capabilities for formulating observational systems, both satellite, in-situ and their combination (NASA and NOAA in particular)

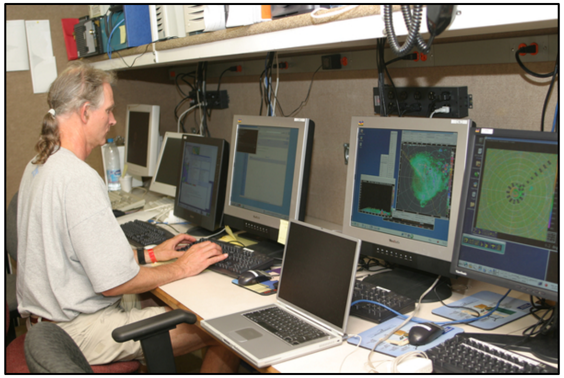
Research Strategy 2 – Increase S2S Forecast Skill

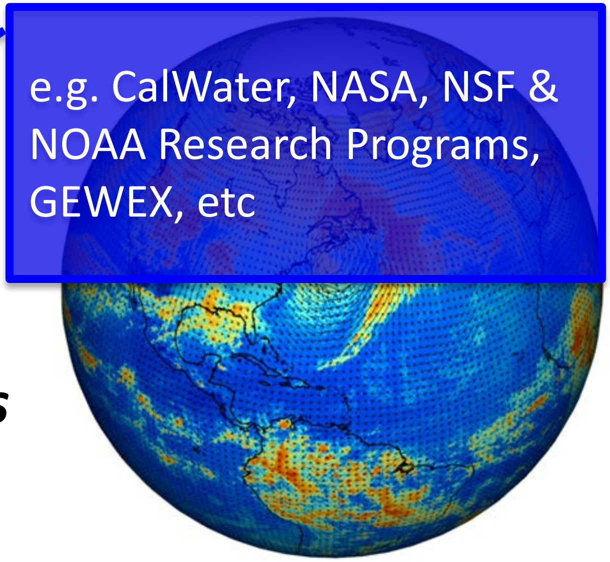
- Data assimilation is the process of initializing and updating Earth system models to be consistent with observations
- Capturing the interactions among components of the Earth system—a process known as "coupling"—is central to strengthening S2S predictions
- Developing data assimilation methods that allow for better coupling is important to improving S2S forecast systems

Recommendation G: Invest in research that advances the development of strongly-coupled data assimilation and quantifies the impact of such advances on operational S2S forecast systems

Research Strategy 2 – Increase S2S Forecast Skill

- Earth system models are critical to forecasting
- Critical Earth system processes need to be parameterized in models – represented through a set of equations rather than being resolved – for the foreseeable future
- Improving physical parameterizations is fundamental to increasing S2S forecast skill





Recommendation H: Accelerate research to improve parameterization of unresolved (e.g., subgrid scale) processes, both within S2S system submodels, and holistically across models to better represent coupling in the Earth system.

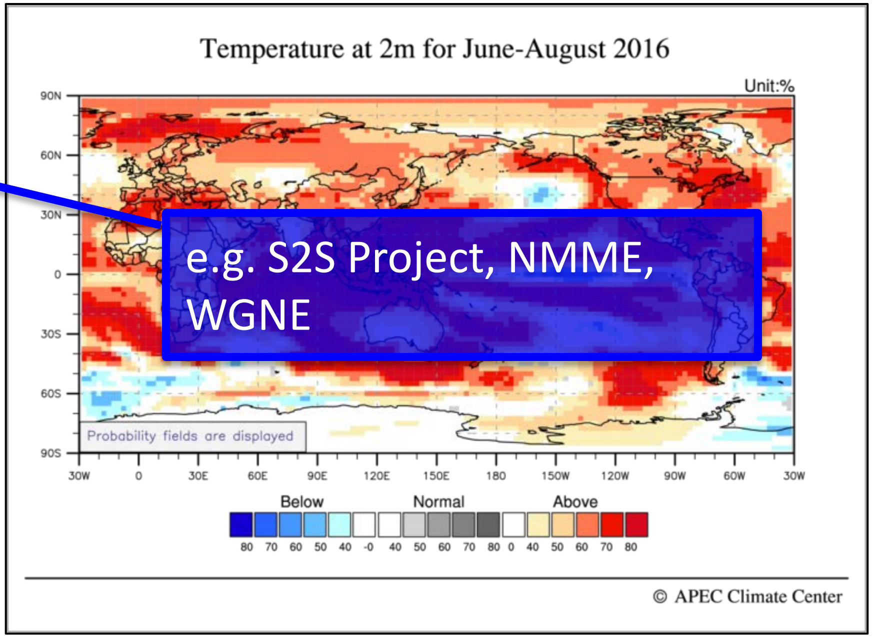
Research Strategy 2 – Increase S2S Forecast Skill

- Optimize the design of S2S forecast systems

Recommendation K: Explore systematically the impact of various S2S forecast system design elements on S2S forecast skill. This includes examining the value of model diversity, as well as the impact of various selections and combinations of model resolution, number of ensemble perturbations, length of lead, averaging period, length of retrospective forecasts, and options for coupled sub-models.

- Multi-model ensemble systems have shown great promise to improve S2S forecast skill

Recommendation L: Accelerate efforts to carefully design and create robust operational multi-model ensemble S2S forecast systems



Research Strategy 2 – Increase S2S Forecast Skill

- Significantly improve the transition of new ideas and tools from S2S research community to operational centers that actually issue routine forecasts to help inform decision-making.

Recommendation M: Provide mechanisms for research and operational communities to collaborate, and aid in transitioning components and parameterizations from the research community into operational centers, by increasing researcher access to operational or operational mirror systems

Tearing down silos

Example: Increasing Forecast Skill to Make Farming More Efficient

With improved S2S forecasts of:

- Temperature
- Precipitation
- Wind speed
- Relative humidity
- Soil temperature
- Projected dates of first/last freeze
- Probability of disruptive events – flood, drought, heat waves, freeze

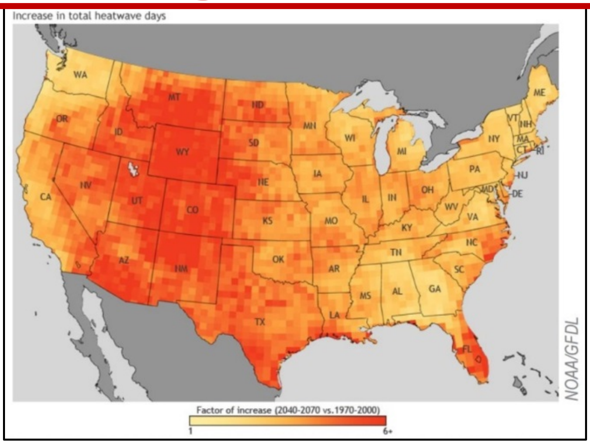
Farmers can better understand:

- What crops and varieties to plant
- When to apply irrigation, nutrients, pesticides & herbicides
- Projected crop yields to support decisions about food production and distribution

Research Strategy 3 - Improve Prediction of Extreme and Disruptive Events and of the Consequences of Unanticipated Forcing Events

- The prediction of events is often more meaningful to stakeholders than predicting mean conditions

- Forecasting the probabilities of such events on S2S timescales will likely involve identifying windows in time when the predictability of such events is elevated



Recommendation D: Focus predictability studies, process exploration, model development and forecast skill advancements on high impact S2S "forecasts of opportunity" that in particular target disruptive and extreme events

e.g. NOAA CPO, NASA+DWR funded S2S research activities

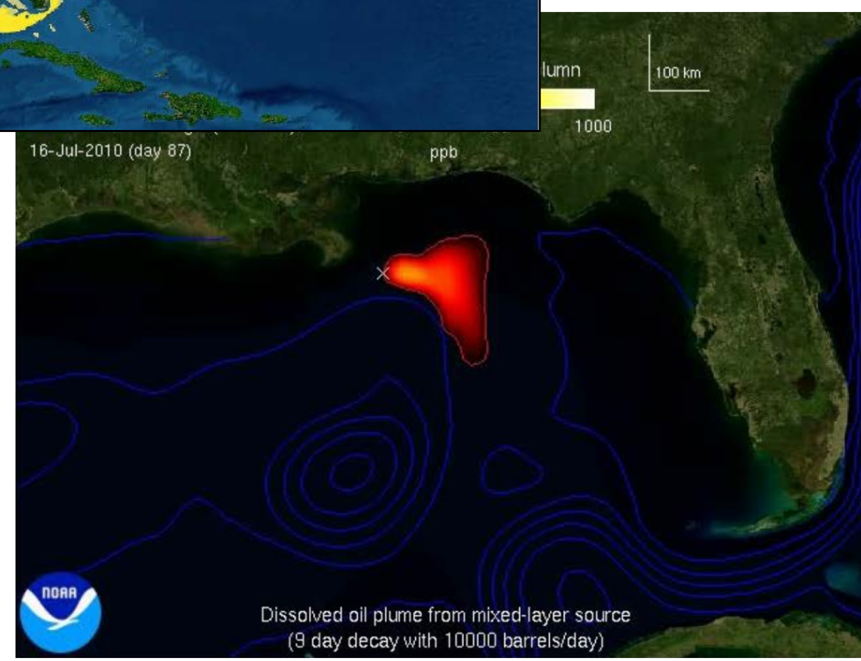
- S2S forecasts can also help predicting the consequences of unanticipated but strong forcing events (volcanos, oil spills, etc.)

Recommendation N: Develop a national capability to forecast the consequences of unanticipated forcing event

Example: Responding to Oil Spills

- Oil spills
  - S2S forecasts of loop currents can help researchers forecast where spilled oil will go
  - Where to direct resources for clean up
  - Need capability in place before event

Quickly assembled model



More deliberately assembled model

Research Strategy 4 – Include More Components of the Earth System in S2S Forecast Models

- A more complete description of the Earth system in S2S forecast systems will improve forecast skill
- Sub-models of the ocean, sea ice, land surface and other components are currently under developed or missing from S2S forecast systems
- S2S stakeholders are looking for forecasts of more variables

Recommendation I: Pursue next-generation ocean, sea ice, wave, biogeochemistry, and land surface/hydrologic as well as atmospheric model capability in fully-coupled Earth system models used in S2S forecast systems.

Example: Improving the Representation of the Ocean and Sea Ice in S2S Forecast Systems

- Navy
  - Forecasting of ocean variables (e.g., wind, wave height, ocean currents)
    - Planning shipping routes
    - Mission planning
  - Sea ice forecasts
    - Anticipating opening of Arctic shipping lanes

Supporting the S2S Endeavor: Cyberinfrastructure

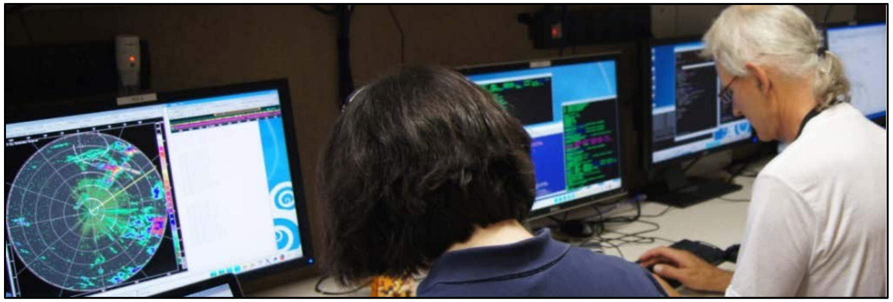
- The sheer volume of observational data, data assimilation steps, and model outputs involved in the S2S forecasting tests the limits of current cyber-infrastructure.
- Similar challenges exist in the weather and climate forecasting fields

Recommendation O: Develop a national plan and investment strategy for S2S prediction to take better advantage of current hardware and software and to meet the challenges in the evolution of new hardware and software for all stages of the prediction process, including data assimilation, operation of high-resolution coupled Earth system models, and storage and management of results

Supporting the Endeavor: Workforce

- Significant barriers exist to training and retaining talented workers in S2S model development
- Also need for more people trained to work across science-user interface

Recommendation P: Pursue a collection of actions to address workforce development that removes barriers that exist across the entire workforce pipeline and in the diversity of scientists and engineers involved in advancing S2S forecasting and the component and coupled systems



Notes on Implementation

- Research agenda is bold and will likely require additional resources
- Table S.1 provides more guidance
  - Possible need for new initiatives
  - Need for both basic and applied research
  - Need for international collaboration
- Report presents important actions needed without proscribing priority or sequence
  - Allows flexibility to changing conditions

Example: Recommendation A

- More detailed actions listed under each recommendation
- Tables (S.1 and 8.1) give further guidance

Recommendation	Research Strategies	Basic Research	Applied Research/ Operational	Benefits Likely in the Short Term	May Need New Initiative	International Collab. Criticlal
Chapter 3						
A: ***Develop a body of social science research that leads to more comprehensive and systematic understanding of the use and barriers to use of seasonal and subseasonal Earth system predictions.***	1, 4	■	■	■		
Characterize current and potential users of S2S forecasts and their decision-making contexts, and identify key commonalities and differences in needs (e.g., variables, temporal and spatial scale, lead times, and forecast skill) across multiple sectors.	1, 4		■	■		
Promote social and behavioral science research on the use of probabilistic forecast information.	1	■		■		
Create opportunities to share knowledge and practices among researchers working to improve the use of predictions across weather, subseasonal, and seasonal timescales.	1	■	■	■		

Recommendation	Research Strategies	Basic Research	Applied Research/ Opera-tional	Benefits Likely in the Short Term	May Need New Initiative	Inter-national Collab. Critical
Chapter 3						
A: ***Develop a body of social science research that leads to more comprehensive and systematic understanding of the use and barriers to use of seasonal and subseasonal Earth system predictions.***	1, 4	■	■	■		
Characterize current and potential users of S2S forecasts and their decision-making contexts, and identify key commonalities and differences in needs (e.g., variables, temporal and spatial scale, lead times, and forecast skill) across multiple sectors.	1, 4		■	■		
Promote social and behavioral science research on the use of probabilistic forecast information.	1	■		■		
Create opportunities to share knowledge and practices among researchers working to improve the use of predictions across weather, subseasonal, and seasonal timescales.	1	■	■	■		
B: ***Establish an ongoing and iterative process in which stakeholders, social and behavioral scientists, and physical scientists co-design S2S forecast products, verification metrics, and decision-making tools.***	1, 4	■	■	■		
Engage users with physical, social, and behavioral scientists to develop requirements for new products as advances are made in modeling technology and forecast skill, including forecasts for additional environmental variables.	1, 4	■	■	■		
In direct collaboration with users, develop ready-set-go scenarios that incorporate S2S predictions and weather forecasts to enable advance preparation for potential hazards as timelines shorten and uncertainty decreases.	1		■	■		
Support boundary organizations and private sector enterprises that act as interfaces between forecast producers and users.	1		■	■		
Chapter 4						
C: ***Identify and characterize sources of S2S predictability, including natural modes of variability (e.g., ENSO, MJO, QBO), slowly varying processes (e.g., sea ice, soil moisture, and ocean eddies), and external forcing (e.g., aerosols), and correctly represent these sources of predictability, including their interactions, in S2S forecast systems.***	2, 3	■		■		■
Use long-record and process-level observations and a hierarchy of models (theory, idealized models, high-resolution models, global earth system models, etc.) to explore and characterize the physical nature of sources of predictability and their interdependencies and dependencies on the background environment and external forcing.	2, 3	■		■		

e.g. Collaborative activities and research involving water managers, DWR, WSWC, CW3E, JPL, NOAA, NASA

e.g. NASA, NOAA, NSF funded S2S research activities

Recommendation	Research Strategies	Basic Research	Applied Research / Opera-tional	Benefits Likely in the Short Term	May Need New Initiative	Inter-national Collab. Criticial
Conduct comparable predictability and skill estimation studies and assess the relative importance of different sources of predictability and their interactions, using long-term observations and multi-model approaches (such as the World Meteorological Organization (WMO)-lead S2S Project's database of retrospective forecast data).	2, 3	■		■		■
D: ***Focus predictability studies, process exploration, model development and forecast skill advancements on high impact S2S "forecasts of opportunity" that in particular target disruptive and extreme events.***	3, 2	■		■		■
Determine how predictability sources (e.g. natural modes of variability, slowly varying processes, external forcing) and their multi-scale interactions can influence the occurrence, evolution and amplitude of extreme and disruptive events using long-record and process-level observations.	3, 2	■		■		
Ensure the relationships between disruptive and extreme weather/environmental events – or their proxies - and sources of S2S predictability (e.g. modes of natural variability and slowly-varying processes) are represented in S2S forecast systems.	3, 2	■		■		■
Investigate and estimate the predictability and prediction skill of disruptive and extreme events through utilization and further development of forecast and retrospective forecast databases, such as those from the S2S Project and the NMME.	3, 2	■		■		■
Chapter 5						
E: ***Maintain continuity of critical observations, and expand the temporal and spatial coverage of in situ and remotely-sensed observations for Earth system variables that are beneficial for operational S2S prediction and for discovering and modeling new sources of S2S predictability.***	2, 3, 4	■	■	■	■	■
Maintain continuous satellite measurement records of vertical profiles of atmospheric temperature and humidity without gaps in the data collection, and with increasing vertical resolution and accuracy.	2, 3, 4		■	■		■
Optimize and advance observations of clouds, precipitation, wind profiles and mesoscale storm and boundary layer structure and evolution. In particular, higher resolution observations of these quantities are needed for developing and advancing cloud-permitting components of future S2S forecast systems.	2, 3, 4	■	■			■
Maintain and advance satellite and other observational capabilities (e.g., radars, drifters, and gliders) to provide continuity and better spatial coverage, resolution, and quality of key surface ocean observations (SSH, SST, and winds), particularly near the coasts, where predictions of oceanic conditions are of the greatest societal importance in their own right	2, 3, 4	■	■	■	■	■

e.g. NASA, NOAA and DWR funded S2S research activities

e.g. NOAA, NASA, DWR w/ states and WSWC advocacy

Recommendation	Research Strategies	Basic Research	Applied Research / Operational	Benefits Likely in the Short Term	May Need New Initiative	International Collab. Critical
Maintain and expand the network of in situ instruments providing routine real-time measurements of sub-surface ocean properties, such as temperature, salinity, and currents, with increasing resolutions and accuracy. Appropriate platforms for these instruments will include arrays of moored buoys (especially in the tropics), AUVs, marine mammals, and profiling floats.	2, 3, 4		■	■	■	■
Develop accurate and timely year-round sea ice thickness measurements; if from remote sensing of sea ice freeboard, simultaneous snow depth measurements are needed to translate the observation of freeboard into sea ice thickness.	2, 3, 4	■	■	■		■
Expand in situ measurements of precipitation, snow depth, soil moisture, and land-surface fluxes, and improve and/or better exploit remotely-sensed soil moisture,, snow water equivalent, and evapotranspiration measurements.	2, 3, 4	■	■	■	■	■
Continue to invest in observations (both in situ and remotely sensed) that are important for informing fluxes between the component interfaces, including but not limited to land surface observations of temperature, moisture, and snow depth; marine surface observations from tropical moored buoys; ocean observations of near-surface currents, temperature, salinity, ocean heat content, mixed-layer depth, and sea ice conditions.	2, 3, 4	■	■	■		■
Apply autonomous and other new observing technologies to expand the spatial and temporal coverage of observation networks, and support the continued development of these observational methodologies.	2, 3, 4	■	■			
F: ***Determine priorities for observational systems and networks by developing and implementing OSSEs, OSEs, and other sensitivity studies using S2S forecast systems***	2, 3, 4	■	■	■	■	
G: ***Invest in research that advances the development of strongly-coupled data assimilation and quantifies the impact of such advances on operational S2S forecast systems***	2, 3, 4	■	■	■	■	■
Continue to test and develop weakly coupled systems as operationally viable systems and as benchmarks for strongly coupled implementations.	2, 3, 4	■	■	■		
Further develop and evaluate hybrid assimilation methods, multiscale- and coupled-covariance update algorithms, non-Gaussian nonlinear assimilation, and rigorous reduced-order stochastic modeling.	2, 3, 4	■	■	■	■	
Optimize the use of observations collected for the ocean, land surface, and sea ice components, in part through coupled-covariances and mutual information algorithms, and through autonomous adaptive sampling and observation targeting schemes.	4, 2, 3	■	■	■		

Recommendation	Research Strategies	Basic Research	Applied Research/ Opera-tional	Benefits Likely in the Short Term	May Need New Initiative	Inter-national Collab. Critical
Further develop the joint estimation of coupled states and parameters, as well as quantitative methods that discriminate among, and learn, parameterizations.	2, 3, 4	■—	—■	■		
Develop methods and systems to fully utilize all relevant satellite and in situ atmospheric information, especially for cloudy and precipitating conditions	2, 3, 4	■—	—■			
Foster interactions among the growing number of science and engineering communities involved in data assimilation, Bayesian inference, and uncertainty quantification.	2, 3, 4	■	■			■
H: ***Accelerate research to improve parameterization of unresolved (e.g., subgrid scale) processes, both within S2S system submodels, and holistically across models to better represent coupling in the Earth system.***	2, 3, 4	■		■	■	■
Foster long-term collaborations among scientists across academia, and research and operational modeling centers, and across ocean, sea ice, land and atmospheric observation and modeling communities, to identify root causes of error in parameterization schemes, to correct these errors, and to develop, test and optimize new (especially scale-aware or independent) parameterization schemes in a holistic manner	2, 3, 4	■		■		
Continue to investigate the potential for reducing model errors through increases in horizontal and vertical resolutions in the atmosphere and other model components, ideally in a coupled model framework (see also Recommendation L).	2, 3, 4	■		■		
Encourage field campaigns targeted at increasing knowledge of processes that are poorly understood or poorly represented in S2S models, including tropical convection, ocean mixing, polar sea-ice and stratospheric processes, and coupling among different Earth system components (e.g., air-sea-ice-wave-land; troposphere-stratosphere; dynamics-biogeochemistry).	2, 3, 4	■		■	■	■
Develop high-resolution (or multi-resolution) modeling systems (e.g., that permit atmospheric deep convection and non-hydrostatic ocean processes) to advance process understanding and promote the development of high-resolution operational prototypes (see also Recommendation I).	2, 3, 4	■			■	
I: ***Pursue next-generation ocean, sea ice, wave, biogeochemistry, and land surface/hydrologic as well as atmospheric model capability in fully-coupled Earth system models used in S2S forecast systems.***	4, 2, 3	■—	—■	■	■	
Build a robust research program to explore potential benefits to S2S predictive skill and to forecast users from adding more advanced Earth system components in forecast systems.	4, 2, 3	■		■		

e.g. CalWater, NASA & NOAA Research Programs, S2S Project

Recommendation	Research Strategies	Basic Research	Applied Research / Opera-tional	Benefits Likely in the Short Term	May Need New Initiative	Inter-national Collab. Criticial
Initiate new efficient partnerships between academics and operational centers to create the next generation model components that can be easily integrated in coupled S2S Earth system models.	4, 2, 3	■	■		■	
Support and expand model coupling frameworks to link ocean/atmosphere/land/wave/ice models inter-operably for rapidly and easily exchanging flux and variable information.	4, 2, 3	■	■	■		
Develop a strategy to transition very high resolution (eddy/cloud-resolving) atmosphere-ocean-land-sea ice coupled models to operations, including strategies for new parameterization schemes, data assimilation procedures, and multi-model ensembles (MME).	2, 3, 4	■	■		■	■
J: ***Pursue feature-based verification techniques in order to more readily capture limited predictability at S2S timescales, as part of a larger effort to improve S2S forecast verification.***	2, 1, 3	■	■	■	■	■
Investigate methodologies for ensemble feature verification including two-step processes linking features to critical user criterion.	2, 1	■		■	■	
Pursue verification methodologies for rare and extreme events at S2S timescales, especially those related to multi-model ensemble predictions.	3, 1, 2	■		■		
Consider the benefits of producing more frequent reanalyses using coupled S2S forecast systems in order for the initial conditions of retrospective forecasts to be more consistent with the real time forecasts, as well as for the purposes of predictability studies.	2, 1		■	■		■
K: ***Explore systematically the impact of various S2S forecast system design elements on S2S forecast skill. This includes examining the value of model diversity, as well as the impact of various selections and combinations of model resolution, number of ensemble perturbations, length of lead, averaging period, length of retrospective forecasts, and options for coupled sub-models.***	2, 3, 4	■	■	■	■	■
Design a coordinated program to assess the costs and benefits of including additional processes in S2S systems, and relate those to benefits from other investments, for example in higher resolution. In doing so, take advantage of the opportunity to leverage experience and codes from the climate modeling community.	2, 3, 4	■	■		■	
Encourage systematic studies of the costs and benefits of increasing the vertical and horizontal resolution of S2S models.	2, 3, 4	■	■			
Evaluate calibration methods and ascertain whether some methods offer clear advantage over others for certain applications, as part of studies of the optimum configurations of S2S models.	2, 3, 4	■	■	■		

e.g. example discussed later in research talk

e.g. S2S Project, NMME

Recommendation	Research Strategies	Basic Research	Applied Research / Operational	Benefits Likely in the Short Term	May Need New Initiative	International Collab. Critical
Explore systematically how many unique models in a multi-model ensemble are required to predict useful S2S parameters, and whether those models require unique data assimilation, physical parameterizations, or atmosphere, ocean, land, and ice components (see also Recommendation L).	2, 3, 4	■	■	■		■
Chapter 6						
L: ***Accelerate efforts to carefully design and create robust operational multi-model ensemble S2S forecast systems.***	2, 3		■		■	■
Use test beds and interagency and international collaborations where feasible to systematically explore the impact of various S2S forecast system design elements on S2S forecast skill, in particular the question how many unique models in a multi-model ensemble are required to predict operationally useful S2S parameters (see also Recommendation K).	2, 3		■			■
Assess realistically the available operational resources and centers that are able to contribute operationally rigorous prediction systems.	2, 3		■		■	
M: ***Provide mechanisms for research and operational communities to collaborate, and aid in transitioning components and parameterizations from the research community into operational centers, by increasing researcher access to operational or operational mirror systems.***	2, 1, 3, 4		■	■		■
Increase opportunities for S2S researchers to participate in operational centers.	2, 3, 4		■	■		
Enhance interactions with the international community, e.g., the S2S Project and APCC, and with the WMO Lead Centers.	2, 3, 4		■	■		■
Provide better access in the near-term to archived data from operational systems, potentially via test centers.	2, 3, 4		■	■		
Develop, in the longer term, the ability for researchers to request re-runs or do runs themselves of operational model forecasts.	2, 3, 4		■			
Encourage effective partnerships with the private sector through ongoing engagement (see also Recommendation 3B)	2, 1		■	■		
N: ***Develop a national capability to forecast the consequences of unanticipated forcing events.***	3, 1		■		■	
Improve the coordination of government agencies and academics to be able to quickly respond to unanticipated events to provide S2S forecasts and associated responses using the unanticipated events as sources of predictability.	3, 1		■		■	
Utilize emerging applications of Earth system models for long-range transport and dispersion processes (e.g., of aerosols).	3, 1		■			

e.g. S2S Project, NMME

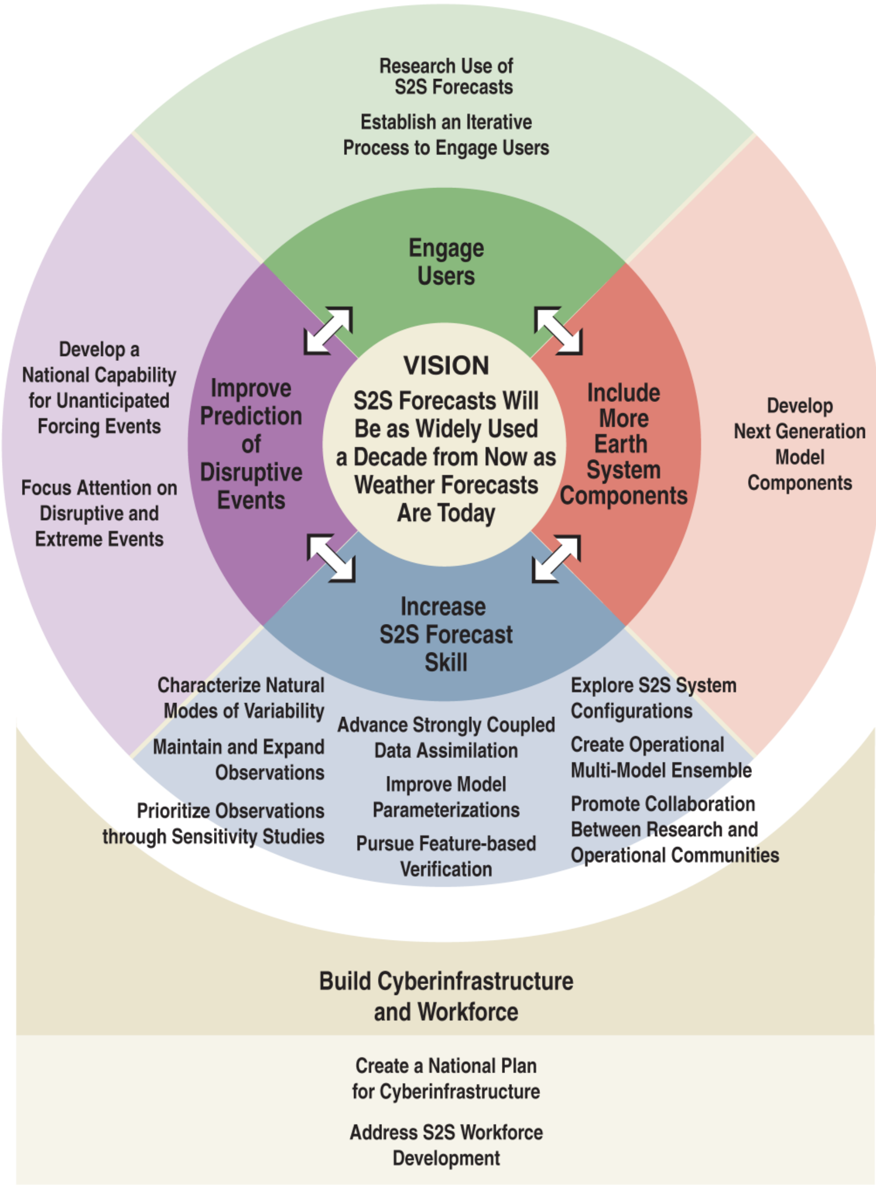
Important – but challenging

Recommendation	Research Strategies	Basic Research	Applied Research / Opera-tional	Benefits Likely in the Short Term	May Need New Initiative	Inter-national Collab. Criticlal
Increase research on the generation, validation, and verification of forecasts for the aftermath of unanticipated forcing events.	3, 1	■	■			
Chapter 7						
O: ***Develop a national plan and investment strategy for S2S prediction to take better advantage of current hardware and software and to meet the challenges in the evolution of new hardware and software for all stages of the prediction process, including data assimilation, operation of high-resolution coupled Earth system models, and storage and management of results.***	Supporting	■	■	■	■	
Redesign and recode S2S models and data assimilation systems so they will be capable of exploiting current and future massively parallel computational capabilities; this will require a significant and long-term investment in computer scientists, software engineers, applied mathematicians, and statistics researchers in partnership with the S2S researchers.	Supporting	■	■		■	
Increase efforts to achieve an integrated modeling environment using the opportunity of S2S and seamless prediction to bring operational agency (ESPC) efforts and IGIM efforts together to create common software infrastructure and standards for component interfaces.	Supporting	■	■	■		
Provide larger and dedicated supercomputing and storage resources.	Supporting		■	■	■	
Resolve the emerging challenges around S2S big data, including development and deployment of integrated data-intensive cyberinfrastructure, utilization of efficient data-centric workflows, reduction of stored data volumes, and deployment of data serving and analysis capabilities for users outside the research/operational community.	Supporting	■	■			
Further develop techniques for high volume data processing and in-line data volume reduction.	Supporting	■	■	■		
Continue to develop dynamic model cores that take the advantage of new computer technology.	Supporting	■	■	■		
P: ***Pursue a collection of actions to address workforce development that removes barriers that exist across the entire workforce pipeline and in the diversity of scientists and engineers involved in advancing S2S forecasting and the component and coupled systems.***	Supporting		■	■	■	
Gather quantitative information about workforce requirements and expertise base to support S2S modeling in order to more fully develop such a training program and workforce pipeline.	Supporting		■	■		

Recommendation	Research Strategies	Basic Research	Applied Research / Opera-tional	Benefits Likely in the Short Term	May Need New Initiative	Inter-national Collab. Criticlal
Improve incentives and funding to support existing professionals and to attract new professionals to the S2S research community, especially in model development and improvement, and for those who bridge scientific disciplines and/or work at component interfaces.	Supporting		■		■	
Expand interdisciplinary programs to train a more robust workforce to be employed in boundary organizations that work in between S2S model developers and those who use forecasts.	Supporting		■		■	
Provide more graduate and postgraduate training opportunities, enhanced professional recognition and career advancement, and adequate incentives to encourage top students in relevant scientific and computer programming disciplines to choose S2S model development and research as a career.	Supporting		■		■	

Bringing It All Together

- Vision and research agenda are bold
- **S2S forecasts will be as widely used a decade from now as weather forecasts are today**
- Fulfilling this vision will take sustained effort and investment



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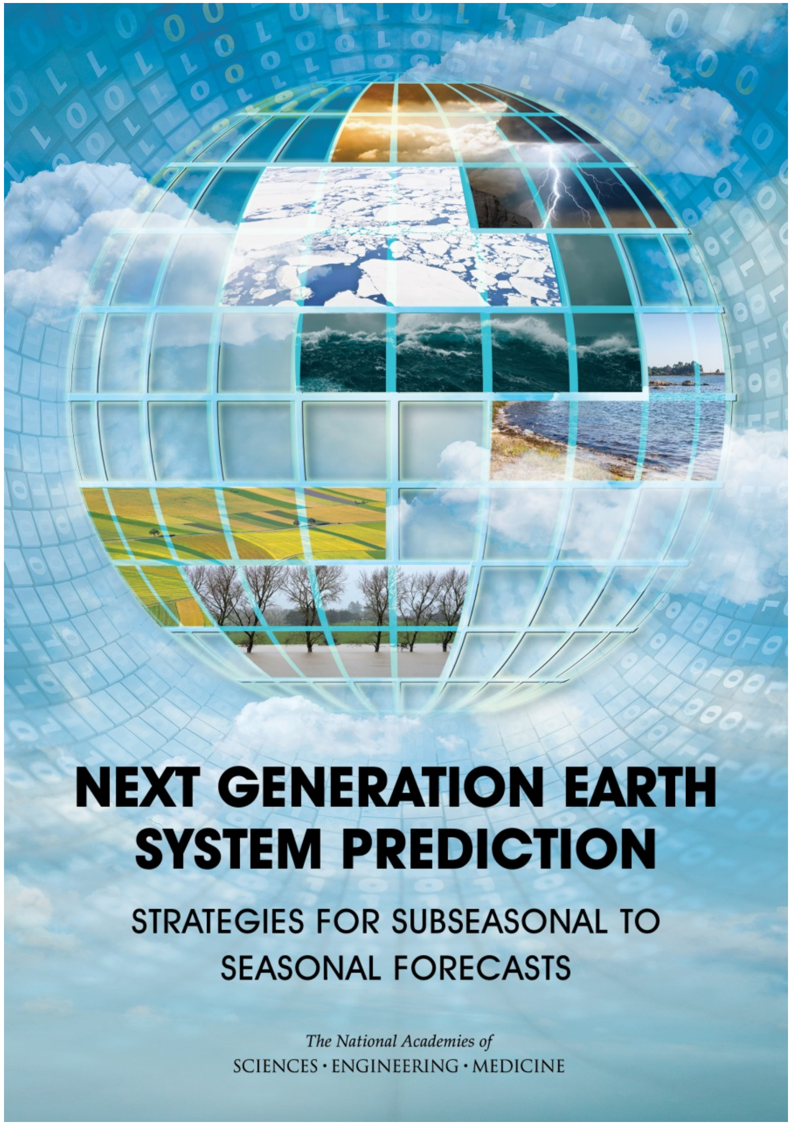

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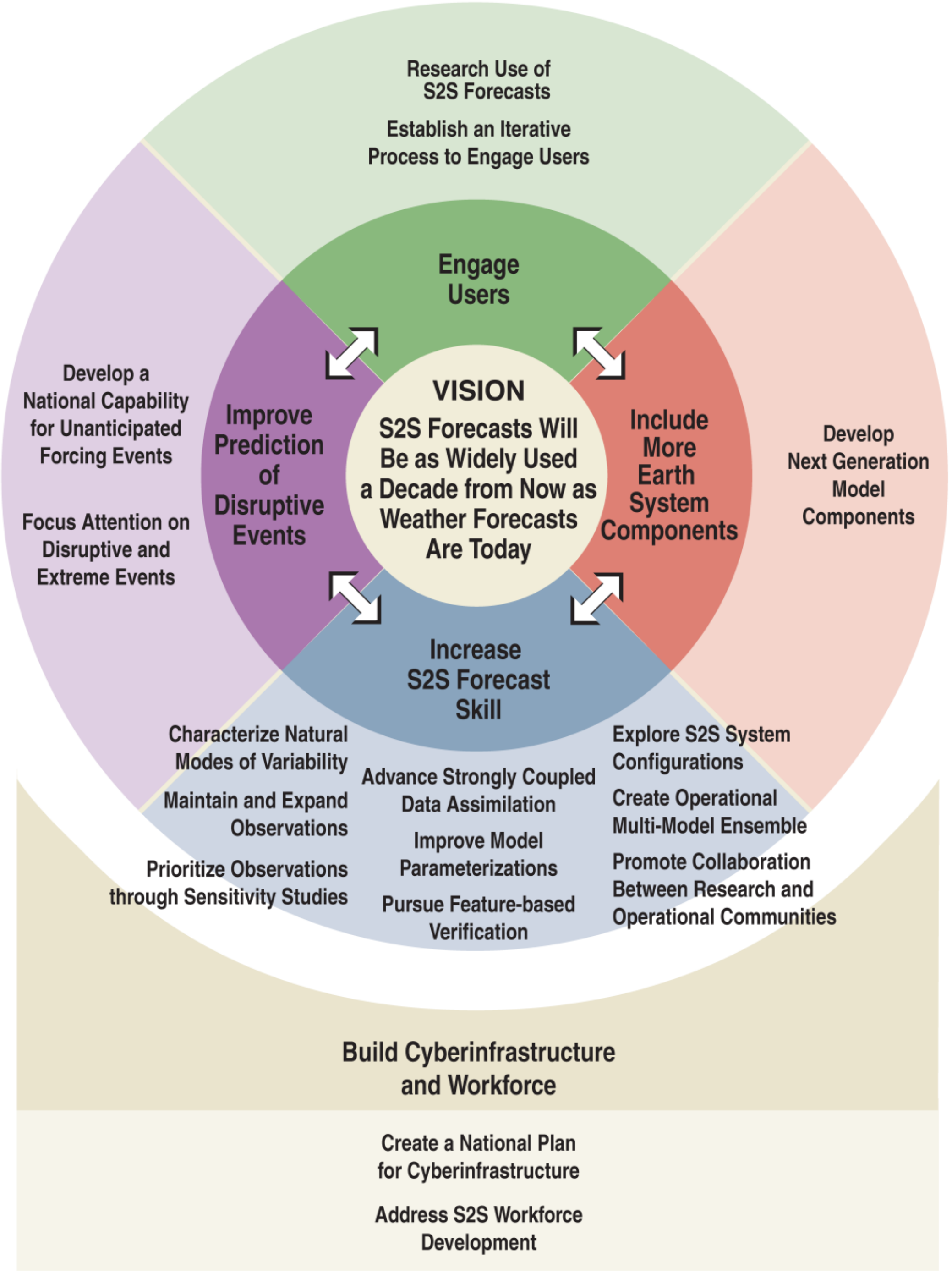
Questions?


Research Use of S2S Forecasts
Establish an Iterative Process to Engage Users
Engage Users
Develop a National Capability for Unanticipated Forcing Events
Focus Attention on Disruptive and Extreme Events
Improve Prediction of Disruptive Events
VISION
S2S Forecasts Will Be as Widely Used a Decade from Now as Weather Forecasts Are Today
Include More Earth System Components
Develop Next Generation Model Components
Increase S2S Forecast Skill
Characterize Natural Modes of Variability
Maintain and Expand Observations
Prioritize Observations through Sensitivity Studies
Advance Strongly Coupled Data Assimilation
Improve Model Parameterizations
Pursue Feature-based Verification
Explore S2S System Configurations
Create Operational Multi-Model Ensemble
Promote Collaboration Between Research and Operational Communities
Build Cyberinfrastructure and Workforce
Create a National Plan for Cyberinfrastructure
Address S2S Workforce Development