IMPROVING SUB-SEASONAL TO SEASONAL PRECIPITATION FORECASTING FOR WATER MANAGEMENT

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WORKSHOP SERIES ON IMPROVING SUB-SEASONAL TO SEASONAL PRECIPITATION FORECASTING FOR WATER MANAGEMENT

June 2016

Introduction

During 2015 and 2016, the Western States Water Council (WSWC), the California Department of Water Resources (CDWR), and the National Oceanic and Atmospheric Administration (NOAA) have cosponsored a series of workshops on advancing sub-seasonal to seasonal (S2S) prediction of precipitation for the benefit of western water resource management. Currently, the ability to skillfully predict sub-seasonal (beyond a 15-day horizon) to seasonal (the extent of a year) precipitation is limited. However, improvements in S2S forecasting capability have the potential to support a wide

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Tony Willardson, Executive Director, Western States Water Council Executive Director

Jeanine Jones, Interstate Resources Manager, California Department of Water Resources

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variety of water management tasks, and could greatly improve decision-making by water managers by providing notice of weather extremes, such as wet or dry conditions. They could also allow for greater operational efficiencies when managing water infrastructure across the West.

As described in the WSWC's Position Statement #366[1], "Supporting Federal Research and Development of Updated Hydroclimate Guidance for Floods & Droughts," the WSWC supports federal programs that can improve S2S forecasting capability. Water managers and other users have been identified as a critical customer of improvements in forecast skill. Great strides have been made to weather models that project conditions over a two-week timeframe. However, beyond that initial modeling horizon, weather forecasts have shown relatively little skill.

On a seasonal timeframe, limited predictive skill can be a function of the El Niño Southern Oscillation (ENSO). In other words, some circumstances have the potential to increase models' skill-levels. However, over the workshop series, the difficulties of reliably predicting precipitation in the right time and the right place – even with strong events, higher resolution models, greater incorporation of sensor data, and myriad other strategies – were highlighted and they remain a tremendous challenge.

The workshops' ultimate goal is to advance the WSWC's position calling on the federal government to improve S2S precipitation forecasting. The WSWC has argued that current predictions are not reliable enough to support water resource decisions and that the federal government should place a higher priority on the science research, infrastructure, coordination, and financial resources that will be required to improve forecasts to a threshold where they can be used for managing water for extremes of droughts and floods on a watershed scale, as well as for storage during drier periods such that cities, farms, and the environment might benefit.

Workshops and Participants

The workshops organized by WSWC and CDWR brought together WSWC members, representatives from water management agencies, and federal agencies to address opportunities for and challenges to advancing forecasting. They included activities, presentations, discussions and break-out sessions with NOAA offices, including the National Weather Service (NWS) (Western Region Headquarters, Climate Prediction Center, River Forecast Center, and weather forecast offices), the Office of Atmospheric Research, and the National Environmental Satellite, Data, and Information Services (NESDIS's) National Centers for Environmental Information. Non-federal representatives included local agency water managers, state water agency directors, and scientists from several western states (Arizona, California, Nebraska, New Mexico, Texas, Utah, and Wyoming).

[1] See Appendix B.

The dates and locations for the workshops were:

- October 21 – 22, 2015 in Salt Lake City, Utah
- December 15, 2015 in Las Vegas, Nevada
- April 29, 2016 in College Park, Maryland
- June 6 – 9, 2016 in San Diego, California

The agendas and attendee lists for each of the workshops are included in Appendix A. All Powerpoint presentations and other related materials are available on the WSWC's website[2].

S2S Workshop I – October 21 – 22, 2015, Salt Lake City, Utah

Summary

The focus of this workshop was to familiarize participants with the context of the workshop series and discuss why S2S prediction improvement is an important challenge to address. Much of the meeting was spent discussing program organization and the needs among the different programs for resources and being able to present those requests in a focused, timely, and strategic way to those who are developing program budgets. Another focus of the meeting was to identify program knowledge gaps and questions, and provide some avenues for investigation to address these. The later portion of the second day was spent in breakout sessions, which are summarized for each breakout group.

Presentations

Grant Cooper, Western Regional Director for the National Weather Service, NOAA, discussed the unique challenges to managing water in the West, pointing to its high degree of spatial and temporal variability. He introduced Tony Willardson, Executive Director of the Western States Water Council and thanked him for the WSWC's support of NOAA's programs.

Tony Willardson gave his perspective on weather forecasting by contrasting the state of the science 36 years ago, when he started working with the WSWC, with today's models and sophisticated tools. He also discussed the needs and wants of both today's scientists and policy-makers, stressing that the two must move forward in tandem. The role of the WSWC is to help with evaluating the former – the science and skills that we currently have – in order to develop better policy strategies. WSWC members are tasked with allocating waters in the West and many other management actions under increasingly complex legal frameworks. Western water law and the prior appropriation doctrine can be thought of in terms of managing risk and uncertainty to users. The more senior the right, the greater the certainty. Thus, we are acquainted with the concepts of uncertainty with forecasting the weather. Ways to mitigate that uncertainty include the ability to move water between different sectors of the economy. Skillful forecasting would assist with moving water optimally. The WSWC will continue to champion the requirements of current weather and hydrologic measurements systems so that these strategies can be employed effectively and resolve water challenges.

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[2] Western States Water Council Webpage – Sub-Seasonal to Seasonal Forecasting Workshop Series. Webpage: http://www.westernstateswater.org/seasonal-forecasting-wswc-workshops-and-materials/. Accessed June 2016.

Kevin Werner, Western Regional Climate Services Director for NOAA, provided comments on the context of the workshop and the meeting's goals. He talked about the difficulty of the challenge of increasing S2S skill and the opportunity for the applications of improved forecasts in water resource management as the motivation for the workshop. During a recent assessment of services provided by NOAA related to drought, the number one request from stakeholders was the ability to understand what might happen in an upcoming winter[3]. He provided an overview of the service assessment and its major findings. He also provided an overview of NOAA products that were currently being provided for the timeframes under discussion. Another workshop goal was to develop a proposal for advancing seasonal prediction for western water resources, including case studies and value propositions related to increased forecasting skill, and the identification of existing knowledge gaps and research questions.

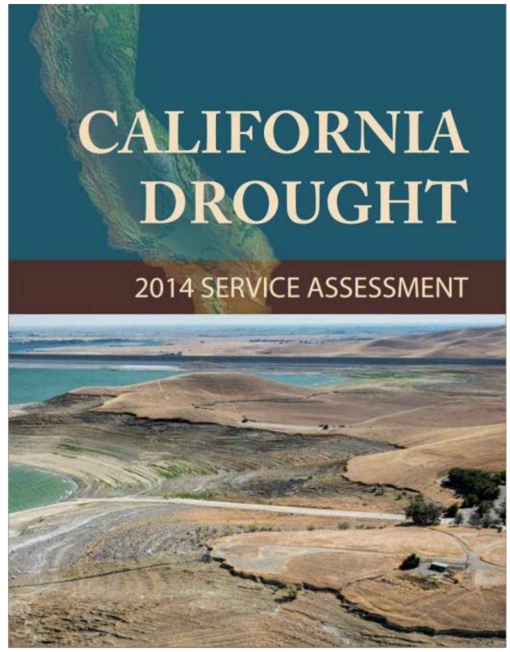

FIGURE 1 NOAA CALIFORNIA DROUGHT - 2014 SERVICE ASSESSMENT

Jeanine Jones, Interstate Resources Manager, CDWR, thanked Kevin for helping to organize the event and for being a point of contact within the NOAA world. She cited literature for earlier droughts that suggest that precipitation forecasting would be important, but we are not a lot farther along in its prediction than we were during the 1970's. A big question to answer during the workshop would be to answer what it takes to get more traction on this problem. Much research has gone into longer-term climate analyses, but a focus on shorter timescales would also be useful. She highlighted WSWC Position Statement #366, to give an example of what might be done to refocus our effort on the topic.

Specifically, Jeanine asked the attendees to focus on the harder part of the prediction equation, and the one that would be more useful to water managers, which is precipitation as opposed to runoff. Another emphasis of the meeting would be to refocus on the basic question: Will this winter be wet or dry? She discussed the importance of this question for water infrastructure and reservoir operations.

Longer timeframes for projections are also of value. State and local water managers don't always have time to change budgets to ask for more money for drought response. If a state or local agency knew the year might be drier than normal, they may be able to supplement their water conservation budgets. Increased workloads, and constraints on negotiating and processing water transfers could be anticipated. Transfers of water between uses or within their systems could be more easily facilitated. Regulatory concerns such as the Endangered Species Act (ESA) and the National Environmental Policy Act (NEPA) compliance could be addressed more easily.

[3] National Oceanic & Atmospheric Administration website. California Drought - 2014 Services Assessment. Webpage: http://www.nws.noaa.gov/om/assessments/pdfs/drought_ca14.pdf. Accessed June 2016.

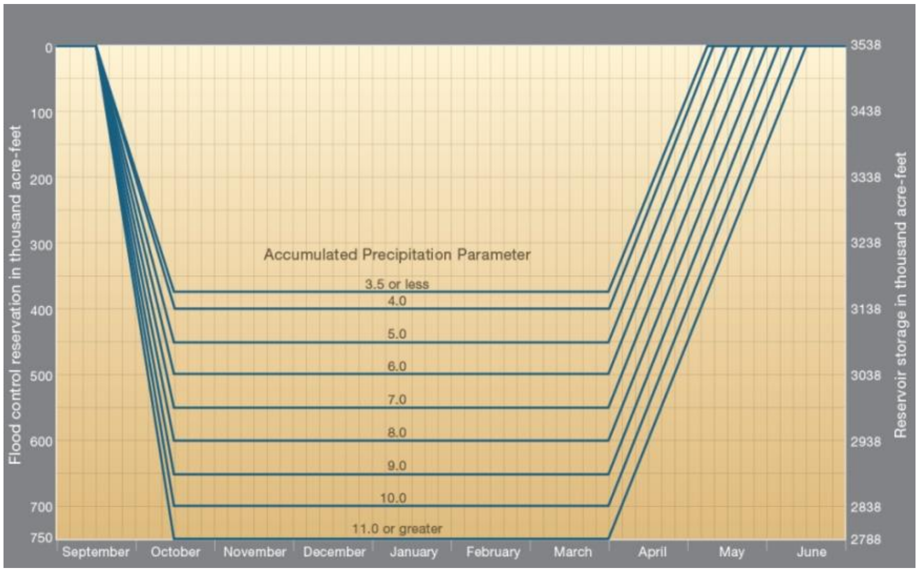

FIGURE 2 LAKE OROVILLE RULE CURVE

There are many examples of situations where a better understanding of S2S precipitation would be beneficial, and the more lead-time an agency has for planning for the coming water year, the better off the state's constituents will be. Jeanine provided a list of decision timeframes where critical information regarding forecast-informed reservoir operations, water transfers, state water project allocations, and other products were released by CDWR. Agricultural water users would likely need even greater lead-time for information because they are required to make critical decisions earlier in the season.

Figure 2 (above) illustrates the benefits of better forecasting for storage management in Lake Oroville. The rule curve for the operations of Lake Oroville is relatively complex compared to U.S. Army Corp. of Engineers (USACE) facilities, which are usually just a flat line, and are based on an understanding of local hydrology developed in the 1950's and 60's. With the advent of satellites and use of their imagery the possibility of more flexible sub-seasonally-based operations have become possible, but there are political and institutional barriers to changing rule curves for reservoirs.

Peter Colohan, Senior Advisor to NOAA's Chief Scientist, presented on the timeliness of the meeting and its diversity, which he thought were very valuable for NOAA. The White House and NOAA are deeply concerned about water in a way that is new. In the past, addressing water problems has used the "disaster du jour" approach – a need to address what is immediate and pressing, or what is causing loss of life and/or property. Work to address the 2012 drought came to a screeching halt due to Hurricane Sandy. It helps to appreciate the current crisis situation in the context of other crises, including budget crises, which are always being grappled with in DC.

Peter mentioned that Kathryn Sullivan, the current Administrator for NOAA, is dedicated to addressing these challenges and working on key problems. She has charged NOAA to work on water issues, and have the agency treat flood and drought as manifestations within the same hydrologic system. NOAA is charged to predict the weather and to characterize drought, but other water events, such as overwhelming flooding in South Carolina, reappear more acutely and detract from attention to drought. The big push within NOAA is to have long-term resilience and move beyond short-term solutions, and bring disparate pieces of the water puzzle together. This is easier said than done, given NOAA's organization chart. NOAA reflects the diverse, rich, and complex systems of earth science, which is a good thing to have expertise in a lot of disciplines. A goal for NOAA is to arrive at an "integrated water" prediction solution. The attributes for the NOAA's water effort, as laid out by Dr. Sullivan is that it be:

1. User- inspired
2. User-oriented
3. Integrated
4. Interoperable
5. Agile and nimble

The National Water Center (NWC) is anticipated to dramatically improve runoff prediction, and precipitation forecasting as well. The NWC will also have an array of other services related to water quality, risk, water availability, and habitat management. NOAA plans to support these efforts with different platforms, software, satellites, etc. and has formed a team to address how NOAA might play into the NWC's work.

To answer a question about forecasting funding in the FY2017 water initiative, Peter said that that was not included, and that the water prediction initiative was chiefly focused on the integrative aspects of water modeling between flooding and the cost, but that that conversation could be leveraged to include this topic.

Fred Toepfer, Hurricane Forecast Improvement Project Program Manager, joined the workshop remotely to describe the events that led to the successful implementation of the Hurricane Forecast Improvement Project (HFIP). He described it as a grassroots effort to better address planning for hurricane landfall and response. During the initial stages of implementation for a budget amendment to include HFIP support, Fred and his team took time to estimate the significant benefits better warning systems would have on individuals (in terms of loss of life and injury) and for businesses. His team used Hurricanes Wilma (2006) and Lilli (2002) as economic benchmarks. The team estimated that a better warning system could save millions of dollars per year. Other things that the team included in their proposal were tangible goals for improvement and performance. They started with a fairly aggressive goal of increasing their ability to project landfall of hurricanes by 2% each year, with a total of 20% improvement over the life of the 10-year program. A unique feature of Fred's team was the assembly of "Tiger Teams" – groups of scientists that focused on particular aspects or problems with hurricane projections such as use of radar and satellite data. Another hurdle for HFIP was the purchase of resources for high-performance computing. They had to stagger purchases and buy more equipment each year to get to a ½ petaflop of computing power, which was necessary for their models' performance and testing.

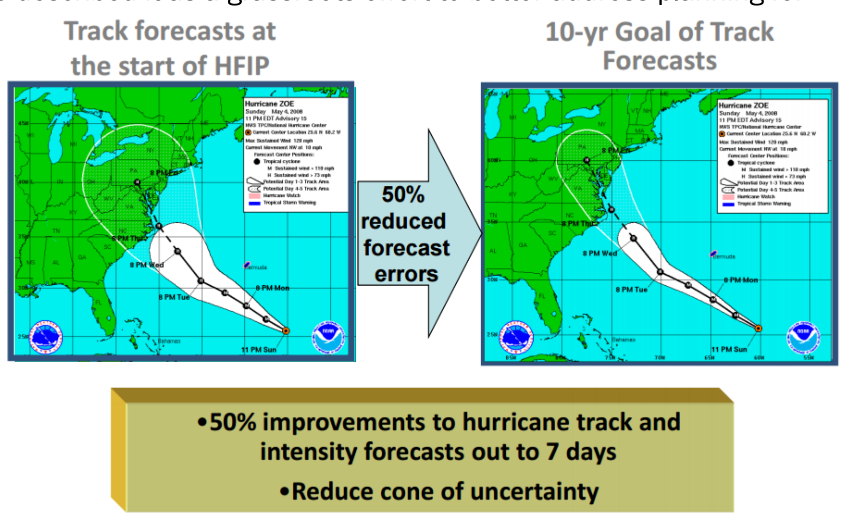

FIGURE 3 HFIP FORECASTING GOALS FOR 10 YEAR HORIZON

Fred's overarching message to the workshop attendees was to craft a narrative surrounding tangible benefits, include specific goals for increasing skill, and have a very targeted and specific plan when moving forward to request funding. In answer to a question about ballpark number on direct investment from NOAA, Fred answered approximately $23 million per year, including in-kind contributions. He also indicated that they had some strong support from some congressional members from states impacted by hurricanes.

Dave DeWitt, Climate Prediction Center Director, talked to the group about developing a white paper that was similar to the HFIP proposal, but would be geared toward S2S prediction skill improvements. He talked about the existing programs at the Climate Prediction Center (CPC) and the products issued by their offices, as well as their limitations. He talked about the need to increase the skill, and highlighted how new and better tools were needed to get to an acceptable threshold. The key challenges for his office are to:

- Improve understanding and prediction of tropical-extratropical interactions;
- Increase understanding and exploit sources of predictability;
- Improve the building blocks: data assimilations, correct model errors, enhanced observations, etc.;
- Improve seasonal prediction tools. Identify cause reduce systematic errors in coupled general circulation models (CGCMS); and
- Improve forecast products to meet user needs

The framework needed to address these challenges given the information provided by others and an evaluation of their own programs include several essential components – on the order of a $15 million annual investment. These include:

- Grants program ($3 million)
- Support modeling centers for model improvements ($3 million)
- Grants program on tailoring products for end users ($2 million)
- Support infrastructure for testing new tools and transitioning to operations ($1 million)
- High performance computing augmentation ($6 million)

Dave proposed that they measure success in a similar fashion to the HFIP program, by targeting a 20% improvement in forecast skill over the first-year baseline at 5 years, and 40% improvement over the first-year baseline at 10 years. In answer to a question about budget numbers for different forecasting timeframes, Dave indicated that the processes that affect weather over a six-month horizon are the same as those at a three-month evaluation, but with a cascading effect. The workgroup and NOAA should aim for higher skill at shorter lead-time first, as opposed to less skill on longer timeframes. The costs that are likely to increase are for computing.

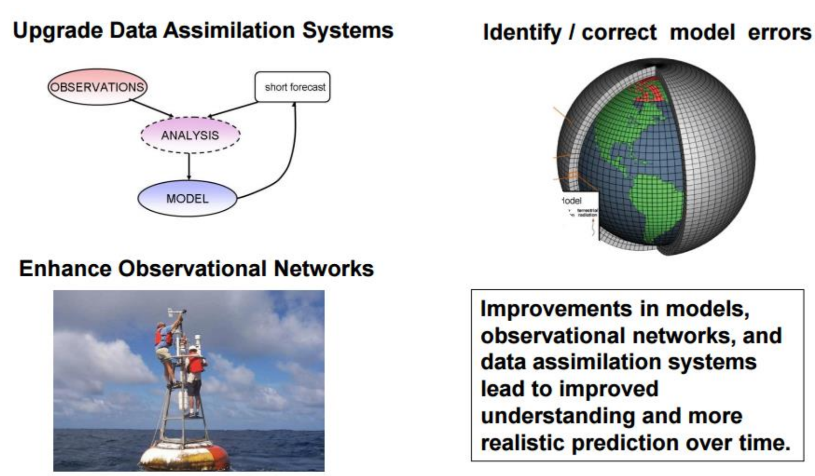

FIGURE 4 IMPROVING THE "BUILDING BLOCKS" OF A FORECAST

The issue of working on western water issues as opposed to national sparked a discussion on how difficult it can be for regional issues to receive support. Dave said that a talk about a broader program that also includes the West would be appropriate, and that the HFIP program shows how that can be done.

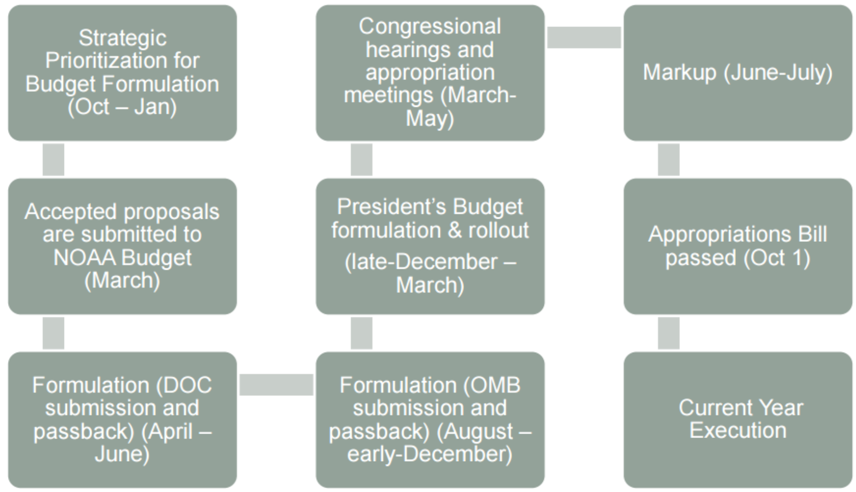

FIGURE 5 NOAA/OMB BUDGET FLOW DIAGRAM

Julie Suhr Pierce, BLM Great Basin Socioeconomic Specialist, described a case study approach for estimating the value of information generated by the USDA NRCS's Snow Survey and Water Supply Forecasting Program. She provided a brief history of the Snow Survey program and the use of Snow Survey/water data. The agency began the study by looking at individual user groups and brainstorming the myriad ways they were using the data. Based on the results from that brainstorming, Julie and her team developed a pragmatic approach to the analysis based identifying the specific economic value of Snow Survey program data to those users. The primary point of Julie's presentation was that the study's estimated dollar value of the program isn't the value of water itself, *per se*, but rather the value of *information* about the amount of water that will be available at different points throughout the year. One take away message from Julie was that it may not be practical or necessary for an agency to attempt complete a perfect or complete global economic analysis, but on a pragmatic level a set of case studies can provide enough information to adequately inform budget offices, leaders, and Congress with respect to the minimum economic value being provided by individual federal programs. The point of the exercise for some leaders was simply to show that a continuation of the snow survey's budget would be a worthwhile federal expenditure. For others, it was to show that snow survey data collection was something that was best left to federal agencies rather than privatized, partly because vendors who package and sell data are not always interested in releasing that data in real-time and partly because a profitability mandate might jeopardize the long-term generation and continuity of snowpack, precipitation, and water supply datasets.

A discussion on probability and risk analysis of products ensued. There is an emerging market for these types of products and NOAA is just beginning to be able to provide actionable probabilistic information. The workshop attendees agreed that it was time to work as partners on the S2S forecasting issues to make sure that the decision support systems being built could leverage other's work. One point that was raised was that while sometimes useful, calculating benefit-cost ratios for individual programs might sometimes lead to suboptimal decision-making as long-term and short-term programs and individual agencies compete for budget dollars.

Aria Remondi, NOAA Budget Office, presented on the various facets of NOAA's budgeting process. Each budget initiative is a two-year process from its beginning to execution. Proponents of a new initiative need to know when and how to pitch their ideas for the budget process. She described the current situation for FY2017 budget formulation. NOAA didn't have a FY2016 budget yet in place, but planning must begin for FY2017, which creates a lot of difficulties.

Her advice for putting new Program Change Summaries (PCSs) to the fore was to connect to recent relevant initiatives that may help the idea succeed, and to make the idea relevant for both external customers and internal staff. She highlighted that there is no intrinsic value in forecasting – the pitch needs to focus on how a forecast will be used, to what end, and what is the impact of that use. If you can get an economic benefit added to your PCS, that is a great bonus, but there is a need to consider politics that change between administrations as well. She recommended that the workshop attendees and NOAA staff consider what could be done by a new program initiative within five years, and then build milestones into that projection. The Office of Management and Budget (OMB) would most likely look at one or two-year tangible milestones that convey greater benefit. OMB also likes to front bold initiatives. The current administration is focused on research and development related to climate/environment and federal efficiency. She also made the point that being specific and justifying any request would make the process go much easier.

Tony began a discussion on WSWC perspectives on the idea of value proposition. He highlighted the WSWC's effort to work with the National Aeronautics and Space Administration (NASA) to include the thermal infrared sensor (TIRS) on the recently launched Landsat satellite package, which is critical for water use. Funding for the TIRS was not initially included in NASA's budget, and it took the Council eight years to get it replaced in the President's budget request. The lessons learned from that effort are not as applicable now for various reasons, one of which is the difficulty getting traction on any budget proposal with the current congress. Tony noted that when he met with an OMB examiner, they had asked about privatization of the TIRS, but a high value has been placed on the idea of making dataset public and available.

Jeanine pointed out that the NWS always wants to know what the dollar value is of a forecast, but the reality of the situation is that forecasting value is largely in avoided costs, so it is difficult to measure. The workshop attendees should look at how to bring the agricultural sector to the table on this effort. They constitute the largest federal expenditure from drought via U.S. Department of Agriculture (USDA) loans, and then the Federal Emergency Management Agency (FEMA) for fire management.

In answer to a question about the non-partisan nature of water, Tony indicated that the challenge for funding for water was that budgeting itself is not non-partisan anymore. Also, the line-item in question needs to be exciting enough to attract enough sponsors to shepherd it through the process. Developing cast studies and value propositions will help with that effort.

The workshop then transitioned to short-form presentations regarding the state of the science of sub-season to seasonal precipitation forecasting

Dan Barrie presented on the NOAA/OAR Climate Program Office (CPO), and how their research is competitive and focused on a variety of climate topics through their Modeling Analysis Predictions and Projections (MAPP) program. The CPO organizes a number of projects and task forces, including a prediction taskforce to address seasonal timeframes. He discussed a number of their models that support other federal agencies and the calls for proposal that address S2S forecasting. The proposals are usually region in scope and could include research of AR. They are very interested in the surface of the ocean-sub-subsurface interface, and hope to include more parameters such as soil moisture. The Department of Energy (DOE) and NASA are also their funding partners for many initiatives.

Andy Hoell, from the NOAA Earth System Research Lab (ESRL), presented on short-term forecast improvements, and how they were initially developed. Part of any effort to improve the science for a topic needs to include methods for estimating that improvement. For S2S forecasts, the chosen metric is the Heidke Skill Score. Looking at the Heidke score for the two-week timeframe, forecasting skill has not increased over recent years, but has been better for years that have an ENSO signal. However, this cannot be the only thing relied upon for good forecasting.

Sarah Kapnick, from the NOAA Global Fluid Dynamics Lab (GFDL) discussed ongoing research into S2S forecasting models. There are several areas where improvements can be made. These include increased observations with fewer errors, knowing what we are curious about for driving model development, data assimilation – combining data in useful ways – and developing analysis and dissemination systems. One aspect of improvement is model validation. Sarah indicated that the models the GFDL team use don't have good enough resolution and hind-casting records. They therefore spend a significant amount of time piecing older data together to find out what works. There are some groups who are working to put together gridded data for snowpack, but the research team needs more information to compare against the models. The initialization of models is also very important for results.

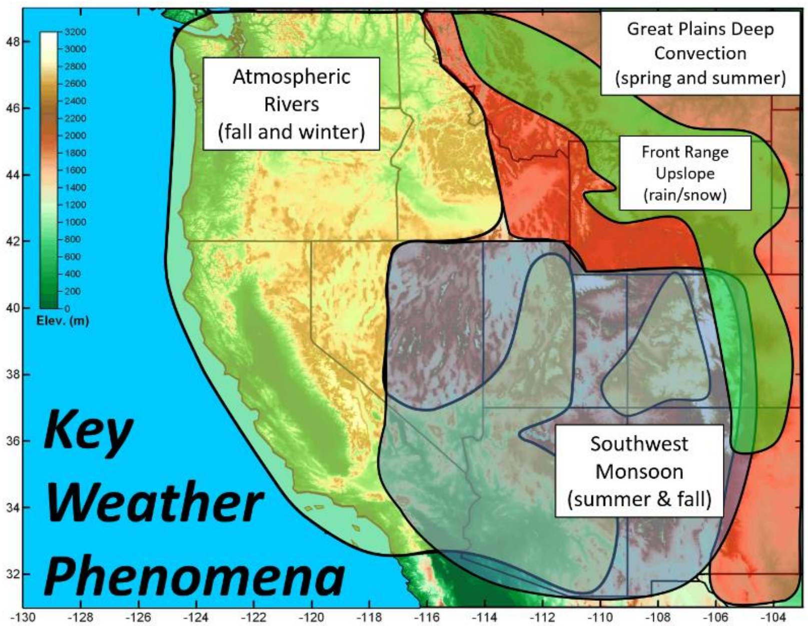

Figure 6 Regions of Key Weather Phenomena in the West

Marty Ralph, Director Center for Western Weather & Water Extremes Scripps Institution of Oceanography at the University of California – San Diego, talked about AR, and explained how much ARs contribute to the total precipitation on the western coast. Other storms are fairly flat and predictable, but the number of ARs that cross the coast can make the difference between a below average and average water year and seasonal flooding. He discussed a study of forecast models from around the world looking at landfall position of ARs as a function of lead-time. 1-day to 5-day lead times have a high degree of skill, whereas 10-days ahead of time is significantly less predictable. In this way, ARs are similar to HFIP. One of his research goals was to establish a baseline for prediction of ARS. He also showed how having an understanding of AR events could lead to better reservoir operation. A recent study in the Russian River valley with many invested stakeholders has shown the potential for more flexible operations based on forecasted precipitation over the watershed above the reservoir. He also showed a case where, had the predictability been in place, some opportunities to save water for later drought would likely have been taken advantage of.

Jon Gottschalck, CPC Head of Forecast Operations, presented on a variety of products issued by the CPC that constitute a "seasonal outlook." He described the symbology that was used to portray areas of equal chance for wet/dry conditions, and areas that would experience above or below normal wetness or dryness based on probabilities. Some communication is lacking on products that are offered as maps. They show anomalies of the median value of the outlook distribution. There is some difficulty in conveying the information – a gap between the research and social science that still needs to be bridged.

Jon also discussed the Heidke Skill Score in greater detail. In Figure 7, the yellow through red dots are positive skill scores, yellow is marginal, and green is zero skill. The skill score graph below is fairly flat and show no improvement over time at this time, except for years where ENSO is predictable. Correctly or incorrectly, less emphasis has been placed on statistical methods for prediction. The emphasis on dynamical model evaluation and development will continue within NOAA, but there is value for the CPC in updating some of their statistical forecasting tools. There is a need to evaluate the best predictors, regions, and use more recent datasets. The skill that could be gained by including these types of models is unknown. Hybrid dynamical and statistical models also have some potential.

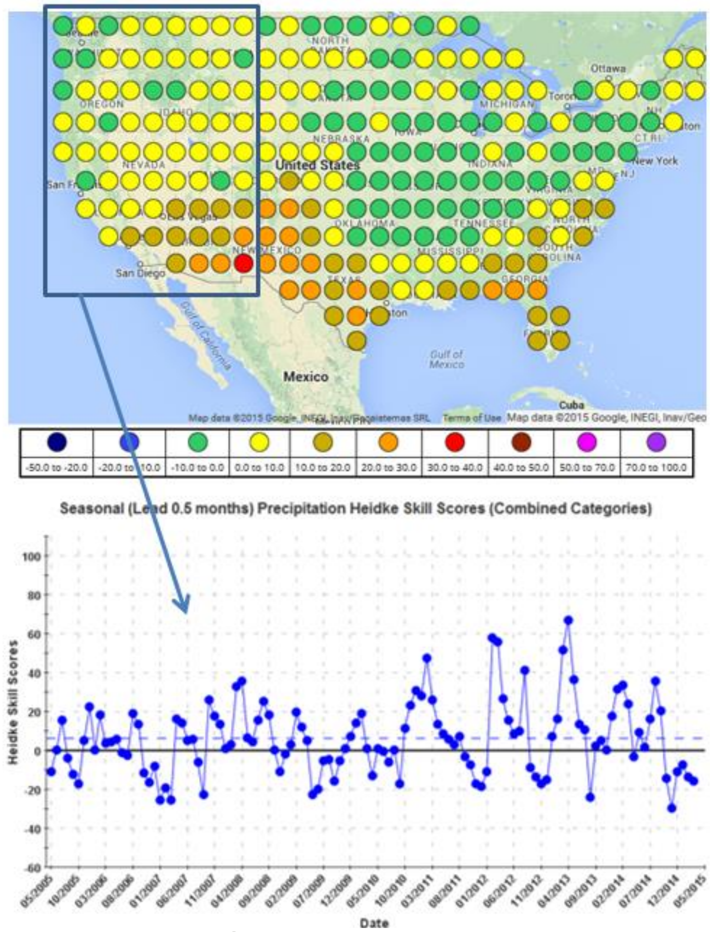

FIGURE 7 REGIONAL SKILL IN WEATHER FORECASTING AND RELATED HEIDKE SKILL SCORES

Mike Staudenmaier, Deputy Chief of the Science and Technology Infusion Division for NWS/NOAA, presented on the current skill for global models on the 8 – 10-day timescale and some climate models that show skillful predictions for some regions. However, even with this new skill, the season forecast and the DSS messaging remains very low and not as useful. Mike address what research questions need to be a higher priority in order to advance forecasting skill in the West. The challenge is moving beyond analog cases and moving toward more physically-based models. He talked about taking "baby-steps" toward ensemble model post-processing that compares climatological or model normal to the ensemble forecast.

Mike also discussed the strengths and weaknesses of the white paper from the workshop attendees. He cited the continued reliance on traditional climate indices like ENSO as a weakness, and made a call for a move to improved ensemble post-processing techniques to "draw forecast signals" out of climate models, specifically identify forecast regimes that produce significant departures from the local climatological normal to which communities have adapted.

Andy Wood presented on the National Center for Atmospheric Research (NCAR) research activities for developing seasonal forecasting of streamflow. The quality of your knowledge concerning the watershed conditions and the accuracy of a climate or weather prediction have a big impact on the skill of streamflow forecasting. Seasonally, streamflow forecasts are not useful until the climate warms in April and May when the snowmelt comes down the mountain sides. The hydrology of the area places a filter on the value of the climate forecast. There is a need to involve hydrologists from the beginning of the process and find out when forecasting skill is needed and when they don't care about prediction skill. Andy cited many knowledge gaps related to his program and identified many areas where questions needed to be addressed, and avenues that might lead to better understanding of streamflow forecasting based on climate forecasts. He also presented an interesting S2S-related effort at streamflow prediction from an international collaboration of research scientists called the Hydrologic Ensemble Prediction Experiment (HEPEX).

Breakout Sessions

Each breakout group was provided the following objective: to identify and develop propositions describing what and how much decision-making will be improved through incremental improvements to seasonal forecast skill. Each group was instructed to share their perspectives on the following questions:

1) How would your agency use improved forecasts?
2) What would you do differently? What would the on-the-ground impact be?
3) Would improvement to the skill of the existing CPC product suite be sufficient or are new products needed? If so, what are they?
4) How do you assess forecast skill? Are the current metrics CPC uses to measure skill sufficient? If not, how would you like to see skill measured?
5) Who else does the workgroup need to be talking to? Are there any other beneficiaries?

Group 1 Discussion – Main points

- There is a need to develop more Upper Colorado River Basin indicators for models and account for regional differences in forecasting
- There is a need for improvement in the 1 – 30-day forecast
- Economic value of improved skill should be worked on and include a by-sector analysis.
- For the U.S. Bureau of Reclamation (USBOR), small improvements on the 1-month to 1-year timeframe can make a big difference to water management with many economic benefits
- Other climate phenomena besides ENSO need to be explored for more skillful outlooks
- MJO and ARs are a source of better information
- Sensor/observing networks need to be sustained and enhanced
- Case studies for communication of the information are critical to demonstrate societal benefits and to make the material accessible
- Knowledge gaps include monitoring data, both in situ and satellite data, availability of the data and distribution of sensors, especially the buoy array. More knowledge is needed concerning the water manager's needs. Finer resolution models and improved physics are a gap in the science.
- Priority research questions include: definition of terms, what events are most important based on user needs, development of models influenced by that understanding, better dynamic downscaling of global climate models to a watershed scale
- Regarding the white paper: there is a need for capacity building for communication and application development of forecasting products, as well as resources for high-performance computing. Collaboration will be key for the paper to come together.

Group 2 Discussion – Main points

- There are so many examples of how better forecasts could benefit different sectors. Should choose three or four of the most compelling examples

- 1 – 3 month forecasts should be addressed first and information releases need to include clear messages about confidence and reliability
- Strong events make predictions difficult in that similar strong indicators don't predict another event's specifics
- On a cross-section of effort required vs. rewards gained, the focus of the proposed initiative should focus on activities that are on the low side of effort and the high side of reward
- The question needs to be answered regarding "big wins" (or busts). Are those better than being better are medium forecast accuracy more often?
- CPC predictions are fine for the media but not currently sufficient for the applications put forth in the workshop

Group 3 Discussion – Main points

- Effort should focus on the benefits to planning, with USBOR being a focus, as there are so many benefits to hydropower and water allocations
- Access to and understanding of forecast products needs to have a high priority; communication is needed for what is being developed so that consumers can be ready to use the new tools
- Decisions require lead time and need more quantified measures of risk (e.g. for this decision is the risk higher or lower for certain actions?)
- Major water sources should be considered individually as distinct regions (e.g. the Columbia River system)
- Observations are important. We need more information for soil moisture, snowpack, land use, and temperature, etc.

Group 4 Discussion – Main points

- The user's needs need to come into the picture early during model development
- There are many requests and a need to prioritize what to tackle first. The whitepaper will be a good way to narrow down research priorities
- Downscaling of national products to watersheds is difficult
- Maintaining/improving/prioritizing observational networks is very important.
- There is a need to explore model resolution and its impacts on forecasting skill. Higher resolution doesn't always translate into a better forecast.
- Hybrid models (statistical-dynamical) should be explored, along with the potential for post-processing
- Can we have a testbed for the entire "funnel" of development. Are efforts only for NOAA, or is this a collaborative experiment?

S2S Workshop II – December 15, 2015, Las Vegas, Nevada

Summary

Workshop II had increased participation from water user stakeholder groups and gave a wider perspective on the utility of better S2S prediction for their needs and operations. Many of the participants were skeptical that forecasts could eventually be created that would be reliable enough to use in the operations of storage and other infrastructure, but could see the utility of having more flexibility to operate. This workshop also provided a deeper dive into the CPC's capabilities and products and more information about the Atmospheric River phenomenon. It was concluded with a valuable group discussion on how to get this initiative or the workshop's white paper to the right audience such that a higher priority would be placed on the tools needed for better forecasting.

Presentations

Jeanine Jones welcomed the attendees and provided an overview of the meeting's context and goals. She cited her background in responding to drought in California for many years, and that seasonal water supply planning and forecasting has been a noticeable omission. With each drought, it was asserted that the S2S capabilities could be improved, but the science isn't there yet. CDWR has been looking into the issue and has tried to move this topic forward. She wanted to identify the "low hanging fruit" for S2S capabilities and other paths that might be pursued to make improvements. Drought brought this issue to the forefront of California's attention, and NOAA's 2014 Drought Service Assessment for California also highlighted the problem.

Jeanine provided a contextual example of benefits that could be reaped if decision-makers had additional information with longer-lead times by citing the Lake Oroville rule curve. Her hope for this workshop was to focus in on seasonal forecasting relevance at the water-user level – agricultural water users, planning responses such as water transfers and water conservation program/budgets, and water rate-setting. She identified a need to justify additional federal investment in improved seasonal forecasting by pointing to the potential reduction in federal drought disaster payments (e.g. USDA), and the savings from improved management of infrastructure.

Kevin Werner talked about the motivation and challenges among the NOAA organizations for tackling the S2S problem. They conducted a literature review to ascertain the status of the science and found that the number one request was to understand the upcoming winter's precipitation. He discussed that report's Findings and Recommendations, and spoke about what a difficult science problem they were tackling, replete with institutional challenges as well. He pointed to the need for strong advocacy, not just by WSWC, but by a wider variety of water stakeholders.

In answer to a question about the how S2S might apply to the West, Kevin answered that there was national value to the project. NOAA needs whatever comes out the S2S initiative to be useful across the country, but also apply to unique cases in the West. Jeanine pointed out that if you look at water resources nationwide, the East has too much water and water quality issues. The West has water scarcity and shortage issues. There is difficulty getting attention on the West's problems. The mountain ranges in the West also present unique problems. WSWC has been pushing for more data to capture those orographic precipitation effects. These unique challenges get lost on a national scale, and the focus seems to shift to hurricanes when they come ashore. That's why this workshop has so much local water user representation. The workshop attendees should explore what events/features contribute to the seasonal precipitation in their region and see how those are handled by the models that are on-hand. There is the potential to increase the skill in forecasts by including those regional features.

An attendee pointed to an example in New Mexico where snowpack might be very good, but due to persistent drought in the area, sublimation of the snow depletes the resulting infiltration and runoff. That is the kind of local feature that could improve forecasting in the region. In fact, the seasonal precipitation forecast might have been excellent for that particular year, but the sublimation resulted in very little runoff.

Pat Lambert presented on how the Western Federal Agency Support Team (WestFAST) might play a role in coordinating multi-federal agency efforts to solve the S2S prediction challenge. Some federal agencies are generating information and also agencies that are consuming forecast products from others. His goal is to make sure that those agencies are communicating well. NASA is interested in this issue and they are data-providers of satellite imagery, etc. The USBOR has a stewardship role over lands and infrastructure that could benefit. There are some agencies budgets that could be helped if we had a better forecast of temperature and precipitation, and not just within NOAA. Some of the WestFAST Principals also reside back East and in DC, and they have the ability to help with some of the institutional barriers between agencies and create synergy.

In answer to a question about incorporating academic research, Kevin and Jeanine answered that some funding comes from WestFAST agencies and that they were big sources of support for the effort. They also mentioned the downward trend of research budgets and the need to reverse that down-slide.

Dave DeWitt gave a presentation that was similar to the one given during Workshop I on Climate Prediction Products. He gave a listing of the many scientific and institutional barriers to improving S2S forecast skill, and also priorities for addressing them. He also described in greater detail what types of circulation patterns and features were at play in forecasts, such as atmospheric circulation patterns, initial state of the climate system, boundary conditions, ENSO and La Niña, soil moisture, sea ice, the Madsen Julian Oscillation (MJO), etc., and other decadal variations or trends.

Dave also talked about the resources needed for a more sustained initiative for S2S prediction on the order of $10 - $15 million per year over ten to fifteen years. He also described the Heidke Skill Score for the attendees and what the established baseline for skill is currently. One of the challenges for the program is that water resource management needs to be somewhat conservative and requires greater certainty. In order to serve those needs, the models need to downscale to a local location, whereas the current scale is too large. A “Stretch-grid” approach might work, followed by a reworking of the statistics.

Kevin Werner made the point that stakeholder input was needed to determine the level of skill that works for different water resource management applications. John Longworth from New Mexico responded that the skill level needed when reservoirs were full in New Mexico was not as important or need to be as great as when reservoirs were low. Half of New Mexico is currently in drought, but all the reservoirs in the state are empty or low. In his scenario, the State Engineer’s Office needs to know whether and when to start allocating water. Monsoon season plays an important role in storage across the state.

In answer to a question about improvements over the past twenty years, Dave said there were not a lot of dynamical models around and those were not well trusted. They did have statistical techniques, but they were not as sophisticated as they are today. Since 1995, climate change forecasting has been based on some probabilistic models, resulting in a "probability space." Scientists then weight the models with respect to their skill and combine them.

Marty Ralph presented on the role of extreme precipitation events in forecasting for the total precipitation and water supply that a region might receive. He answered a lot of questions from attendees about skill scores and how they would start at the two-week horizon where their skill is the best and work their way forward from there.

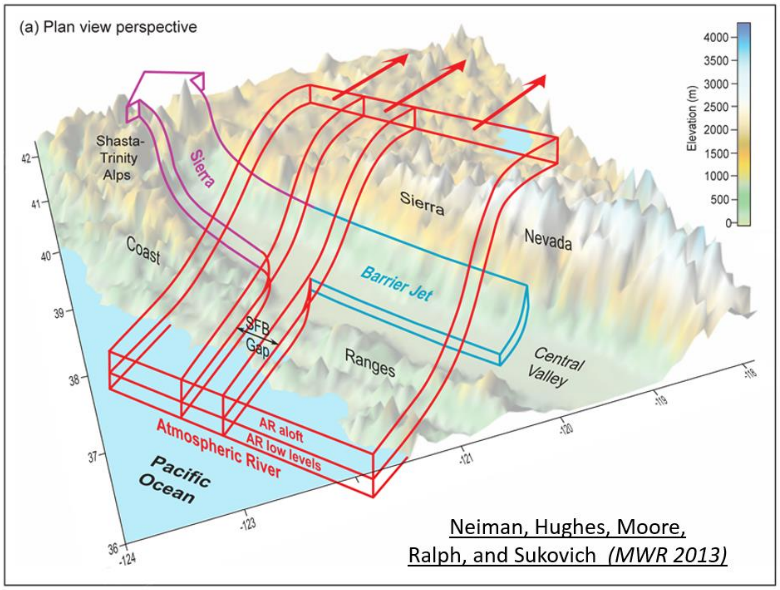

FIGURE 8 THE SIERRA BARRIER JET IS KEY TO REGIONAL PRECIPITATION

A research project that has yielded new information is a study of the Sierra Barrier Jet. This is a phenomenon of air current that climbs to the North along the coast and Central Valley of California. There is a need to understand how this and ARs from the ocean come together and interact with each other on a watershed scale. The top ten wettest days in the last decade for California were when the Sierra Barrier Jet and an AR confluence. In fact, both phenomena needed to be present to be one of the "wettest days."

Marty described how the annual average precipitation for the West was derived, and that the West has a much higher degree of covariance around the average. This implies the need for more specialized tools for the area. Many federal agencies don't appreciate this dramatic difference in precipitation in the West. One of the primary reasons to conduct AR research is because of the variation – if there are no ARs it is a very dry year, and if you get a couple of ARs it's a wet year. Another finding is that ARs are very important factors for snowpack within inland states, including as far east as the front range of Colorado.

Marty's parting comment was that there is no silver bullet to solving the problem of S2S prediction, but that having a 21st Century observations network in place will be absolutely vital. Right now, it is difficult to maintain the network and it is under-funded. If we didn't have the buoy arrays in place, we would be blind about the ENSO phenomenon.

In answer to questions about the ENSO year predicted, Marty said that only two other ENSO events were predicted to be as large as the current ENSO formation. During prior events of this magnitude localized flooding was a challenge. The CPC forecast for heavy precipitation is much above average for Southern California and Western Arizona.

Jeanine followed-up with questions about resources. She wanted to know how the group or CPC or some other NOAA office might pursue this kind of work. We now have an initial understanding of ARs, but how much could you learn if the program could be expanded. Perhaps having an understanding of the physics of the "big ones" would provide a pathway toward seasonal predictions inland. She provided some comparisons for different programs, including CDWR budgets, the NWS, and the USBOR.

Marty described the instrumentation used for the AR research, most importantly satellite information. Scanning radars, balloons, and the buoy array can feed information right into numerical models. The noise in received signals is an indicator for water vapor.

Jeanine Jones provided a presentation dedicated to the potential applications that could be developed were S2S prediction skill to be increased. An important feature of these applications are the relevant timelines that play into decision-making. She provided many examples, including California's reservoir storage and climate models that predict that California snow in the Sierras will disappear. Scientists expect that more of California's precipitation will come in the form of rain. However, most of the reservoir systems were designed based on pre-1950s hydrology. They have already seen the maximum runoff times inching backward in the year. This is of high concern for CDWR and other water managers. One thing that would help a great deal would be to have some new tools for operating reservoirs that are more sophisticated.

Figure 9 is a slide of a portion of a storm that could have been captured and retained if they had had more information about the upcoming year, and the flexibility at the reservoir to keep the water behind the dam.

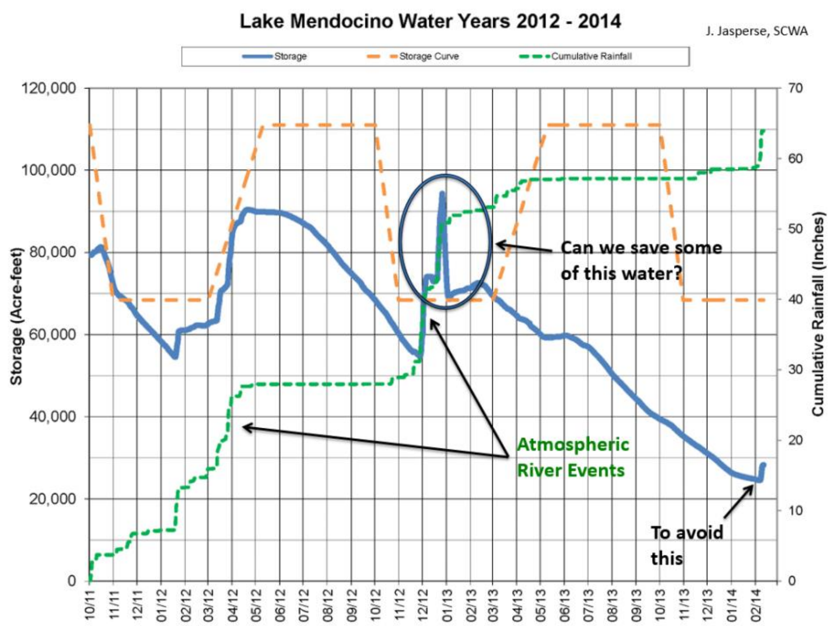

FIGURE 9 PRECIPITATION EVENTS AND STORAGE WITHIN LAKE MENDOCINO

Dan Bunk provided an overview of the annual operations at Lake Powell and Lake Mead. There is an operational decision-making hierarchy for that system. To assist with the operations, an Annual Operating Plan (AOP) is released during December. Forecasting plays into the AOP to a degree. The USBOR uses software called Riverware to study what might occur on the system on a monthly basis. It is a basin-wide model of the reservoirs, the river, and its tributaries. During recent drought years, the system's storage capacity went from full to about half full in five short years. This lead to new operation guidelines in 2007, which will also expire in 2026. Forecasts are taken into account when estimating releases from Lake Powell to Lake Mead.

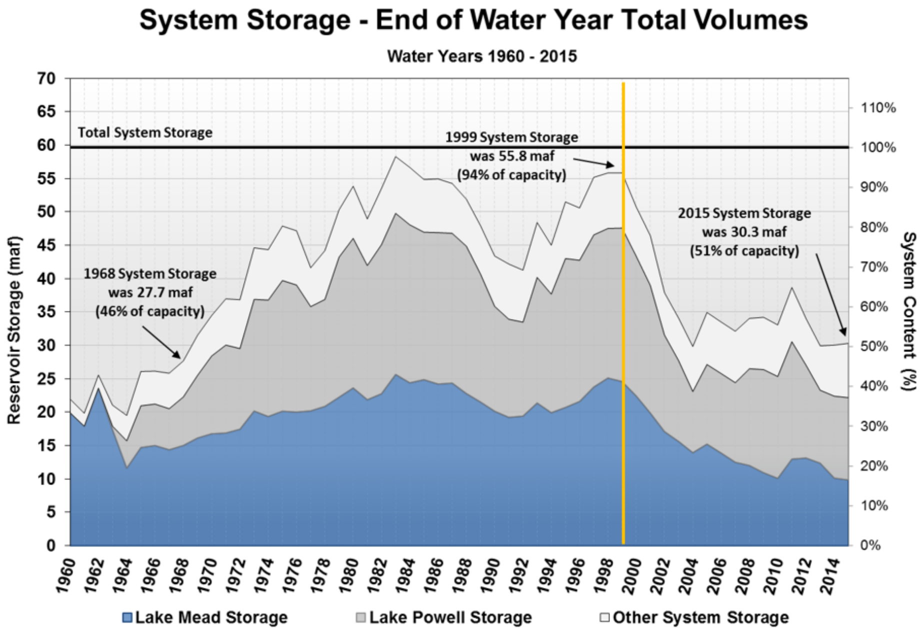

FIGURE 10 COLORADO RIVER BASIN RESERVOIR STORAGE

Dan showed the potential Lake Powell release scenarios that show a range of possible releases based on inflow. At the time, nine million acre-feet were projected to be released for balancing the reservoirs, but there was also a lot of uncertainty. Improvements in seasonal forecast for the region would help with later in-year projections (April – July), although the system always experiences surprises also. Dan also showed a comparison of Lake Powell inflows with ENSO events to show that they subtly contribute to the lake's storage. He briefly discussed the Secure Reservoir Operations Initiative and how better forecasts might impact operations on Lake Powell and Lake Mead.

Group Discussion

The workshop attendees took time to have a group discussion on what had been presented earlier in the day. Questions included: How do we move forward? How can we get more resources and discussion on a federal level? Can we predict wet conditions or dryness? On the strategy side, what can the WSWC do to identify and put forward a 10-year sustained initiative. To the attendees, the amount of funding involved doesn't sound like very much money, but within the NOAA research programs and RISAs, the amounts are large. How can we help other agencies also? Can their knowledge be used to cite additional use cases or value propositions? Ultimately the success or failure of such an initiative will be determined by participation.

The attendees discussed the benefits of better precipitation forecasting from better weather-climate sensors and networks on the ground. The on-the-ground data could be used for validations purposes. Setting up such sites requires a lot of work and cost. The installation might be able to be leveraged for forecasting if you added something like water vapor sensors to the equipment. These would be very useful.

The group also discussed information dissemination. Weekly weather calls from local offices were of great benefit to the river masters in some areas. Such calls are direct communication from the weather service to the population that needs the information. This is very useful when we think we're going to get extreme events, or even just additional snowpack. There could be a linkage to federal budget proposals, and perhaps requires a broader conversation than just water managers. There is a large community of rangeland managers that can get hammered by drought.

Applications and research within an academic realm was brought up, with some larger funded proposals and studies as examples. The attendees were glad to hear of WestFAST and understand that federal agencies could coordinate with each other. Drought has been able to compete with other problems more recently and getting help from an academic setting of from additional federal agencies is more likely. Another aspect to all of the forecasting is where data collection is competing. Getting the science right and getting a unified message out to the public is a daunting task.

Putting a bill forward for the S2S initiative was a larger conversation. Getting bills authorized for National Integrated Drought Information System (NIDIS) support was a good example of how to go about doing it. The workshops are allowing the conversations to take place to make it a higher priority and put pressure on the federal government, instead of just making token efforts. Participants, especially state agency attendees, agreed that knowledge of S2S and resulting runoff forecasts were critical for reservoir storage estimates and planning, but they were also skeptical that the science could provide a high enough degree of certainty that they would actually use them in more precise reservoir or other infrastructure operations.

Jeanine spoke of the difficulty in getting the operations changed. Part of the difficulty with Forecast Informed Reservoir Operations (FIRO) was that, if you have a reservoir with a USACE rule curve on it, it was established at the time of creation. To change any rule curves, you need new NEPA processes and a congressional declaration. With the pilot project on the Russian River system issues of drought, flooding, and Endangered Species Act (ESA) are small enough to be tractable, as opposed to political issues. FIRO is going forward as a “guinea pig” project with USACE. But any progress moving in a more flexible direction is valuable. It will take a long time to adjust the political process. It would also be helpful to have some examples of benefits to Midwestern states on the Missouri River System.

AR were discussed as an angle that could yield a lot of benefit. Marty said that ARs can often be seen coming, but it’s hard to predict where they're going to hit. Sometimes you can look back and see something developing. He and his team are figuring out areas where storms typically develop and where they don’t.

S2S Workshop III – April 29, 2016, College Park, Maryland

Summary

The Western States Water Council (WSWC), in cooperation with the California Department of Water Resources (CDWR) and National Oceanic and Atmospheric Administration (NOAA), held a workshop on the challenges and opportunities related to improving S2S precipitation forecasting capabilities on April 29, 2016. The meeting was held at NOAA's Center for Weather and Climate Prediction in College Park, Maryland.

Presentations

Dr. Louis Uccellini, Director of the National Weather Service (NWS), provided opening remarks and highlighted Dr. Kathryn Sullivan's commitment to building NOAA's water related capabilities as a legacy program. He added that she is a force on regional conservation issues, and mentioned that they would be at two regional listening sessions in June, one at the National Water Center in Tuscaloosa, Alabama and another in Sacramento, California.

Dr. Uccellini described some of the major worldwide loss events, including floods and drought. He described these in the context of increased vulnerability to extreme weather events, exacerbated by an increasing population, signs of sea-level rise, and the greater amount of infrastructure at risk. He pointed out that over time, we have dramatically improved our ability to forecast extreme events over the 4 to 8-day time period. Connecting forecasts to decision-makers is the basis for building what he termed a “Weather Ready Nation” (WRN). He described NOAA’s commitment to expanding the concept to a “Weather and Water Ready Nation” as a significant budget priority, with new full-time equivalent (FTE) positions. He commented that given the current federal budget, the request for new FTE's was an unusual and substantial request.

NOAA has focused on providing better forecasts and warnings, and consistent products and services. He added that if NOAA's products are inconsistent, people begin to shop around for the services they need. NOAA wants to be the source for actionable environmental intelligence. He said the “last mile” will be to connect a forecast to critical, national, state, and location decisions. He used an example of the USACE’ desire for a 30-day forecast for Mississippi and Missouri River navigation management.

NOAA’s goal is to improve an impact based decision support system (DSS) with multiple and reliable dissemination pathways, working with partners and embedding NWS personnel in emergency operations. He used as an example having personnel on site at the Boy Scouts of America National Jamboree. NWS wants to be able to develop relationships and know partners' needs, which involves incorporating social sciences into NWS operations. They have or will have some 2,800 WRN Ambassadors. The NWS is working to effectively address the grand challenges we now face, from western drought, to southeast flooding, and even harmful algal blooms.

To improve decision support, Dr. Uccellini noted the importance of enhanced observations, referring to ocean buoys, the JASON low-earth orbiting satellites which use altimeter data to measure sea levels, the next generation Geostationary Operational Environmental Satellites (GOES-R) providing images of weather patterns and severe storms (as frequently as every 30 seconds), and the Joint Polar Satellite System (JPSS), which is a significant scientific and technological advancement with sophisticated meteorological data and observations of the atmosphere, ocean, and land for short-term, seasonal, and long-term monitoring and forecasting. NOAA is also working to upgrade data assimilation systems, as well as reduce dynamical modeling errors through improved understanding of physics and earth systems.

Dr. Uccellini stated that the National Water Center is intended to focus on scientific excellence and innovation, driving improvements in water prediction to support decisions for a water resilient nation. It will provide decision support from floods to drought, and help accelerate research on extreme events. The Center is also hosting the National Water Model, which envisions making forecasts for 2.7 million river reaches, not just current forecast points. It will project flow rates, as well as water levels. Flood and drought forecasts also require an understanding of soil moisture and snow pack. NOAA is also working with the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) on national flash flood forecast interoperability.

NOAA is looking at health vectors, including beach water quality, harmful algal blooms and hypoxia, and elimination of Vibrio campbelli in seafood. He again reiterated that NOAA is poised to extend its national focus from “weather ready” to “water ready”, improving weather and water forecasts and transforming the NWS hydrology program from observations to forecasts and warnings for decision support. Eventually, NOAA's efforts will help better quantify and communicate forecasts and convey risk, map forecasts to infrastructure, and allow shifting of risk preferences among all decision-makers.

In response to questions, Dr. Uccellini noted NOAA and the NWS are working with international agencies and "bulking up" to disseminate big data. NOAA is also working with the emergency management community to allow chatting with forecasters. One challenge is to input quantitative precipitation forecasts (QPFs), or the total amount of liquid precipitation (in inches) expected during specific periods, typically 6 to 24 hours, out to one week and incorporate them into river forecast center operations. NOAA is also working to push forecasts out to 30-days, and then to seasonal forecasts, using multi-model ensembles.

Michael Farrar, Acting Deputy for the Laboratories and Cooperative Institutes, Office of Oceanic & Atmospheric Research (OAR), addressed the science supporting S2S prediction. OAR laboratories and programs provide the foundational science for better forecasts, earlier warnings, and a greater understanding of earth systems. S2S forecasting is a key science priority for OAR, which has a history of advancing seasonal prediction. OAR is also helping improve western water management via better understanding of water cycle processes and advances in monitoring and prediction methodologies. However, further progress can be made with targeted investments.

Within OAR, the Climate Program Office (CPO) and its Modeling, Analysis, Predictions and Projections (MAPP) program leverages the expertise of the scientific community through grants. Further, under OAR's National Earth System Prediction Capability Initiative (ESPC), it leverages the federal science community to improve predictions in support of policy and planning efforts that span days to decades. OAR's water cycle research is integral to national and international efforts.

OAR and the NWS have developed a strong relationship, with OAR advancing NOAA operation models, and CPO's Climate Test Bed Project delivering new multi-model seasonal prediction systems (involving the North American Multi-Model Ensemble – NMME). NOAA's Drought Task Force and the National Integrated Drought Information System (NIDIS) research has also led to improvements in our ability to understand, predict and map drought.

OAR/CPO are investing some $3 million per year in S2S research initiatives, including a sub-seasonal prediction experiment (SubX), experimentation with high-resolution seasonal prediction systems, data assimilation for improved initial conditions, hybrid statistical-dynamical multi-model techniques, and enhanced understanding of processes and predictability. New initiatives require new and additional resources.

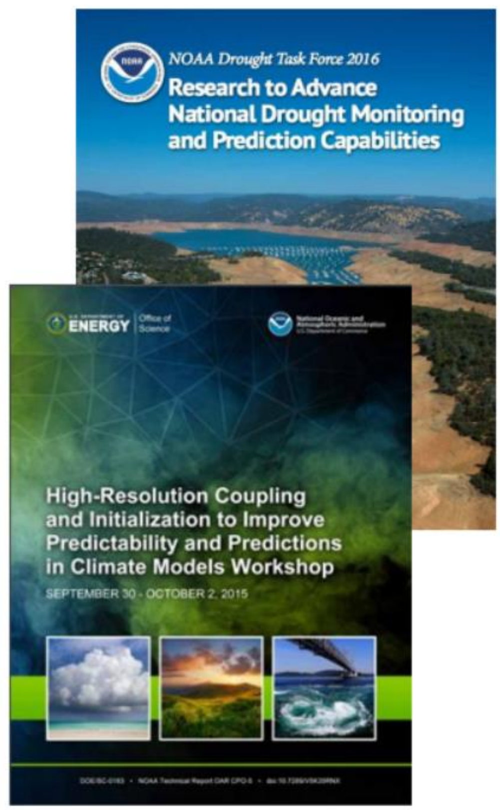

FIGURE 11 NEW INITIATIVES AT NOAA AND NWS

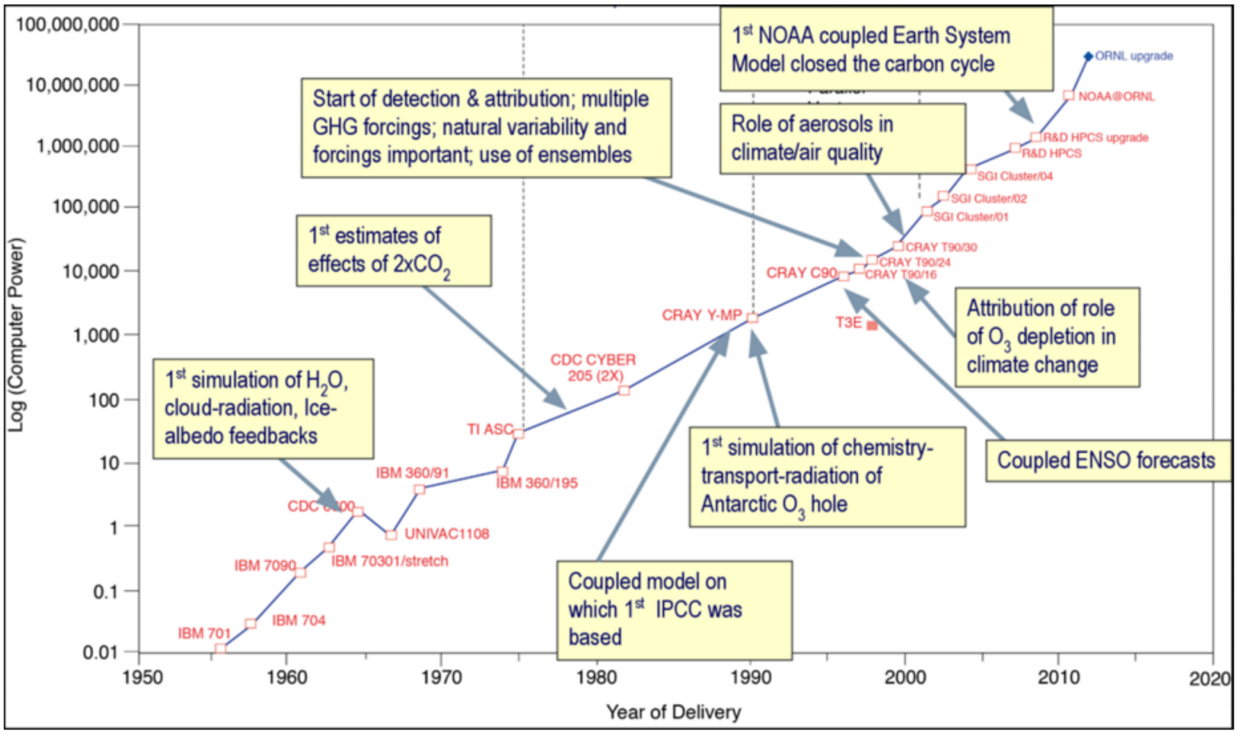

FIGURE 12 GROWTH IN GFDL COMPUTATIONAL POWER OVER TIME

High Performance Computing (HPC) capacity is one of the challenges/limiting factors in advancing predictions from weeks to seasons, given model complexity and spatial resolution. In the past, major advances in HPC have followed events such as Superstorm Sandy, which spurred major investments. NOAA is working cooperatively towards a stable plan for increased HPC investments, as OAR's scientific capabilities have far outpaced available HPC capacity.

Kevin Werner, NWS, Director of the Office of Organizational Excellence and Jeanine Jones, Interstate Resources Manager, California Department of Water Resources, noted that this was the fourth meeting in a series of workshops on S2S precipitation forecasting. The first was held in San Diego in May 2015 and a summary of that meeting was published. Other workshops were held in Salt Lake City in October 2015, and Las Vegas, Nevada in December 2015. The focus is on precipitation and not drought. Precipitation varies across the nation, but nowhere is the variation greater than in the West, particularly the Desert Southwest.

Both the science and water resources management communities have long aspired to have improved seasonal forecasts that could be applied to operations. The opportunities for improvement have been cited in climate prediction literature since the 1990s supported by western water resources stakeholders in general, and Colorado River water users in particular (which face the greatest variability in precipitation).

Kevin mentioned NOAA's 2014 California Drought Service Assessment and one of the top findings was the number of stakeholder requests for seasonal prediction capability focused on cool season mountain precipitation, both in California and in the Colorado River basin.

Annual stakeholder meetings first convened in 2010 have been held to discuss and document needs, and improvements to S2S precipitation forecasts out to two years. It is a major recurring theme among stakeholder agencies, who also want more information on the 30-year average and objective water supply forecasts. A March 2011 Climate and Streamflow Forecasting Workshop held at the Colorado Basin River Forecast Center in Salt Lake City, Utah was convened to tackle the problem and evaluate 15 years of applied climate and flow forecasting research in the western United States. It found variable use of predictions in water resource management and project operations.

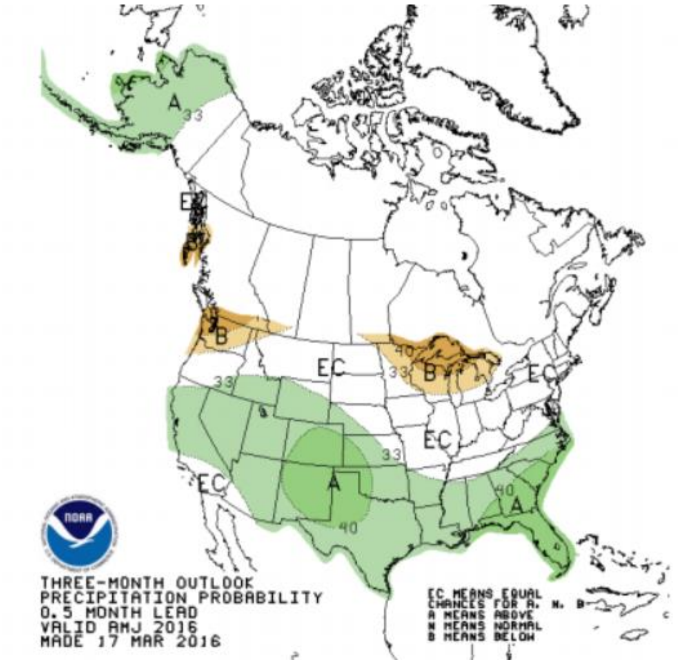

FIGURE 13 NOAA'S 3-MONTH PRECIPITATION OUTLOOK

NOAA's California Drought Service Assessment covered ten months, focusing on three sectors, with ten team members conducting over 100 interviews and synthesizing over 400 comments into 62 pages, with 43 recommendations. The top stakeholder request was: "What is the forecast for the upcoming winter's precipitation?" However, as the Assessment states, "These forecasts typically have very low skill and confidence, rendering them near-useless for most decision makers interviewed."

Finding 5.3 within the Assessment states: accumulated precipitation — typically snow — in the key watersheds of the Cascades, Sierra Nevada, Southern California mountains, and groundwater recharge areas are the primary source for water resources in California and the western states, yet no focused seasonal forecast capacity exists for this all-important resource in order for agencies to make effective planning decisions and water allocations.

A related recommendation 5.3a states: NOAA should invest in developing and operationalizing seasonal forecast techniques targeted at accumulated cool-season precipitation, specifically snowpack accumulation and snowmelt runoff in the watersheds important for water resources.

Lead time is very important for decision-making, especially for water management, including public health and safety decisions, reducing impacts of extreme events, balancing trade-offs between costs and risk, increasing water management efficiency, operating within legal and regulatory frameworks, and responding to increased competition for limited resources (including effecting water transfers and banking).

Timely and accurate forecasts would better help managers and other decision makers determine how much water will likely be available to meet water users' needs and when it will be available, as well as determine when hydrologic shortages my trigger extraordinary conservation measures, such as curtailing or limiting certain uses. Knowing that water supplies will be short allows managers to warn users before adopting restrictions, seek alternative supplies, and negotiate contracts or other agreements, to acquire water through temporary transfers, dry year leases. Users may draw down groundwater reserves or deplete reservoir storage, or otherwise draw on water banking arrangements to meet demands. If the winter is predicted to be dry, water can be retained in storage and allocated for use, rather than releasing water from reservoirs to evacuate the flood control pool behind a dam.

On the other hand, if it appears it will be a wet year and flood risks may likely be elevated, managers can release water from storage to capture dangerously high flows and pre-position resources to avoid or mitigate damages and the loss of lives or property. In extreme cases, they may require evacuation of some communities or neighborhoods. In wet years, managers may also be able to take advantage of high flows for artificial groundwater recharge.

Drought and floods not only impact economic interests, but environmental resources as well, including fish and wildlife species of concern, or federally protected. Recreation and outdoor activities may need to be curtailed or limited.

These types of decisions require lead times of weeks or months and involve real risks as well as opportunity costs. Often decisions seek to protect lives and livelihoods, the public health and welfare, as well as infrastructure and property. In dollar terms, the costs may be millions to billions of dollars invested, or at risk of loss. By way of comparison, little is invested in observations, research, data assimilation, modeling, and improving our skill in forecasting, and communicating risks and opportunities to water managers, emergency managers, public officials, private entrepreneurs, recreation, and environmental, and other interests.

While recognizing the current lack of S2S forecasting skill, the number one indicator providing some forecasting skill is the observation of periodic variations in sea surface temperatures (SST) and winds over the tropical eastern Pacific Ocean. The ENSO is a warming of SST which typically brings wetter than usual conditions to the desert U.S. Southwest, and drier conditions in the Northwest.

Other sources of skill involve trends in temperature, precipitation and climatology, as well as other observations of physical processes such as the Madden-Julian Oscillation (MJO), North American Oscillation (NAO), Pacific Decadal Oscillation (PDO). The interaction between the oceans, atmosphere, and land also impact precipitation. Both snow cover and soil moisture are critical to determining short and long-term run off.

Observations, statistical forecast tools, and dynamical forecast models (based on our limited understanding of earth systems and physical processes), as well as the consolidation of trends and forecasts are all part of this complex process.

The 2016 water year began with one of the strongest El Niño signals ever, indicating that California could look forward to a wet year and relief from drought and dry conditions, and the Northwest would likely be drier than average. In fact, the opposite happened.

Marty Ralph, from the Scripps Institute of Oceanography, and the Center for Western Weather and Water Extremes, showed a map of the U.S. presenting coefficients of variation of total precipitation across the Nation. Citing work at Scripps by Mike Dettinger in 2011, Marty observed that annual precipitation in the West is 2-3 times more variable than in the Eastern U.S. Just a few winter storms each year along the West Coast yield more than half the total precipitation and provide much of the West's water supply.

In California, these few large storms, or their absence, account for a disproportionate amount of annual precipitation variability. Ten years of observations and research has led to the recognition of the importance of these so-called “atmospheric rivers,” (ARs) which typically approach the California coast from the southwest, bringing warm, moist air from the tropics. Storms of 2-3 days’ duration, often called a “pineapple express,” come straight from the region around Hawaii. Some mega-storms may last for a few weeks and work their way down the coast. If the AR strikes perpendicularly to the coast and pushes inland over the Coastal and Sierra Mountains, much of the water vapor can condense as it rises and cools, falling as abundant rain or snow. Moderate storms may bring close to 15 inches of rain. Barrier jets paralleling the mountains can also distribute large amounts of precipitation.

Given current observations and research, ARs account for 25%-45% of annual precipitation along the U.S. West Coast, 25%-35% in the Northwest, and 35%-45% of precipitation in California, demonstrating the need for further study. AR seasonality and duration also impact soil moisture and runoff. The largest recorded precipitation events on the West Coast are comparable to the largest events on the East Coast (tropical cyclones). Roughly 95% of the heaviest hourly rainfall rates in coastal northern California have occurred during AR landfall conditions.

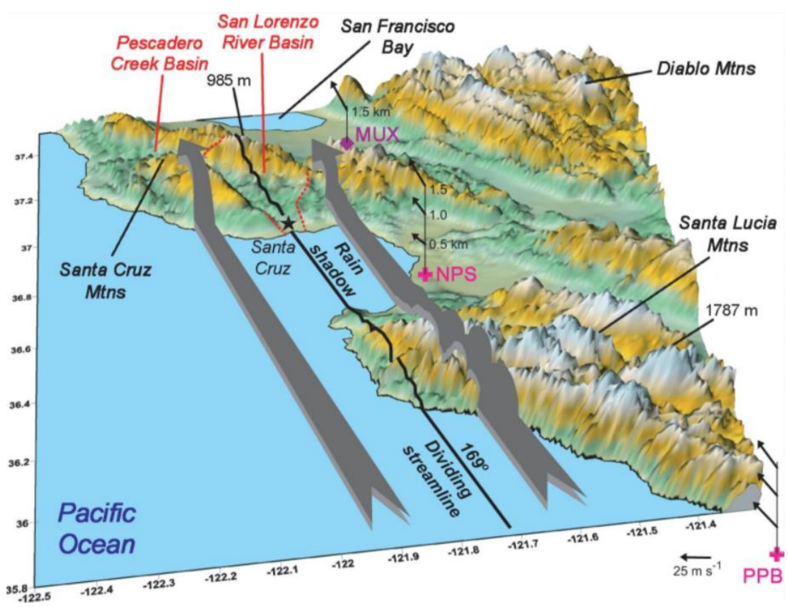

FIGURE 14 AR "ANGLE OF ATTACK" CAN DETERMINE FLOODING

Similar AR monsoonal events have been observed in Arizona as water vapor transported over the Mogollon Rim and associated mountains provide ideal conditions for heavy orographic rains. Of note, some 75% of water vapor transport is in the lowest 3.3 kilometers (km) of the atmosphere. In this part of Arizona, 70%-90% of the ten highest annual peak daily flows occur between November 1st and March 31st.

During this same period: 80% of the top ten daily flows occurred along the Virgin River, at Littlefield, Arizona; 50% on the Little Colorado at Cameron; 90% on the Verde River near Camp Verde; 100% on the Salt River near Roosevelt; and 60% on the Gila River near Clifton, but only 20% on the Santa Cruz River near Cortaro. In the Santa Cruz basin near Nogales, 60%-100% of the ten highest peak flows occurred from July 1st to October 31st. West Coast AR events and inland penetration have also been observed in Idaho, Montana, New Mexico, Oregon, Utah, and Washington.

Marty also illustrated dominant regional and seasonal variations in the primary weather phenomena that lead to extreme precipitation and flooding. These also contribute largely to water supply in the Western U.S., with ARs along the West Coast and into Idaho in the fall and winter, the Great Plains Deep Convection in the spring and summer, the Front Range Upslope rain and snow events (in Colorado, Montana and Wyoming), and the Southwest Monsoon in Arizona, Colorado, Nevada, New Mexico, and Utah. Often these phenomena can overlap. See Figure 15 below for a map depicting the regions.

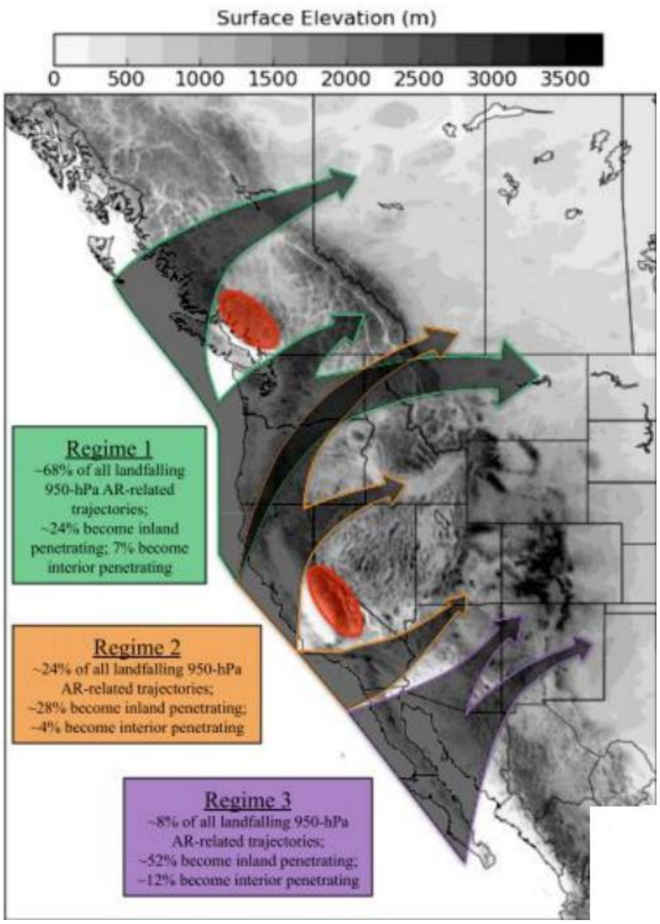

FIGURE 15 INLAND PENETRATION OF ATMOSPHERIC RIVERS OVER WESTERN NORTH AMERICA

An AR-focused long-term observing network (over 100 field sites) is being installed in California as part of a joint project between CDWR, NOAA, and Scripps. It includes GPS receivers for integrated water vapor, soil moisture and temperature probes, wind profilers, and snow level radar which will supplement existing observations and instrumentation. Marty has prepared a similar plan for expanded observation networks westwide.

Ed Clark, the Director of Geo-Intelligence Division of the National Water Center, NWS, NOAA, addressed informing decisions for a "Water-Prepared Nation." He described progress in standing up the National Water Center in Tuscaloosa, Alabama – including a National Water Model and Water Intelligence – as well as a multi-year strategic science and services plan to meet stakeholder priorities. The Center opened on May 26th, 2015 and is intended to be an operations center and a catalyst to transform NOAA's water prediction program.

He summarized the findings and recommendations of a National Academy of Sciences report on Weather Services for the Nation, including work to prioritize core capabilities, improve and accelerate research and pathways for collaboration, establish a hydrologic prediction testbed, and implement a consistent framework for hydrologic prediction skill assessment.

Stakeholders want actionable water intelligence with high resolution, integrated water analyses, predictions, and data that links together demographic, economic, environmental, hydrologic, infrastructure, and political data, to provide an integrated understanding of near and long-term outlook and risks. Priorities involve addressing decisions related to drought, climate uncertainty, flooding, water availability, and water quality.

FIGURE 16 NATIONAL WATER CENTER RIBBON-CUTTING CEREMONY

The National Water Center's mission is Nationally Integrated Water Prediction (IWP) covering earth system modeling and geo-intelligence, decision support services, accelerating research to operations, and interagency and academic collaboration. He went on to describe the National Water Model (NWM) Version 1.0 as a foundation for sustained growth in operational hydrologic forecasting and product experimentation and implementation. The goals are to provide forecasts and streamflow guidance for underserved locations, produce spatially continuous national estimates of hydrologic states (including soil moisture, snow pack, etc.), and implement a modeling architecture that permits rapid infusion of new data and science, and allow for geo-intelligence linkages.

WRF-Hydro forms the NWM core and provides a community-based hydrologic modeling framework supported by various partners. The model is not dependent on a particular forcing data source or choice, and is able to operate over multiple scales and with multiple physics options. The model provides for short-range, medium-range, and long-range analysis and assimilation with various cycling frequency, forecast duration, meteorological forcing, and spatial discretization and routing. Some 1,240 reservoirs and water bodies are parameterized with a level pool scheme. The experimental output includes hydrologic forecasts of river channel discharge and velocity at 2.7 million river reaches, as well as reservoir inflow, outflow, and elevation – plus surface water depth and subsurface flow, soil and snow pack, energy and water fluxes, and streamflow anomalies.

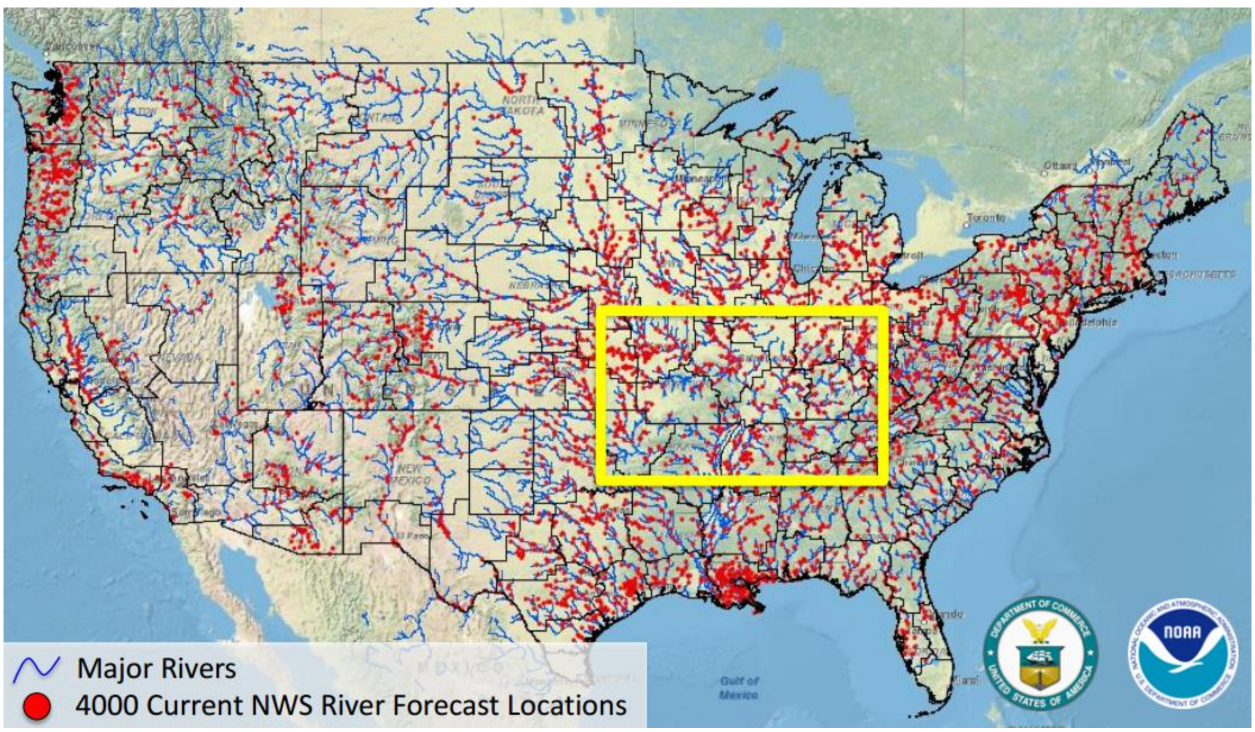

FIGURE 17 MAJOR RIVERS AND NWS HYDROLOGIC FORECAST LOCATIONS

In addition to NWM Development and Demonstration, the National Water Center's multi-year strategic science and services plan includes a centralized water resources data service to provide enhanced water forecasts and information, a test and evaluation service for objective verification and validation of the skill and utility of the NWM, nested hyper-resolutions NWM zoom capability, real-time flood forecast inundation mapping, and enhanced impact-based decision support services to improve flash flood forecasting, link forecasts, and geospatial information to assess impacts and risks, and generate actionable water intelligence for enhanced decision support at appropriate scales. Future proposals involve new and improved prediction services, new delivery models for information and services needed by a broad spectrum of stakeholders, development of next generation integrated earth system models, secure high performance computing, storage and networking capabilities, and link state-of-the-science terrestrial freshwater and coastal estuary models to create a fully coupled “summit-to-sea” integrated water prediction modeling system.

Clark quoted Norman McLean: “Eventually, all things merge into one, and a river runs through it.”

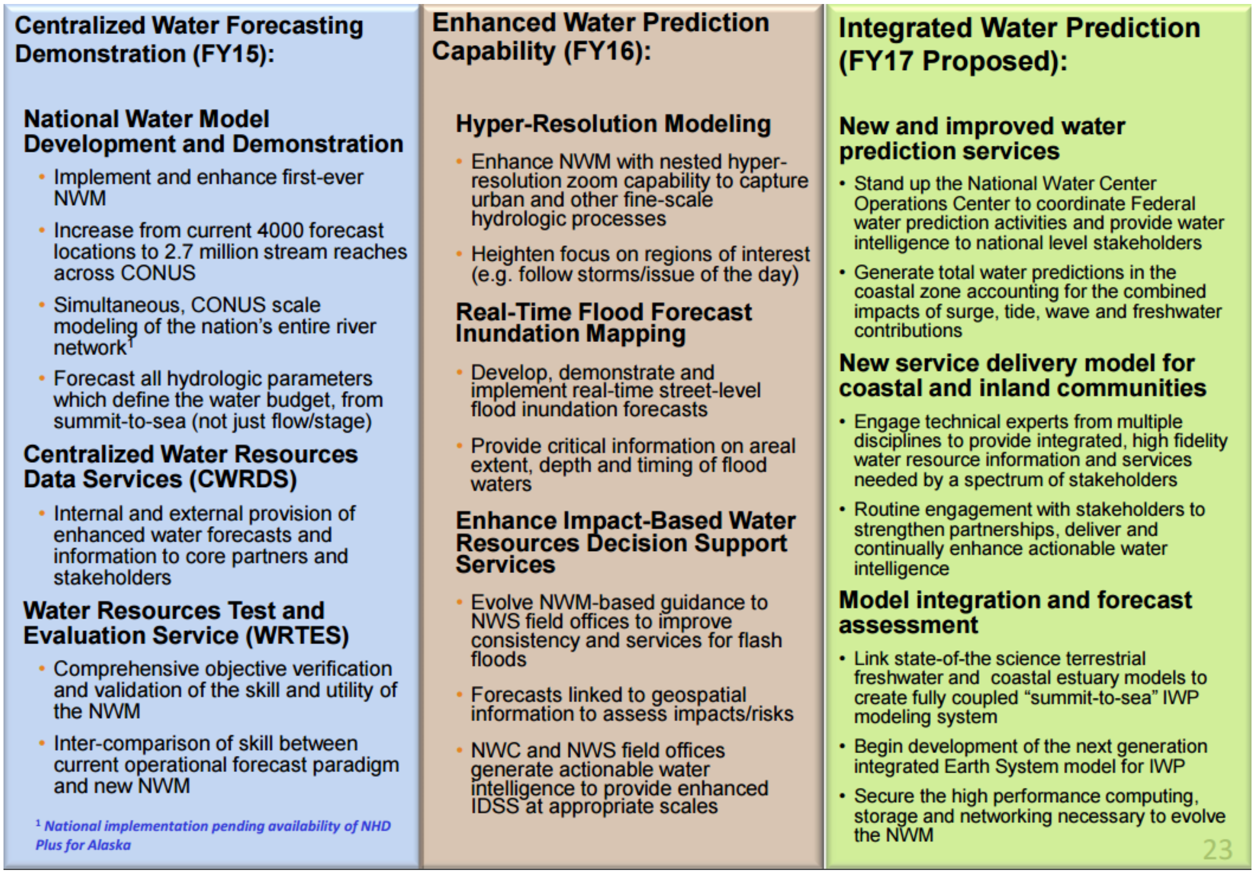

FIGURE 18 STRATEGIC SCIENCE AND SERVICE PLAN FOR THE NWM: INTEGRATED WATER PREDICTION

Dan Barrie, NOAA, Climate Program Office (CPO), addressed the Office of Atmospheric Research, described the Modeling, Analysis, Predictions, and Projections (MAPP) Program, and explored S2S prediction and predictability. CPO initiatives (and its predecessor Office of Global Programs) have targeted prediction system improvements for 20 years, and there have been improvements. NOAA’s Geophysical Fluid Dynamics Laboratory (GFDL) modeling leadership continues with a dynamical core that is one of two finalists to serve as the foundation for the next-generation NWS prediction system. NOAA’s Earth System Research Laboratory (ESRL) led an El Niño rapid response experiment to collect an unprecedented high-resolution dataset of observations of tropical conditions and the extratropical response. This dataset will be critical to better understanding El Niño and to improving models and forecasts, amongst other outcomes. CPO, through the OAR-NWS Climate Test Bed, led the development of the North American Multi Model System (NMME), a major interagency effort, which includes input from seven research and operational climate models. The Climate Test Bed is a joint effort focused on enabling the transition from research into operations.

The MAPP and Climate Variability and Predictability Programs are the current leaders in support for seasonal prediction research. They are focusing on: (1) advancing statistical and dynamical modeling, including multi-model ensemble prediction systems; (2) understanding model biases, and improving model processes and physics; (3) developing novel climate reanalysis techniques; and (4) improving data assimilation and monitoring systems.

MAPP researchers are currently looking at seasonal prediction of ARs, simulating ENSO-AR variability and ENSO Modulation of both AR frequency and average landfall latitude. They are also looking to highlight areas where there may be additional predictability, evaluating different models, model errors and the possible use of intelligent weights.

A scientific assessment of the causes of the 2011-2014 California Drought found that a high pressure ridge off the West Coast diverted storms, together with contributions from SST forcing and a La Niña in the first year. A separate assessment of El Niño impacts on California winter precipitation noted that El Niño typically brings greater precipitation in late winter, with higher "odds" of a wet Southern than Northern California. Questions regarding the 2015-2016 winter forecast and impacts of temperature and evapotranspiration are still being evaluated.

MAPP has recommended Fiscal Year 2016 S2S research funding for a number of new, relevant transition projects that include experimental multi-model sub-seasonal ensemble prediction, better representation of snow and other biases, statistical techniques to improve teleconnection response over North American, and new drought products more relevant to water managers.

MAPP has also recommended support for a number of new projects targeting S2S timescales, including statistical and other approaches (linear inverse modeling) to find new and less expensive sources of improved forecast information, work on blocking and AR phenomena, and improvements in North American precipitation prediction from multi-model data.

GRDL's Forecast-Oriented Low Ocean Resolution (FLOR) model incorporates the higher horizontal resolution in the atmosphere and land, higher vertical resolution in the atmosphere, and a significantly improved land model, together with relatively low resolution ocean and sea ice components, to create a coupled model that is relatively computationally efficient, but can be used to address problems of regional climate and extremes. The FLOR system shows significant improvements for ENSO prediction. A high resolution (HiFLOR) uses smaller grid spacing to improve simulation and allow consideration of phenomena like mountain snow to be better represented.

With the possibility of a 2016-2017 La Niña, ESRL is looking at the precipitation impacts. Both moderate and strong La Niñas impact precipitation in the West. Models agree that the West is generally dry with observations for Central Pacific-oriented La Niñas. Assuming models are correct, there will likely be a small La Niña precipitation impact. The quasi-geostrophic Eliassen Palm (EP) model presents flux on the sphere, computed from daily-average values of wind and temperature observations. There is EP model and observation disagreement with only four observed La Niña events.

ESRL research is also examining model forecasts and the loss of skill from one month to nine months' lead time. Researchers have posed the questions, "Why can past observations verify some models, but not others? What about the atmospheric response?"

Modeling and prediction work is focused on achieving a better representation of precipitation and related processes in the global climate models, improving data assimilation techniques for model initialization, using higher data resolution, and targeting "forecasts of opportunity." Our understanding of which systems deliver the best representation of predictability sources is increasing.

NOAA CPO MAPP is also focused on: (1) better understanding the seasonal predictability of precipitation; (2) the causes, onset, amelioration and predictability of drought; (3) an events driven approach to understanding regional storms and their influence on precipitation; (4) communication with stakeholders and feedback on the development and interpretation of climate model results for water resources predictions; (5) integration of available observations for validation and reanalysis; (6) sustained observation systems; and (7) the human capacity for doing analysis, quality control and data assimilation.

The first major challenge is the HPC capacity needed to run the models. HPC research is very limited, and we need “order-of-magnitude” improvements, not just more computing time using present capabilities. Increased HPC would: (1) help to decisively explore S2S prediction at global high resolution ocean/atmosphere/land systems; (2) support “scale-aware” physics that in turn support experimentation; (3) improve initialization of prediction systems at appropriate spatial scales; and (4) allow an increase in the number of ensemble members to properly sample variability. The second major challenge is defining the natural limits to seasonal precipitation predictability.

Ed Dunlea, a Senior Program Officer at the National Research Council, described the work of a National Academies of Sciences (NAS) committee on a recent report entitled: Next Generation Earth System Prediction – Strategies for Subseasonal to Seasonal Forecasts. The study was sponsored by the Office of Naval Research, Heising Simons Foundation, NASA, and NAS Arthur L. Day Fund. The task was to describe a strategy to increase the Nation's capacity for S2S forecasting and develop a 10-year scientific research agenda to accelerate progress.

Ed examined how weather, water, and climate forecasts are vital to decision-making by businesses, governments, and individuals. The NAS report addressed sub-seasonal (2-13 week forecasts) and seasonal (3-12 months) timescales. Such longer-range S2S forecasts would benefit many sectors of society, filling a gap between weather forecasts and climate projections, and allowing for improved planning and preparation to help save lives, protect property, and increase economic vitality.

S2S forecasts are increasingly used in agriculture, energy, and water resource management — but more engagement with users in other sectors will increase use. However, our current scientific knowledge, gaps in observations and modeling, and computational capacity currently limit the accuracy of S2S forecasts. The study indicates that there is significant room for forecast skill improvement.

The NAS vision is that S2S forecasts will be as widely used a decade from now as weather forecasts are today, recognizing that fulfilling this vision will take sustained effort and investment.

Figure 19 NAS' Committee Vision

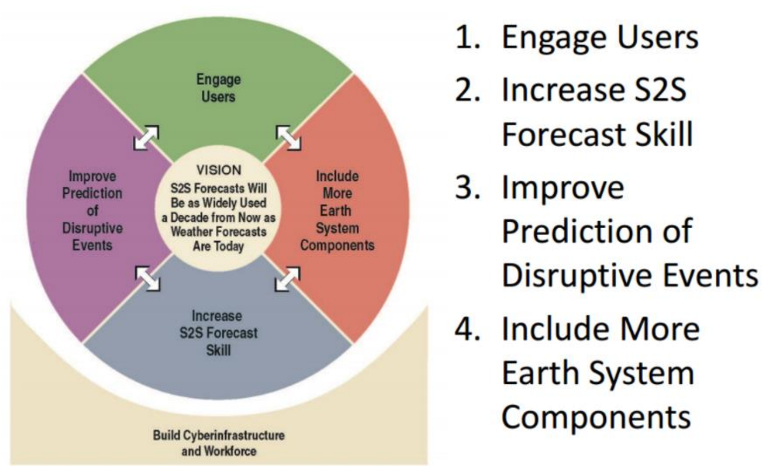

FIGURE 20 NAS FULFILLING THE VISION: RESEARCH STRATEGIES

The Committee recognized that there is currently a mismatch between S2S forecasts and many end users' needs. There needs to me more dialogue between researchers, forecasters, and users in order to accelerate application of S2S forecasts to decision-making, and guide development of forecast verification metrics and products. Government, academia, and the private sector should all play a role.

Next, there is a need to improve all parts of forecast systems starting with sources of predictability, observations, and data assimilation. The Committee highlighted the need to characterize natural modes of variability, maintain and expand observations, prioritize observations through sensitivity studies, and advance strongly coupled data assimilation. There is also a need to improve models, verification methods, and multi-model ensembles – moving improvements from research to operations – through improving model parameterizations, pursuing feature-based verification, exploring different S2S system configurations, creating operational multi-model ensembles, and promoting collaboration between the research and operational communities.

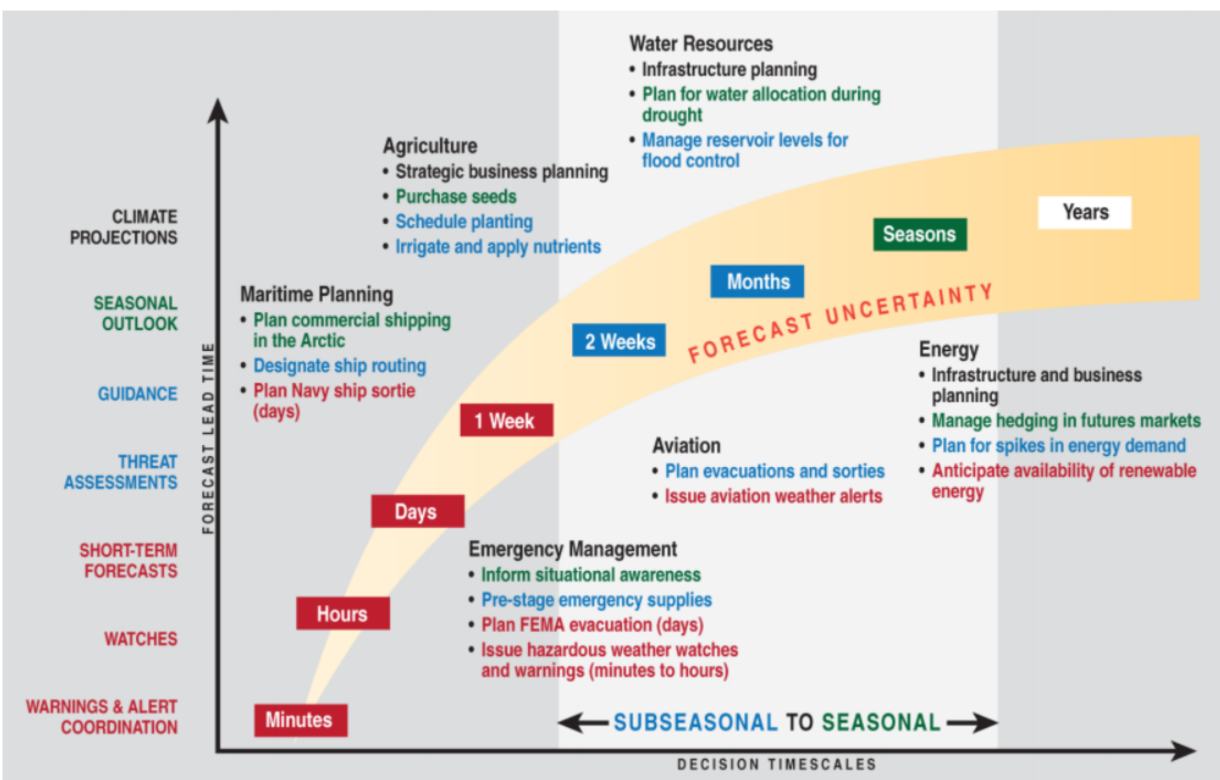

FIGURE 21 UNCERTAINTY OVER VARIOUS DECISION TIMESCALES

Research is also needed to improve prediction of extreme and disruptive events and of the consequences of unanticipated forcing events, such as volcanoes, building improved national capabilities.

Dunlea noted a more complete description of the Earth system in S2S forecast systems will improve forecast skill, with sub-models of the ocean, sea ice, land surface and other components that are currently under developed or missing from S2S forecast systems. S2S stakeholders are looking for forecasts of more variables, and the Committee recommended development of next-generation model components.

Cyber infrastructure and workforce components should not be overlooked. S2S forecasting involves enormous amounts of data (observations, data assimilation steps, and model outputs). Similar challenges exist in the weather and climate forecasting fields. The Committee recommended creating a national plan for cyberinfrastructure. There are also significant barriers that exist to training and retaining talented workers in S2S model development, and a need for more people trained to work across the science-user interface, requiring more effort to address S2S workforce development.

The Committee's recommendations are presented without prescribing priority or sequence – which allows flexibility to address changing conditions.

Dunlea provided an example of a specific recommendation for developing a body of social science research that would lead to more comprehensive and systematic understanding of the use and barriers to use of seasonal and sub-seasonal Earth system predictions, bridging basic and applied/operational research, with short-term benefits. Other recommendations may need development of new initiatives, and some require international collaboration.

Dave Dewitt, Director of NOAA's Climate Prediction Center (CPC), presented a Framework for Establishing a Seasonal Precipitation Forecast Improvement Project (SPFIP). The vision is the development of a holistic program to improve seasonal forecast skill through improved understanding of known sources of predictability, exploration of new sources, and improvement of the representation of these processes in our models. Realizing this vision will require a substantial and sustained commitment of resources and a need to leverage all members of the short-term climate prediction community including operational centers, federal labs, and academic partners. He referred to background work and a number of foundational documents.

The National Climatic Data Center (NCDC) has noted that recorded droughts in the U.S. have had severe economic impacts (more than $1 billion in damages) during 16 of the 21 years from 1980 to 2011, with an estimated annual average direct drought loss of $9.5 billion (adjusted to 2011 dollars; Smith and Katz, 2013)).

For the purposes of Dave's presentation, seasonal forecasting refers to the first 3-month season and includes the first month's forecast. Although the focus of the forecasting is on precipitation, it should be recognized that the work to be undertaken will also benefit seasonal temperature forecasts. Predictability is used qualitatively to describe the extent to which the representation of a physical process contributes to prediction skill. Estimates of the lower-bound on predictability are obtained from the skill of current forecasts. Improving skill of extended range precipitation forecasts is one of the most difficult problems in earth-system modeling. Forecast skill rapidly decays with lead time.

Dave noted the CPC publishes seasonal outlooks for precipitation and temperature, but the skill level is limited (especially for precipitation) given current seasonal forecast tools. He explained ENSO and its role in seasonal forecasts for the U.S. and discussed examples of where our most skillful tools don't perform well – indicating gaps in our knowledge or naturally limited predictability or both – covering the one month (January to March (JFM) 2015 NMME forecast). Outside of the central and eastern Tropical Pacific, the NMME skill in predicting SST variability is greatly reduced.

Why use multi-model ensembles (MME) for forecasts? It allows for representation of model uncertainty. It takes advantage of the possibility of complementary skill between models. The MME skill is frequently higher than that from the most skillful member in the ensemble (though if one model is dominantly better this is not always true). NMME is frequently our most skillful tool, but there is still room for improvement. Users' perspective on the skill level of these forecast tools and hence their utility will vary.

ENSO isn't the only factor controlling the seasonal distribution of precipitation over the U.S. However, it is commonly accepted that accurate forecasts of ENSO and its associated teleconnections are a necessary, but not sufficient condition for accurate seasonal precipitation forecasts. The NMME SST one-month forecast for January 2015 called for a moderate canonical El-Niño, while observed anomalies were confined to western Pacific. Associated precipitation forecasts called for a modest probability of above normal precipitation, while record breaking drought was observed.

Currently, the CPC's state-of-the-art MME Dynamical Forecast System has low skill in predicting near-Equatorial Western Pacific SST. If SST in this region is what drives the largescale patterns of the past two years, then there are problems within the model. The NMME precipitation forecast for December 2015 at a one-month lead during a near-record El Niño did not predict some major precipitation anomalies.

Borrowing heavily from the collective recommendations made in the foundational documents, especially the 2010 NRC/NAS Report on Inter-seasonal to Inter-Annual (ISI) Climate Prediction and Predictability, there are key science issues that need to be addressed to improve seasonal forecast skill. The main conclusions:

• There are no "silver bullets," and there is no single action that will lead to a revolutionary leap forward in ISI predictions.

• Incremental increases in ISI forecasting quality are to be expected as the building blocks of ISI forecasts are improved and we increase our knowledge of possible sources of predictability.

NOAA projects are targeting opportunities to increase our understanding and exploitation of different sources of predictability, through: (1) an El Niño rapid response field campaign; (2) maximizing the value of dynamical model ensembles; and (3) a new multi-decadal climate reanalysis. NOAA is also working to improve our understanding of tropical-extratropical teleconnections, and systematic model errors. CPC is using hybrid dynamical-statistical techniques and calibration using reforecasts to increase skill, while improving diagnostic studies using updated dynamical models and more sophisticated data assimilation techniques.

NOAA is targeting certain "building blocks" to improve ISI prediction, including enhancing observational networks, upgrading data assimilation systems, and seeking to reduce model errors through improved dynamics and physics.

THE SPFIP's science goal #1 is an improved understanding of the physics and modeling sources of seasonal predictability. This involves studying the Madden-Julian Oscillation (MJO), stratosphere-troposphere interactions, ocean-atmosphere coupling (including ENSO), the North Atlantic Oscillation

(NAO) and Arctic Oscillation (AO), land-atmosphere feedback, polar sea ice, ARs, pacific decadal oscillation (PDO), and the role of sea surface temperature (SST) forcing versus internal variability.

Science goal #2 is to identify causes and reduce systematic errors in coupled atmosphere-ocean general circulation models (CGCMS) through a better understanding of double intertropical convergence zones, excessively strong equatorial cold tongues, weak or incoherent intra-seasonal variability, and associated teleconnections, a failure to represent multi-scale organization of tropical convection, and poorly represented cloud processes, especially low-level clouds, in order to increase model resolution to better resolve physical processes and orographic variations.

Goal #3 is to improve seasonal prediction tools through an improved representation of physical processes in the CGCMS -- including deep and shallow convection, planetary boundary layers in the atmosphere and oceans, as well as sea ice, soil moisture and snow cover – while also exploring new statistical techniques and hybrid dynamical-statistical techniques, and ensuring rigorous cross-validation to estimate true forecast skill.

The foundation of the SPFIP framework is ensuring adequate resources are obtained, recognizing the difficulty of the problems. Essential framework components include: (1) grant programs supporting mission-driven research on understanding sources of predictability; (2) supporting modeling centers for model improvements; (2) supporting grant programs for tailoring products for end users; (3) supporting infrastructure for testing new tools for transitioning to operations; and (4) augmenting HPC capabilities.

Dave noted he is currently updating the framework to reflect the findings and recommendations in the recently released NAS S2S report. The primary authors are close to finalizing the framework and it will be released once it is done.

Will Stelle, NOAA's West Coast Regional Administrator, and a self-proclaimed "fish guy", concluded the presentations speaking without notes about NOAA Fisheries interests. For a fish guy, water is home and a three-dimensional habitat for living organisms. His experience has been mainly in implementing the Endangered Species Act (ESA) to protect salmon. He described the life cycle of a Chinook salmon from its birth in high elevation coastal tributaries to the ocean and back to die. The ESA says: "You can't kill me!" Not as a smolt, fry, fingerling, juvenile, adult, or spawner.

The story of the West is a story of dams and water development and management. It is important to consider fish in this story, and the need to manage water releases, stream temperatures, pumping operations, and stream/river flows to estuaries and the ocean – which some people consider wasted water. He provided an overview of the Sacramento-San Joaquin River and San Francisco Bay Delta issues in California and the conflict between fish, farmers, and municipal and industrial users. Given the financial stakes for all, the lack of precision in forecasts can be expensive and improved hydrologic and water temperature projections will be highly valuable.

Dave DeWitt wrapped up the meeting, sharing that his next task was to finalize and distribute the concept on the Seasonal Projection Forecast Improvement Project. All participants and stakeholders need to make the case for S2S improvements.

S2S Workshop IV – June 6 – 9, 2016, San Diego, California

Summary

On June 7-9, the Western States Water Council, in cooperation with the California Department of Water Resources (CDWR) and National Oceanic and Atmospheric Administration (NOAA), brought together leading scientists and state water officials in a workshop in San Diego, California to discuss the state of the art with respect to Improving Sub-Seasonal and Seasonal (S2S) Precipitation Forecasting. This was the fourth in a series of workshops this past year. At this workshop, Arizona, California, Colorado, Nebraska, Texas and Wyoming were represented, together with NOAA, including the National Weather Service, as well as the National Atmospheric and Space Administration (NASA), U.S. Bureau of Reclamation (USBOR), and U.S. Geological Survey (USGS).

Presentations

Jeanine Jones, Interstate Resources Manager, CDWR, reviewed recent NOAA-WSWC collaborative activities, including four earlier workshops. She noted that the specific focus of the workshop would be on S2S precipitation forecasting and not on research to advance national drought monitoring and prediction capabilities, though better precipitation forecasting will benefit the latter. Jeanine emphasized the importance and value of better precipitation predictions, and greater “lead times,” in order to improve water resources management decision-making. The purpose of this collaborative effort is also to highlight the lack of resources being directed to improving S2S precipitation forecasting, and specifically Western U.S. precipitation prediction needs. She noted the differences between the variability of precipitation in the West, compared to the East.

Stakeholders continue to ask, “Will next year be wet or dry?” NOAA and other federal and state agencies are working to find ways to answer this question, but improving our capacity to predict precipitation several weeks or months in advance with any skill will require a sustained commitment of resources to help us better understand complex and interconnected physical earth system processes. What limited skill we have depends on our understanding of oceanic and related meteorological events such as El Niño, the warming of equatorial waters that influence the movement of the jet stream, and western U.S. weather patterns. However, this past year an unusually strong El Niño led to expectations of extreme wet weather across the U.S. Southwest, which did not happen.

Jeanine noted the NAS report on strategies for improving S2S forecasts, and NOAA’s California Drought 2014 Service Assessment, as well as the startup of the National Water Center in Alabama, with a focus of runoff modeling, and soon to be held NOAA listening sessions in Tuscaloosa, Alabama and Sacramento, California.

She addressed the importance of lead time in forecasts and the value in public health and safety decisions, balancing risk/cost trade-offs, increasing water management efficiency, operating within legal and regulatory frameworks, reducing impacts of extreme events, and responding to increased competition for resources. Myriad decisions depend on perceptions of future “wet or dry” scenarios. Unfortunately, at present, forecasting skill is so low as to be of little or no use to water managers. Heidke skill scores for precipitation forecasts 90-days out are negative and bear little resemblance to observed precipitation.

Jeanine surveyed some sources of NOAA forecast skill, with ENSO at the top of the list, but even with the “Godzilla” ENSO continuing, dry conditions in Southern California and flooding in Washington were the opposite of what was projected. We need to identify specific near-term actions (low-hanging fruit) over the next few years, which may include pilot projects, AR predictions, and increasing support for sustained and expanded observations.

Mike Anderson, California State Climatologist, further reviewed what was predicted for 2015/2016 and what happened. The mighty El Niño predicted materialized, with great expectations for warmer coastal and wetter conditions westwide. El Niño did not bring the expected results with continuing drought conditions in California and little snow at the end of March 2015.

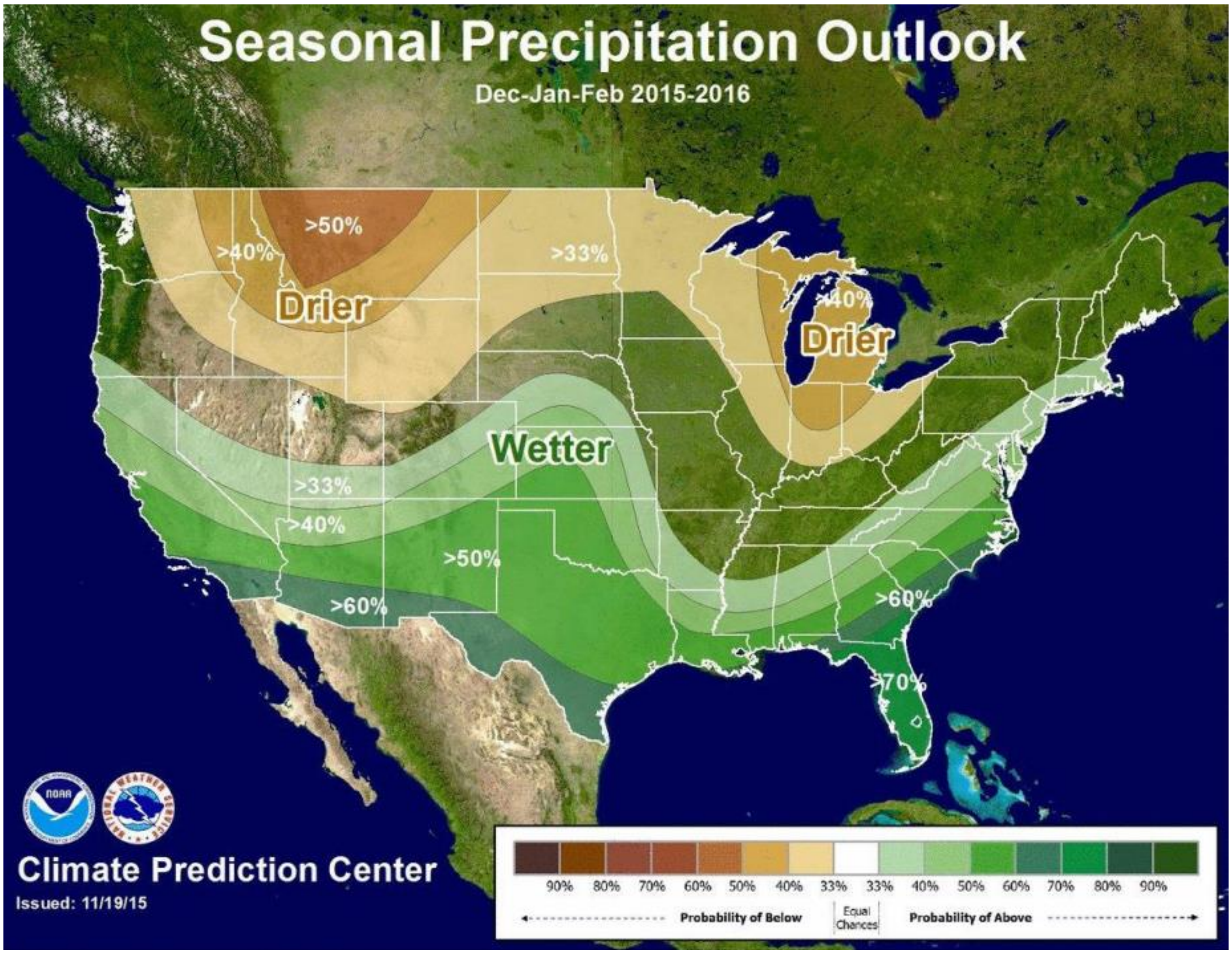

FIGURE 22 CPC'S SEASONAL PRECIPITATION OUTLOOK FOR THE DEC-JAN-FEB 2015-2016 TIMEFRAME

Mike also reviewed the key phenomena affecting California water supply and flood mitigation planning, which are related to the size, number and strength of atmospheric river events, operating on different space and time scales.

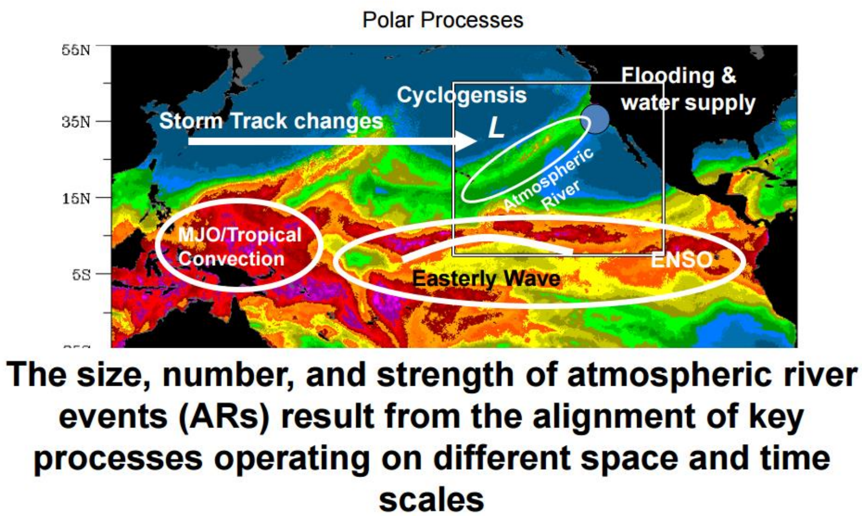

FIGURE 23 KEY PHENOMENA AFFECTING CALIFORNIA WATER SUPPLY/FLOODING

In summary, El Niño influenced the wintertime atmospheric circulation as expected for the most part (February/March anomaly), but precipitation and temperature outcomes varied from expectations, and snowpack was not as large or long-lasting as was hoped for. California sea levels were higher, but didn't coincide with a major storm event. What's next? La Niña!

Alex Tardy and Roger Pierce, with the San Diego Weather Forecast Office addressed using and interpreting CPC outlooks, which break down projections of temperature and precipitation anomalies into two or three classes (and communicating confidence in these probabilistic forecasts). They reiterated observed conditions varied from expectations.

Summarizing, they noted that El Niño conditions characterized by unusual SST warming can take the normal jet stream from Oregon and bring it south across Southern California for much of the winter and spring months. The result is often a pattern that brings a series of stormy periods in the winter and spring months, but not a particular storm. El Niño was present and strengthening slowly through Fall 2015, and El Niño at the strong phase correlates to above normal precipitation in Southern California but not necessarily the whole state. Currently the 2015/2016 El Niño is the strongest on record (2.4 °C increase in the center).

Above normal precipitation and frequent storms are expected for southern California with El Niño with the best chance from December through March. El Niño can impact the jet stream to bring more frequent storms to California during the wet season but not necessarily stronger storms (not just the Pineapple Express or ARs). Some of the wettest months have been El Niño years but individual large precipitation events have occurred in non- El Niño and La Niña years (such as January 1993 and December 2010). El Niño does not guarantee above normal precipitation and there have been several dry or average years in California during an El Niño. The California Drought will continue, since the current 4-year deficits are equivalent to 1-2 seasons missed, and the entire state will need much above normal precipitation and above normal snowpack.

Duane Waliser, Chief Scientist, NASA-JPL, outlined recommendations from the NAS S2S report that outlined a research agenda towards realizing a future in which we will use S2S forecasts in decision-making to the same extent that we now use 5-10-day weather forecasts with similar skill. It is a bold vision. Duane was a member of the NAS Committee that wrote the report[4].

4

Dave DeWitt, NOAA Climate Prediction Center (CPC) Director, described NOAA's Seasonal Precipitation Forecast Improvement Project (SPFIP) initiative to improve forecasts 3-4 weeks out and the use of dynamical models of earth systems, coupled with statistical models. A discussion of the pros and cons of the two different types of models followed, leading to a comment that together these modeling techniques have brought us to where we are today with accurate short-term weather forecasting. To improve our understanding of dynamical earth systems, including our oceans, atmosphere, land and ice cover, we need to invest more resources in advances our understanding of the physics. Present S2S predictions are based on course models with limited understanding of interactions between physical systems. We need better tools to have better forecasts. There is no one "silver bullet." Progress will be incremental, but compounding[5].

Dave offered that NOAA's goal is to improve S2S forecast skill by 20% over 5 years, and 40% over 10 years. However, this will require additional resources on a sustained basis. He compared SPFIP to the Hurricane Forecast Improvement Project (HFIP) investment, which allowed NOAA to better project hurricane paths and landfall, with significant benefits for emergency managers and others.

More needs to be done to understand potential sources of S2S predictability, and the limits thereof, as well as how best to transition observations and forecasts to operations. Forecasts are currently based on very course model resolution with a poor understanding of all the physics. "We are not going to get more skillful dynamical models in the near future, but that doesn't mean we shouldn't continue to invest in physics and science research. We need better tools to have better forecasts."

ENSO is a necessary, but not the only signal needed for understanding and improving forecasts. There are also model biases which compound errors, which need to be addressed. Dave indicated some dissatisfaction with NOAA's modeling of tropical convection, with consequences for predicting the path of the jet stream. He believed that a better understanding of the physics between the key links in weather and climate are necessary.

Dave expounded on some of the key science challenges that need to be addressed to improve S2S forecast skill. First, understanding the processes controlling organization of tropical convection is a pervasive weakness of weather and climate models. Studies suggest that beyond 10 days, variations in tropical heating are a (the) major source of predictability, including weather events. Tropical climate biases often appear very early in model integrations. Second, we need to improve our understanding and prediction of tropical-extratropical interactions including storm tracks and blocking events, MJO, AR, and "Pineapple Express" events, all of which affect West Coast precipitation. Third, we need to better understand stratospheric and tropospheric interactions, the role of sea ice and interconnections between the oceans and atmosphere (including SST) and land and atmosphere (soil moisture and land processes), as well as long-term trends and climate variability. These interactions offer opportunities to exploit related sources of predictability.

Dave identified the fourth challenge as improving our "building blocks," including enhancing our observation networks, upgrading our data assimilation systems (observations to analysis to models and short forecasts), followed by identifying and correcting model errors. Improvements in models, observational networks, and data assimilation systems lead to improved understanding and more realistic prediction over time. Dave reiterated a number of goals outlined earlier in his presentation at Workshop III.

5

He noted that the dramatic failure of state of the art dynamical models (including NMME) in predicting the precipitation anomalies in the western and central U.S. during the record 2015-2016 El-Niño suggests that either there is less predictability in the system then we previously believed or the current generation of models misrepresent or don't represent at all key processes. Particularly, models in the West need finer resolution to resolve mountain orographics.

Dave opined that improving forecasts first out to three months will improve longer-term forecasts. Forecast improvement has been flat for the past 15 years. NOAA needs target experiments and more high performance computing power to address the challenge posed by S2S forecast prediction. Then there is always the challenge of uncertain funding. Dr. Uccellini believed that shifting funding to operational improvements may be short-sighted. Funding for basic physics research will lead to improved forecasts.

NOAA also needs more support and partners in the S2S forecasting effort. Improvements need to be driven by the needs of the user community. In this case, that is the water resources user community. Users should communicate what products are useable and useful from a stakeholders' perspective, and propose the initial metrics.

Sarah Kapnick is a NOAA Physical Research Scientist, Geophysical Fluid Dynamics Laboratory (GFDL) in Princeton, New Jersey. Her research focuses on the mechanisms controlling extreme storms and mountain snowpack. In the Desert Southwest, neither dynamical models nor statistical models do well. She described work on GFDL's high resolution version (HiFLOR) of a Forecast-Oriented Low Ocean Resolution (FLOR) model. This higher resolution (25-kilometer grid) coupled climate model addresses the need to account for mountain orographics and precipitation impacts.

However, the computing power, time, and related costs increase exponentially compared to low resolution models. It can take five hours to run one year, followed by 18 hours of processing and six hours of post-processing. Data requirements jump from 91 megabytes to 71 gigabytes, and the computing costs are 120 times higher. Moreover, observations and data that match the model resolution may not always be available. The importance of data and observation systems was stressed throughout the workshop.

At a 25km resolution, Sarah noted, the seasonality and the timing of extreme precipitation begin to appear from the HiFLOR model runs. Improvements in forecast results also appear. Some significant skill may be possible in predicting snow accumulation perhaps nine months out. Snow skill scores of .25 in Southern California and .60 in mountainous terrain have been demonstrated. She also emphasized the importance of adding information on the state of the stratosphere to the model initialization, which can significantly impact prediction skill.

Sarah noted the pioneering work of Mark A. Cane, now at Columbia University, with experimental forecasts based on the 1895 El Niño that were published in June of that year in Nature. Mark has said, "If you're predicting the weather you get to verify your models every three or four days. For El Niño, you have to wait four years to find out if you're right."

Marty Ralph, Director of the Center for Western Weather and Water Extremes (CW3E) at the Scripps Institution of Oceanography, described examples of research regarding atmospheric rivers (ARs) and the need for a westwide observing network. ARs move water vapor equivalent to 26 Mississippi Rivers around the hemispheres at low altitudes. ARs moving north of Hawaii towards the West Coast, coupled with the Sierra Jet, move moisture up and over the mountains, producing copious amounts of precipitation. These AR conditions are associated with California's wettest days, accounting for perhaps 85% of the variability in precipitation. Therefore, the number of AR related storms is directly related to wet and dry California water years. He noted that warming temperatures at mid-latitudes will lead to greater water vapor transport, an estimated 20% increase at mid-latitudes and up to 100% more across Artic regions, which would be expected to lead to warmer and wetter poles (which are now essentially deserts) and a subsequent loss of sea ice.

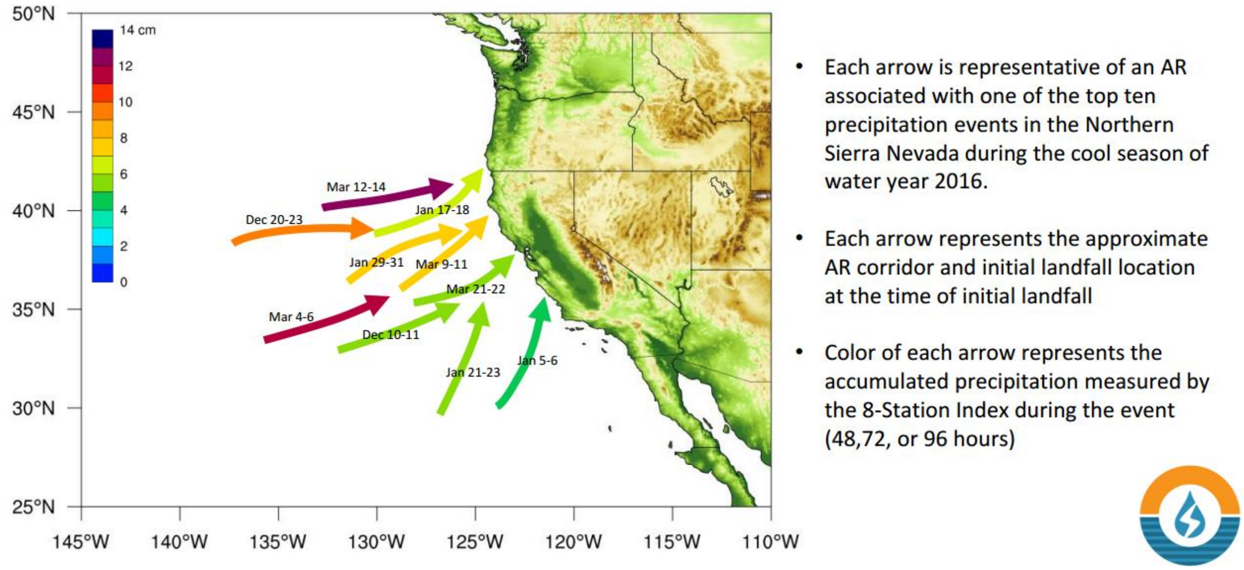

FIGURE 24 AR TRACKS: A PRELIMINARY SCHEMATIC

Marty also addressed a reanalysis of the "Top-10" precipitation days in California for different regions and ranges. To summarize, 46 of 50 (92%) extreme daily precipitation events are associated with land-falling ARs on either the day before or the day of precipitation. Further, 45 of 50 (90%) extreme daily precipitation events are associated with Sierra Barrier Jet (SBJ) conditions on either the day before or the day of precipitation. Next, 38 of 50 (76%) extreme daily precipitation events are associated with both land-falling ARs and SBJ conditions. Lastly, the 10 wettest days (100%) in the Northern Sierra 8-station Index (i.e., the top 0.3% of all days in 10 years) were all associated with both a land-falling AR and an SBJ. Can we build a tool that uses this result to produce an alert of high risk based on associated diagnoses of forecast model output?

Marty summarized the Top-10 wettest events of Water Year (WY) 2016. They were identified and examined in terms of their strength and nature of the storms that produced them. The 10 events produced 54% of WY2016 precipitation. All ten were AR events. All ten had winds from the West or Southwest. All struck Northern California or the Oregon Coast and forced water vapor into the Northern Sierra/Shasta area.

Duane Waliser noted that ARs appear globally, not just off the U.S. West Coast, but also impact weather and climate from Chile and Argentina, to South Africa and Australia, as well as the Western United Kingdom and Northern Europe, and other areas. He added to Marty's observations that over 90% of the water vapor moving towards the poles is carried by ARs. He also opined that we don't really know how good the global climate models are, leaving a lot of uncertainty.

Heather Archambault, NOAA Climate Program Office (CPO), described the work of CPO's Modeling, Analysis, Predictions and Projections (MAPP) Program and initiatives and opportunities in high-resolution modeling. CPO focus areas include: (1) observing systems, climate monitoring and data stewardship; (2) understanding and modeling earth system science, to produce predictions and projections; and (3) informing decision through building information systems, regional capacity, communication and education. Together with OAR, CPO and MAPP provide a mission-oriented competitive research program at the interface between science and services.

MAPP, through annual competitions, supports five focus areas, including prediction, climate reanalysis, climate and earth system modeling, drought and other applications, and climate projections. “Climate Competitive Research” is the NOAA/OAR budget line. MAPP task forces allow for a sustained, coordinated research effort by MAPP investigators. MAPP is working at home and abroad with partners to improve S2S predictions. In Fiscal Year 2016, there is over $3 million in S2S prediction research investments, including transition to operations work. Global coupled models, together with adequate process physics, has the potential to significantly improve S2S predictions. MAPP is working towards targeted improvements to model physics. However, systematic experimentation and assessment is limited due to a lack of funding. Of note, the House NOAA appropriations “mark” included a 40% reduction for climate research.

Heather summarized the history behind the North American Multi-Model Ensemble (NMME). The basic concept is that on average, NMME achieves superior forecast skill relative to any single model prediction system by combining predictions from leading climate models. NMME was developed and demonstrated as ready to be transitioned into operations with support from NASA, the Department of Energy (DOE), and the National Science Foundation (NSF). NMME completed transition to NWS operations in May 2016. The largest seasonal prediction dataset publicly available provides a platform for prediction and applications research projects. Further research to improve NMME continues, and a special NMME issue in Climate Dynamics is open for submissions through September 2016.

A MAPP-developed Empirical Sub-Seasonal Prediction Tool is being used for CPC experimental week 3–4 outlooks. It generates probabilistic forecasts by leveraging information about current states of ENSO and the MJO (and for temperature and trend information).

Heather stated that there are theoretical limits to deterministic weather predictions. Weather predictability arises from our understanding of atmospheric initial conditions and atmospheric processes. Also, the longer the lead time, the lower the prediction skill is. Climate predictability is based on natural modes of variability in coupled Earth systems, slowly-varying processes, and trends. Climate model skill is based on probabilistic verification.

MAPP’s strategy in supporting new S2S research and transition projects involves: (1) testing prediction tools via a Climate Test Bed (targets short-term advances and the transition from research to operations); and (2) understand how to improve prediction systems’ representation of predictability sources (research targets medium-term advances). She outlined the NAS Strategy to advance S2S Prediction Capability. Other MAPP supported work includes: (1) the Subseasonal Prediction Experiment (SubX) testing experimental sub-seasonal prediction systems; (2) projects on land surface models and data assimilation for better representation of snow and other biases; (3) statistical techniques to improve prediction of teleconnection response over North America; and (4) new drought products tailored to water managers.

Global high-resolution in coupled models, together with adequate process physics, have the potential to significantly improve models and S2S predictions. However, a systematic experimentation and assessment of benefits in the “modeling trade space” is currently lacking due to costs. This requires substantial investments in research and computing infrastructure, with benefits from coordination between the S2S predictions and climate modeling communities.

In summary, MAPP programs' research and transition have been key to improving seasonal predictions. New FY 2016 MAPP initiatives are aimed at closing the weather-climate prediction gap – pioneering on select activities recommended in the S2S NAS report. These new initiatives represent only tip of iceberg of what NOAA could do to advance S2S prediction (see, e.g., NAS S2S report). Increasing resolution for global coupled models may improve predictions in many respects, further work is needed to systematically explore trade-offs between resolution and other aspects of modeling.

Ken Nowak, U.S. Bureau of Reclamation, presented on the Bureau's S2S forecasting activities, specifically on research and prize competitions that they hoped would advance the science and assist in water allocation, flood and drought management, stakeholder planning and environmental decision-making. The competitions issue a national challenge to solve a specific, typically difficult problem, and establish monetary and/or non-monetary incentive prizes. Winners must achieve predetermined performance metrics established by sponsors. Anyone can compete at their own risk (but there are limitations on federal employees competing). Competitions can be effective where: (1) an adequate or strong solution has been evasive or expensive; (2) you find yourself saying that somebody, somewhere probably knows a better way of doing this; (3) market forces may not provide appropriate incentives to solve...or solve well the problem; and (4) you would like to reach beyond the usual sources of potential solvers and experts that commonly work in your domain.

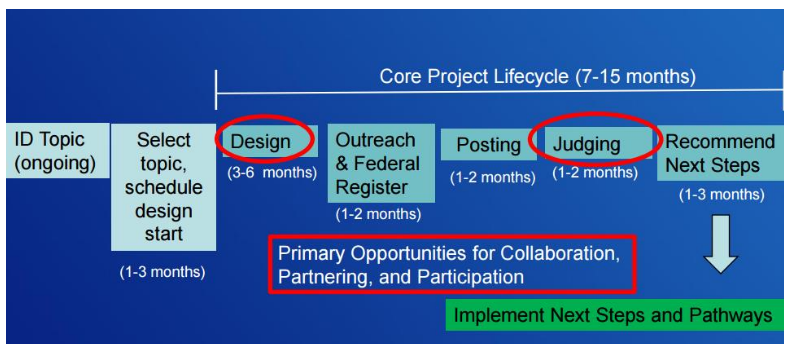

FIGURE 25 WORKFLOW AND SMALL "ONLINE CROWDSOURCING" COMPETITIONS

Selected projects provide a forum for collaboration, partnering and participation with Reclamation as well as other competitors. They are planning a challenge for investigations of both the drought and flood aspects of S2S prediction, and hope to be able to incorporate work done on West Coast atmospheric rivers. Forecasting models and data are complex, and partnering through competition helps access specialized institutions, engage topic experts, leverage years of experience and resources, and boost participation in research processes.

Reclamation and Scripps CW3E are working to create a catalog of past ARs spanning approximately seven decades, study the catalog to understand AR processes, and develop methods to aid AR forecasting at the S2S timescale.

Ken also addressed the benefits of federal collaboration, which: (1) leverages collective federal capabilities; (2) ensures a federal solution does not already exist; (3) avoids duplication; (4) catalyzes interagency working relationships; (5) better defines and solves joint problems; (6) ensures solutions will have broader impact; (7) better serves the stakeholders and the public; and (8) meets required consultation across the federal government under prize competition law.

Reclamation is the U.S. Army Corps of Engineers and NCAR on a System for Hydromet Ensemble Research and Prediction Applications (SHERPA). It will provide an experimental streamflow forecast testbed with both “hind-casts” and real-time projections, as well as leverage advances in data sets and hydrologic models.

More information on research projects and prize competitions is available at: www.usbr.gov/research.

Kwabena Asante, GEI Consulting Engineers and Scientists, presented a statistical analysis of hydrology in California under climate variability. Given existing forecasting challenges, GEI began a California storm characteristics database and analysis of storms and climate variability. They integrated the University of California-Irvine’s Center for Hydrometeorology and Remote Sensing (CHRS) Connect Storm Database, and looked at other statistical climatology applications. DHRS is extracted from a satellite-derived precipitation dataset called the Precipitation Estimation from Remote Sensing Information using Artificial Neural Network (PERSIANN) with global coverage, from 2000-2015, which is periodically updated.

GEI’s work presents a sensor view of seasonal precipitation and migrates to a storm view of precipitation. California in WY 2013 experienced very high early season precipitation (October to December), and only minor events after January 1st.

Kwabena described work for CDWR in cataloging the location, duration and intensity of over 700 storms and their relationship to different climate phases, both positive and negative. They also analyzed storms by drainage area, finding the most storms in the North Coast of California, which was expected, but surprisingly the fewest storms are in the Sacramento area. The most storms occur in October, but the mean number varied by basin. They created a new data base for use by the California Flood Emergency Response Information Exchange (FERIX) and reservoir storage management. It remains to be seen whether storm characteristics data can be used to improve precipitation and water supply forecasts.

Select storm characteristics are amplified or suppressed in spatially consistent patterns under the climate phases analyzed. The altered storm characteristics could form the basis for generating storm-based forecasts at S2S time scales. Statistically-derived storm impact databases and applications being developed that can integrate storm forecasts into existing decision processes.

Nelun Fernando, Texas Water Development Board (TWDB), described their use of S2S climate information and statistical forecasts of May-July seasonal rainfall over Texas. In Texas, the record 2011 drought coincided with a “double-dip” La Niña. The Spring (May-July 2011) drought intensification was not forecast. Drought conditions forecast for December 2011-February 2012 based on La Niña were not realized with moisture transport from the Gulf of Mexico ending the meteorological drought.

She presented examples of statistical modeling and observations. May and June are usually the highest precipitation months in Texas, but once a high pressure system sets up it tends to persist through the summer and can block storms. Strong summer droughts are characterized by the rapid intensification in the spring/early-summer, and 92% of strong summer droughts (going back to 1895) had anomalously low rainfall in the spring. Dry spring seasons lead to an anomalously high atmospheric pressure system over Texas and a reduction in rainfall.

TWDB is looking at precursors to and the persistence and predictability of drought – including April processes that drive summer rainfall deficits – as well as convective processes, antecedent soil moisture, and other factors. TWDB developed a process-based statistical model to predict May– July (MJJ) rainfall over the South Central U.S. and key processes active in the spring (April) that drive summer rainfall deficits, including: (1) geopotential height at 500 hPa (~3 km above land surface); (2) convective inhibition energy (that prevents convective rainfall processes); and (3) soil moisture.

Their seasonal rainfall forecast tool involves model trained using data reanalysis, and hybrid dynamical-statistical forecasts using 3- to 1-month lead forecasts of April predictor fields. A model was created using Canonical Correlation Analysis with the Climate Predictability Tool. Forecast skill level exceeds skill due to persistence (i.e. autocorrelation) over most of Texas and Oklahoma.

Related to drought and water resources planning, TWDB is the state agency tasked with developing and securing water for Texas. TWDB prepares a state water plan (SWP) based on 16 regional water plans. Plans must provide for the preparation for, and response to, drought conditions. Water user groups must prepare regional water plans must identify sources of water, include drought response triggers, and have a drought water management strategy. The SWP addresses the needs of all water user groups during a repeat of the 1950s drought of record.

Regional water planning regions need better information to implement drought action triggers. The seasonal rainfall forecast tool provides county-level information on impending drier-than-normal conditions. Such information can be fed into water availability models (WAMS) used to allocate water from surface water reservoirs.

TWDB received a WaterSMART grant to further develop the forecast tool through the Drought Resiliency funding solicitation of the U.S. Bureau of Reclamation's (USBOR) Drought Response Program. Work started on October 1, 2015 and is scheduled to be completed on September 30, 2017. The USBOR project involves automation of the drought forecast tool and provides probabilistic forecasts of average May-July rainfall for each county in Texas. Forecasts are updated on a bi-weekly basis from January 15 through May 1. Forecast lead times begin with a 6-month lead (January initial conditions – forecast fields), followed by a 5-month lead (February initial conditions), then 4-month lead (March initial conditions), and 3-month lead (April initial conditions - observations). All forecasts are available on the Water Data for Texas Website.

The USBOR project is also supporting experimental probabilistic reservoir storage forecasts. Reservoir storage forecasts can be tailored as probabilistic forecasts of whether storage will drop below drought trigger thresholds defined in drought contingency plans. For a particular reservoir, we would be able to provide 3-month lead time forecasts of the likelihood of storage dropping below drought trigger thresholds. Advanced warning could be provided at the beginning of May (based on observed April conditions). Advanced warning would cover the coming May-July cumulative storage period.

The Board also provides a Texas flood viewer using the TexMesonet. S2S timescale information is needed for forecasts for flash-flood inducing rainfall.

In conclusion, statistical methods, based on process understanding, have worked for projections over Texas for the May-July main rainfall season. Results can be used to guide dynamical model error correction with land surface feedback processes and cloud cover and radiation processes (particularly in spring). TWDB would like to use model output from other NMME models (but so far not all the fields, mainly soil moisture, are provided on the data archive). Sub-monthly rainfall forecasts would help with flood preparedness.

Some remaining unknowns for managing Texas' drought and floods, include: (1) sources of predictability in other seasons; (2) How much rainfall is needed to overcome a soil moisture deficit so that runoff occurs? (3) reservoir inflow given soil saturation and flooding; (4) predicting "rain bombs" with lead times of about two weeks; (5) What causes the strong westerly winds at the 850 hecto Pascals (hPa) level in April in years of drought (not La Niña)? (6) soil moisture leads 500 hPa geopotential height anomalies by 2-3 weeks in the MJJ season; and (7) How can this finding be exploited to improve S2S forecasts?

Nolan Doesken, Colorado State Climatologist, noted that in 1973 the federal government abolished its "State Climatologist" program nationwide. Later that same year, Colorado re-established the State Climate program with support through the Colorado Agricultural Experiment Station at Colorado State University (CSU). Other states took similar action. The Colorado Climate Center provides valuable climate expertise to the residents of the state through its threefold program of: (1) climate monitoring (data acquisition, analysis, and archiving); (2) climate research; and (3) climate services (providing data, analysis, climate education and outreach). But many of our stakeholders also expect "prediction!" Believe it or not our stakeholders fully expect reliable seasonal forecasts a few months in advance.

Fort Collins CSU Historic Weather Station has provided continuous monitoring since the 1880s, measuring temperature, precipitation, snow, wind, solar, evaporation, soil temperatures, humidity, clouds, etc. The National Weather Service still faithfully maintains a "taken for granted" network of weather stations in Colorado and across the country – the Cooperative Observer Network. The NWS Cooperative Network is the only source of basic climate information (daily measurements of temperature and precipitation) that covers the entire country down to the local county scale with 120+ years of continuous observations. There are about 5,000 daily maximum/minimum temperature stations, some 8,000 daily precipitation stations, and 3,000 automated hourly precipitation stations.

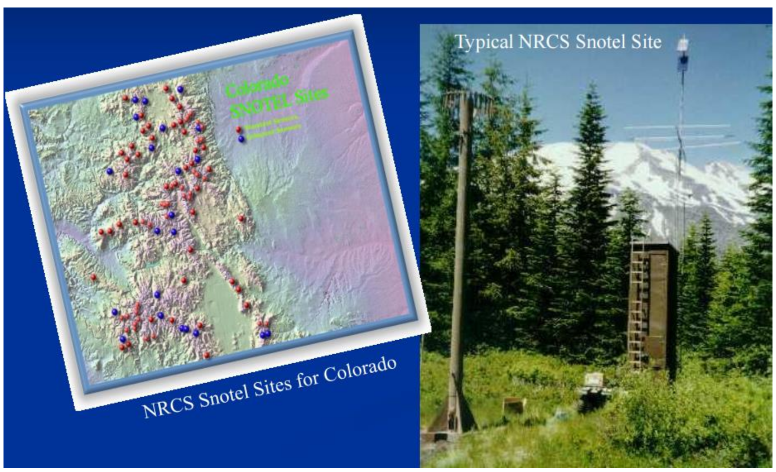

FIGURE 26 NRCS SNOTEL SITES IN COLORADO

Snow surveys began in the 1930s to help predict streamflow, and a west-wide system in operated by the USDA, Natural Resources Conservation Service (NRCS).

There are many other weather and climate data observing systems.

Nolan addressed climate information needs for agriculture and natural resources management, as well as extension and outreach to engage stakeholders and assess user needs. He illustrated the CoAgMet system of weather observing sites, and promoted the Community Collaborative Rain, Hail and Snow Network (CoCoRaHS) – an extended group of volunteers taking daily, timely precipitation measurements that provides valuable information that is mapped nationwide. For Colorado, he noted that measurements of seasonal precipitation since 1890 show great variability from place to place but no significant trend is apparent statewide.

He also noted the Western Association of Agricultural Experiment Station Directors supports a number of regional and national multistate research and coordination projects. Our Priority is to work together to improve climate information for stakeholders. We've contributed to progress in precipitation analysis tools, spatial mapping in complex terrain, data collection, continuity, and quality, network enhancement and preservation, gap filling, instrumentation improvements, evapotranspiration estimation, drought monitoring, user needs assessments, and stakeholder engagement.

Also, USDA-supported Western Extension Research Activities (WERA) 102 Climatic Data and Analyses for Applications in Agriculture and Natural Resources is a long-standing and active coordinating group with a keen interest in precipitation, forecasts, and stakeholder needs.

Nolan observed, "Whatever comes next is sure to be 'very interesting'."

During a facilitated discussion and wrap up, a number of needs and potential next steps forward were addressed and some assignments made for future action. However, findings and recommendations were left for future efforts.

Conclusion

All the workshop agenda and participant lists, with contact information are included in the appendices. PowerPoint presentations are posted online on the Western States Water Council website[6].

The WSWC would like to express its appreciation for the support of the California Department of Water Resources for the workshops, and the participation by myriad federal agencies (but especially NOAA, NWS and related agencies), state and local officials, and others. The presentations summarized herein help provide a picture of the state-of-the-science and the challenges we face in achieving skillful S2S precipitation projections with sufficient lead-time for evaluating and improving water resources management and other economic, emergency, environmental, natural resources, public health and welfare, related social impacts, and decision-making.

[6] Ibid. pg. 4.

GLOSSARY OF TERMS

AOP	Annual Operating Plan
AR	Atmospheric Rivers
CDWR	California Department of Water Resources
CW3E	Center for Western Weather and Water Extremes
CPC	Climate Prediction Center
CPO	Climate Program Office
CSU	Colorado State University
CoCoRaHS	Community Collaborative Rain, Hail and Snow Network
CUASI	Consortium of Universities Allied for Water Research
CGCMS	Coupled General Circulation Models
DOE	Department of Energy
DSS	Decision Support System
ESPC	Earth System Prediction Capability
ENSO	El Niño - Southern Oscillation
FEMA	Federal Emergency Management Agency
FTE	Full-Time Equivalent
GFDL	Geophysical Fluid Dynamics Laboratory
GOES-R	Geostationary Operational Environmental Satellites
GPS	Global Positioning System
HiFLOR	High Resolution Version of a Forecast-Oriented Low Ocean Resolution (FLOR)
ISI	Inter-seasonal to Inter-annual
ESA	Endangered Species Act
FERIX	Flood Emergency Response Information Exchange
FLOR	Forecast-Oriented Low Ocean Resolution
hPa	Hecto-Pascals Level (unit of pressure)
HPC	High Performance Computing
HFIP	Hurricane Forecast Improvement Project
HEPEX	Hydrologic Ensemble Prediction Experiment

IWP	Integrated Water Prediction
JPL	Jet Propulsion Laboratory
MJO	Madsen-Julian Oscillation
MAPP	Modeling, Analysis, Predictions and Projections
MME	Multi-Model Ensembles
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCDC	National Climatic Data Center
NEPA	National Environmental Policy Act
NESDIS	National Environmental Satellite, Data, and Information Services
NIDIS	National Integrated Drought Information System
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
NWM	National Water Model
NWS	National Weather Service
NAO	North Atlantic Oscillation
NMME	North American Multi-Model Ensemble
NAO	North American Oscillation
OAR	Oceanic and Atmospheric Research
OMB	Office of Management and Budget
PDO	Pacific Decadal Oscillation
PCSs	Program Change Summaries
QPFs	Quantitative Precipitation Forecasts
SST	Sea Surface Temperatures
SPFIP	Seasonal Precipitation Forecast Improvement Project
SBJ	Sierra Barrier Jet
SWP	State Water Plan
S2S	Sub-Seasonal to Seasonal
SubX	Sub-Seasonal Prediction Experiment

SHERPA	System for Hydromet Ensemble Research and Prediction Applications
TWDB	Texas Water Development Board
TIRS	Thermal Infrared Sensor
USACE	U.S. Army Corps of Engineers
USBOR	U.S. Bureau of Reclamation
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
WAMS	Water Availability Models
WY	Water Year
WRN	Weather Ready Nation
WestFAST	Western Federal Agency Support Team
WSWC	Western States Water Council

APPENDIX A – Agendas and Attendees

Workshop I – Agenda

NOAA / WSWC Workshop on Advancing Seasonal Prediction for Water Resources

October 21-22, 2015 • Salt Lake City, UT

MEETING LOCATION: Wallace F. Bennett Federal Building, 125 South State Street, Salt Lake City, UT 84138, Second Floor Conference Room (see map at end).

AGENDA

MEETING GOALS:

1. Identify research and forecasting efforts needed to advance seasonal prediction for western water resources management (ultimately to allow support earlier management of water resources through application of forecasts with improving skill).

2. Develop a budget proposal for advancing seasonal prediction for western water resources, including value proposition, knowledge gaps, and research questions.

WED OCT 21	**DAY 1 ACTIVITIES AND OBJECTIVES**
8:30-8:45	Welcome and Introductions (Grant Cooper, NWS Regional Director and Tony Willardson, Western States Water Council Director)
8:45-9:30	Context and Meeting Goals (Kevin Werner, NOAA Regional Climate Services Director and Jeanine Jones, California Department of Water Resources)
9:30-10:00	NOAA Agency Perspectives & Opportunities (Peter Colohan, Senior Advisor to NOAA's Chief Scientist)
10:00-10:15	BREAK
10:15-10:45	Hurricane Forecast Improvement Project Lessons Learned (Fred Toepfer, Hurricane Forecast Improvement Project Program Manager)
10:45-11:30	Introduce proposed Seasonal Precipitation Forecast Improvement Project (Dave DeWitt, Climate Prediction Center Director)
11:30-1:00	LUNCH - on your own
1:00-3:30	Value Proposition

- Presentation from Julie Suhr Pierce, BLM on her process for putting together the 2010 NRCS Snow Survey report (approach, lessons learned) – 30 min
- Presentation from Aria Remondi, NOAA budget, on NOAA budget strategy and key questions to consider in developing a NOAA Program Change Summary (PCS) – 15 min

- WSWC perspectives on value proposition including what elements of a value proposition are helpful for WSWC policy positions and outreach (Jeanine Jones and/or Tony Willardson) 15 min.
- Convene breakout groups to identify and develop value propositions. Each break-out will be led by a forecast user who will share their thoughts on the value proposition questions below (see break-out instructions) – 1hour
- Key Questions:

1. How would your agency use improved forecasts? E.g. what would be the benefit be?
2. What would you do differently? What would the on-the-ground impact be?
3. Would improved skill to the existing CPC product suite be sufficient or are new products needed? If so, what are those products?
4. How do you assess forecast skill? Are the current metrics CPC uses to measure skill sufficient? If not, how would you like to see skill measured?
5. Who else should we be talking to? Who else could use this?

- Breakout group reports – 30 min

3:30-3:45 BREAK

3:45-4:30

Identification of Knowledge Gaps and Priority Research Questions

- Short (10 min, 3 slide max using slide template provided) presentations from science experts on key research opportunities from different perspectives addressing these questions:

1. What are the knowledge gaps to advance seasonal forecast skill for western watersheds?
2. What are the priority research questions that need to be answered to advance seasonal forecast skill for western watersheds?
3. What are the strengths and weaknesses of the white paper as currently presented?

- Dan Barrie, NOAA Climate Program Office
- Andy Hoell, NOAA Earth System Research Lab
- Sarah Kapnick, NOAA Global Fluids Dynamics Lab
- Marty Ralph, University of California, San Diego

4:45-5:00 Daily Wrap

5:00 Adjourn

THUR OCT 22 DAY 2 ACTIVITIES AND OBJECTIVES

8:30-8:45 Day 2 Welcome

8:45-9:15 Identification of Knowledge Gaps and Priority Research Questions (con't)

- Short (10 min, 3 slide max using slide template provided) presentations from science experts on key research opportunities from different perspectives addressing these questions:

1. What are the knowledge gaps to advance seasonal forecast skill for western watersheds?

2. What are the priority research questions that need to be answered to advance seasonal forecast skill for western watersheds?

3. What are the strengths and weaknesses of the white paper as currently presented?

- Dave DeWitt, NOAA Climate Prediction Center
- Andy Edman, NOAA National Weather Service Western Region
- Andy Wood, National Center for Atmospheric Research

9:15-10:15 Identification of Knowledge Gaps and Priority Research Questions Break Out groups

Participants will be randomly assigned to break out groups of 4-6 people to discuss knowledge gaps and research questions to feed into white paper. In particular groups will identify additions, subtractions, and revisions focusing on the methodology in the proposal. (60 minutes):

- What are the knowledge gaps to advance seasonal forecast skill for western watersheds?
- What are the priority research questions that need to be answered to advance seasonal forecast skill for western watersheds?
- What are the strengths and weaknesses of the white paper as currently presented?

10:15-10:30 BREAK

10:30-11:30 Group Report Out & Meeting Wrap

Activities/Interactions:

1. Groups will report out (20 minutes)
2. Wrap up discussion as needed
3. Pre-brief on optional NWS tour (Grant Cooper, Michelle Stokes)

Adjourn

11:30-1:00 Optional LUNCH on your own for participants interested in NWS tour

1:00-2:00 Optional Tour at NWS SLC field office (Grant Cooper, Michelle Stokes)

NWS Colorado Basin River Forecast Center and Weather Forecast Office is located near the airport at 2242 W North Temple. This is a 15-minute drive from downtown Salt Lake City. Parking is available onsite. Logistics will be discussed before lunch.

2:30-5:00 White Paper Writing Team Session – Writing Team Only – at NWS SLC Field Office

Kevin Werner, Dave DeWitt, Jeanine Jones, Tony Willardson, Grant Cooper, Peter Colohan, Veva Deheza, and Timi Vann,

Workshop I – Attendees

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Workshop II – Agenda

Western States Water Council Workshop on Seasonal Precipitation Forecasting for Water Resources

December 15, 2015 • Las Vegas, Nevada

Caesars Palace, Convention Center, Pisa Room

WORKSHOP GOALS: (1) Share current seasonal prediction techniques and communicate the present state of the science; (2) Explain confidence/skill levels and efforts to advance seasonal prediction for Western water resources; (3) Identify water user needs for timely information and the potential value added from improved seasonal forecasts, for developing requests for federal agency follow-up

Tues Dec 15	AGENDA
8:30	**Welcome and Introductions** Jeanine Jones, Western States Water Council (WSWC)/California Department of Water Resources (CDWR)
8:45	**Meeting Purpose & Goals, Agency Roles** Jeanine Jones, WSWC/CDWR Kevin Werner, Regional Climate Services Director, National Oceanic and Atmospheric Administration (NOAA) Pat Lambert, Western Federal Agency Support Team (WestFAST) Liaison to WSWC
9:30	**NOAA Perspectives & Opportunities: State of the Science & Future Research** Dave DeWitt, Director (via phone), Climate Prediction Center, NOAA
10:15	**BREAK**
10:30	**Western Precipitation Observations, Role of Extreme Precipitation Events** Marty Ralph, Director, Center for Western Weather and Water Extremes (CW3E), University of California San Diego/Scripps Institution of Oceanography
11:00	**Potential Applications for Improved Seasonal Precipitation Forecasting** Jeanine Jones, WSWC/CDWR
11:30	**Example Present State-of-Practice for Water Operations Planning – the Colorado River Annual Operating Plan** Dan Bunk, River Operations Group Manager, USBR Lower Colorado Region
Noon	**LUNCH - on your own**
1:30	**Group Discussion – Case Histories to Support Federal Budget Proposals, & Water Agency Goals for Improving Forecasts and Forecast Communication** Moderators, Jeanine Jones, WSWC/CDWR & Kevin Werner, NOAA
3:00	**Adjourn**

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Workshop III – Agenda

NOAA/WSWC
Advancing Sub-seasonal to Seasonal (S2S) Precipitation Forecasting for Western Water Management

Center for Weather and Climate Prediction
5830 University Research Court, College Park, MD
April 29, 2016

9:00 Welcome and Introductions
Louis Uccellini, Director, National Weather Service
Michael Farrar, Acting Deputy Assistant Administrator, Laboratories and Cooperative Institutes
Tony Willardson, Executive Director, Western States Water Council

9:30 Review of WSWC and NOAA Discussions
Kevin Werner, Director of Office of Organizational Excellence, NWS
Jeanine Jones, Interstate Resources Manager, California Department of Water Resources

9:45 Importance of Improved Forecasting for Water Management: Water Year 2016 and El Nin□o
Kevin Werner and Jeanine Jones

10:15 Unique Characteristics of Precipitation in the West
Marty Ralph, Scripps Institution of Oceanography

10:45 NOAA's National Water Center; Informing Decisions for a Water-Prepared Nation
Ed Clark, Director, Geo-Intelligence Division of the National Water Center

11:15 NOAA Research on S2S Predictability and Prediction, and Research Budget
Dan Barrie, MAPP Program Manager, NOAA's Climate Program

11:45 Summary of NAS Report on a Research Agenda to Advance S2S Forecasting
Edward Dunlea, National Academies of Sciences, Engineering, and Medicine

12:15 Working Lunch: Seasonal Prediction Forecast Improvement Project – Concept Paper
Dave DeWitt, Director, Climate Prediction Center, NWS

1:00 NOAA Water Initiative Status
Will Stelle, West Coast Regional Administrator, NOAA Fisheries

1:30 NOAA Budget Priorities and Pending Congressional Legislation
Merriam Norris, Director, OAR's Formulation and Congressional Analysis Division

2:00 Group Discussion – Making Progress on Near-Term Applications for Improving S2S Forecasts

3:15 Develop Schedule of Activities/Upcoming Events

3:45 Adjourn

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AGENDA
Workshop

Improving Sub-Seasonal and Seasonal Precipitation Forecasting

Sponsored by
Western States Water Council and California Department of Water Resources

June 7-9, 2016

Doubletree San Diego Downtown
1646 Front Street, San Diego, CA

Tuesday June 7

11:00 **Registration**

1:00 **Welcome and Opening Remarks, Workshop Background & Desired Outcomes**

Tony Willardson, Executive Director, Western States Water Council (WSWC)
Jeanine Jones, Interstate Resources Manager, California Department of Water Resources (CDWR)

1:45 Review of Recent NOAA/WSWC Collaboration Activities – Jeanine Jones, CDWR

2:15 Water Year 2016 – What was Predicted and What the West Received – Mike Anderson, State Climatologist, CDWR

3:00 Break

3:15 Water Year 2016 – What Happened with the Communications and with the Forecast?
4:00 Communicating Probabilistic Outlooks – Roger Pierce, Meteorologist-in-Charge, and Alex Tardy, Warning Coordination Meteorologist and Decision Support Services Lead, San Diego Weather Forecast Office

5:00 Adjourn

Wednesday June 8

8:00 Continental Breakfast

8:30 New NAS Report on a Research Agenda to Advance S2S Forecasting – Duane Waliser, Chief Scientist, Earth Science & Technology Directorate, NASA Jet Propulsion Laboratory (JPL)

9:15 Seasonal Precipitation Forecasting Improvement Project & Relationship to NOAA Week 3/Week 4 Initiative – Dave DeWitt, Director NOAA Climate Prediction Center

10:00 Break

10:15 Example Research Activities

Status of HiFLOR Model Development – Sarah Kapnick, Physical Research Scientist, NOAA's Geophysical Fluid Dynamics Laboratory

Atmospheric River Observations – Marty Ralph, Director, Center for Western Weather & Water Extremes, Scripps Institution of Oceanography

AR/MJO Predictability – Duane Waliser, Chief Scientist, NASA JPL

12:00 Lunch (on your own)

1:30 Example Programmatic Activities

NOAA CPO S2S Prediction Initiatives and Scientific Opportunities in High-Resolution Modeling – Heather Archambault, Modeling, Analysis, Predictions & Projections, NOAA Climate Program Office

USBR R&D Program – Kenneth Nowak, Water Availability Research Coordinator, USBR

Pending Congressional Legislation – WSWC

3:15 Break

3:30 Low-Hanging Fruit, Where Do We Go Next? (Facilitated Discussion)

4:45 Summary & Report Out

5:00 Adjourn

Thursday June 9

8:00 Continental Breakfast

8:30 Potential Applications/Users for Improved S2S Forecasts

California DWR Statistical Modeling Example – Kwabena Asante, GEI Consultants, Inc.

Texas Water Development Board (TWDB) Statistical Modeling Example – Nelun Fernando, Hydrologist, TWDB

USDA Western Extension Research: Climate Information for Agriculture & Natural Resources – Nolan Doesken, Colorado State Climatologist, Colorado State University

10:15 Break

10:30 Water Year 2017, What Could We Do/Say? (Group Discussion)

11:30 Action Items & Closing Remarks

12:00 Adjourn

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APPENDIX B – WSWC Position Statement III66

RESOLUTION

of the
WESTERN STATES WATER COUNCIL
supporting
FEDERAL RESEARCH AND DEVELOPMENT OF UPDATED HYDROCLIMATE GUIDANCE FOR FLOODS & DROUGHTS
Helena, Montana
July 18, 2014

WHEREAS, Western states continue to experience extreme flooding, droughts, or wildfires that threaten public safety, tax aging water infrastructure, and/or have significant economic consequences; and

WHEREAS, according to the National Oceanic and Atmospheric Administration (NOAA), the nation's top ten multi-billion dollar disasters have occurred since 1980, with six of those in the last decade; and

WHEREAS, we must be prepared to effectively manage for frequent, extensive, and severe storms, floods, coastal inundation, and droughts; and

WHEREAS Western states experienced extreme drought in 2011-2014, as well as recent floods of record in areas such as parts of the Missouri River Basin in 2011 and Colorado in 2013, and further Winter Storm Atlas in 2013; and

WHEREAS, key long-term observation networks needed for monitoring extreme events, such as USGS streamgages and the NWS Cooperative Observer network, face continued funding and programmatic challenges that threaten the continuity of crucial long-term data records; and

WHEREAS, snow water content and soil moisture monitoring are also critical for drought and flood forecasting and management, but the NRCS snow survey and water supply forecasting program, related SNOTEL sites, and its Soil Climate Analysis Network remain underfunded; and

WHEREAS, some of NOAA's probable maximum precipitation estimates used by water agencies for dam safety and other analyses have not been updated since the 1960s and the federal Guidelines for Determining Flood Flow Frequency Analysis (published as Bulletin 17B) have not been revised since 1981; and

WHEREAS, flood frequency analyses are used by public agencies at all levels of government to design and manage floodplains, and for construction of flood control and stormwater infrastructure, with Bulletin 17B still representing a default standard of engineering practice; and

WHEREAS, federal funding for hydrology research has waned since the 1970s-1980s, and alternative statistical methodologies for flood frequency analyses or deterministic analytical procedures are not being supported and transitioned to common engineering practice; and

WHEREAS, the Federal Emergency Management Agency has adopted a process for local communities to explicitly incorporate "future conditions hydrology" in the national flood insurance program's flood hazards mapping; and

WHEREAS, the present scientific capability for forecasting beyond the weather time domain – beyond the ten-day time horizon – and at the sub-seasonal to interannual timescales important for water management is not skillful enough to support water management decision-making; and

WHEREAS, the Council has co-sponsored a number of workshops on hydroclimate data and extreme events, to identify actions that can be taken at planning to operational time scales to improve readiness for extreme events; and

WHEREAS, multiple approaches have been identified at these workshops that could be employed at the planning time scale, including ensembles of global circulation models, paleoclimate analyses, and improved statistical modeling, that could be used to improve flood frequency analysis or seasonal forecasting; and

WHEREAS, advances in weather forecasting research, such as that of NOAA's Hydrometeorological Testbed program on West Coast atmospheric rivers, demonstrate the potential for improving extreme event forecasting at the operational time scale; and

WHEREAS, WGA and NOAA signed a Memorandum of Agreement in June 2014 on improving resilience to droughts and floods;

NOW, THEREFORE, BE IT RESOLVED, that the federal government should update and revise its guidance documents for hydrologic data and methodologies – among them precipitation-frequency estimates, flood frequency analyses, and probable maximum precipitation – to include subsequently observed data and new analytical approaches.

BE IT FURTHER RESOLVED, that the federal government should place a priority on improving sub-seasonal and seasonal precipitation forecasting capability that would support water management decisions.

BE IT FURTHER RESOLVED, that the Western States Water Council supports development of an improved observing system for Western extreme precipitation events such as atmospheric river storms, as well as baseline and enhanced stream, snow and soil moisture monitoring capabilities.

BE IT FURTHER RESOLVED, that the federal government should sustain and expand its Hydrometeorology Testbed – West program, in partnership with states and regional centers, to build upon the initial progress made in that program for developing and installing new technologies for precipitation observations.

BE IT FURTHER RESOLVED, that the Western States Water Council urges the federal government to support and place a priority on research related to extreme events, including research on better understanding of hydroclimate processes, paleo-flood analysis, design of monitoring networks, and probabilistic outlooks of climate extremes.

BE IT FURTHER RESOLVED, that the Western States Water Council will work with NOAA and WGA in supporting efforts on climate extremes, variability, and future trends.