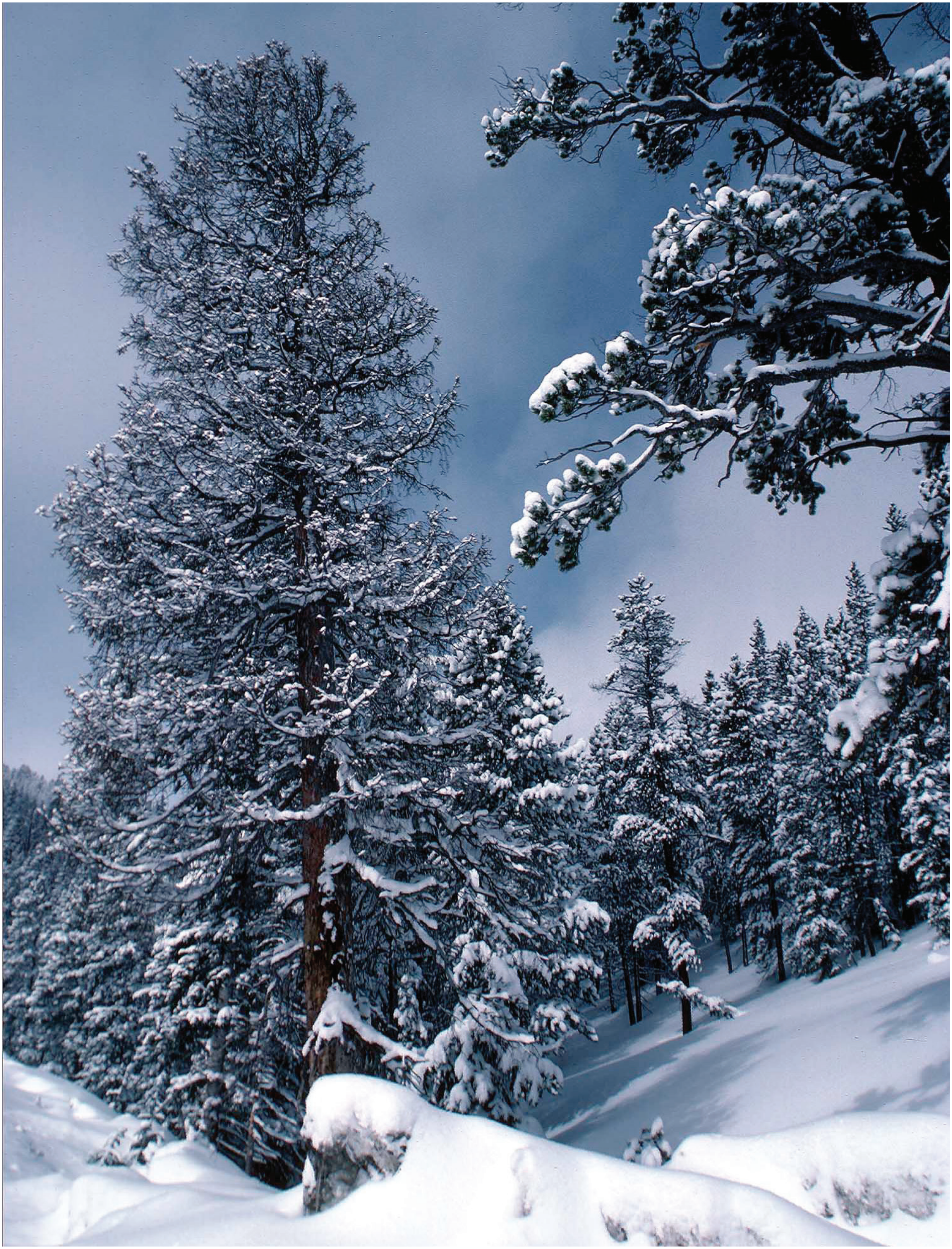
Understanding the Water Cycle

Findings from NOAA's Water Cycle Science Challenge Workshop

28 August – 1 September 2011, NOAA Earth System Research Laboratory, Boulder, Colorado

28 September 2012



Workshop Program Committee

Bert Davis (Co-Chair)	US Army Engineer Research and Development Center
Marty Ralph (Co-Chair)	NOAA/OAR/ESRL
Gary Bardini	California-Dept. of Water Resources (with Mike Anderson)
Kurt Brown	Bureau of Reclamation (with Levi Brekke)
Mike Dettinger	US Geological Survey
Ralph Ferraro	NOAA/NESDIS/STAR
Dave Jorgensen	NOAA/OAR/NSSL
Jim McNamara	Boise State University
Christa Peters-Lidard	NASA
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Rapporteurs for Breakout Sessions

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Lynn Johnson	CIRA/Colorado State Univ., NOAA
Kelly Mahoney	CIRES/Univ. of Colorado/Boulder, NOAA
David Novak	NWS/NCEP/Hydrometeorological Prediction Center

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Alex McColl	NOAA/OAR/ESRL

Submitted to the NOAA Research Council on behalf of the workshop participants and the Workshop Program Committee.

Marty Ralph and Bert Davis (Workshop Co-Chairs)

28 September 2012

Front Cover Photo by: Paul Neiman, NOAA. Colorado snow photo by: Tim McCabe, NRCS. Back Cover Photo by: Barb DeLuisi, NOAA.

Table of Contents

Understanding the Water Cycle

Executive Summary

A. Illustrative Motivations

Many motivations for advancing water-cycle science and services (Fig. 1) emerged from the workshop; a few of the most pressing were:

- "There is a collision in the Western US between 19th Century water law, 20th Century water infrastructure, and 21st Century population growth & climate change."
  —*Brad Udall, Western Water Assessment - Keynote*
- "Flood losses nationally have risen dramatically, even after being adjusted for inflation (Fig. 2). Flood losses averaged $4.7 billion/year in the 1980s, $7.9 billion/year in the 1990s and $10.2 billion/year in the 2000s."
  —*Don Cline, NOAA/NWS/Hydrology Laboratory - Invited*
- "Progress on predicting extreme precipitation seriously lags progress of other forecasts, and represents a major current gap."
  —*Dave Novak, NOAA/NCEP/HPC - Invited*

B. Background, Purpose, Planning

In August 2010 NOAA completed a report entitled "Strengthening NOAA Science," sponsored by Dr. Jane Lubchenco, the Undersecretary for Oceans and Atmospheres. The report (Sandifer and Dole 2010) identified 7 NOAA Science Grand Challenges, including "***Improve understanding of the water cycle at global to local scales to improve our ability to forecast weather, climate, water resources and ecosystem health."*** The topic was then selected by NOAA leadership for further development through engagement of external partners and stakeholders via the "Water Cycle Science Challenge Workshop" that is reported on below.

A key purpose of the workshop was to discuss and develop recommendations to NOAA Leadership that can be integrated into the next NOAA 5-Year Research Plan and into other NOAA science planning activities. The NOAA Research Council (RC) provided the following guidance for the workshop and is the formal recipient of this report. The workshop should "encompass the current state of understanding, identify gaps that can be addressed over the next five years, identify NOAA's role in filling those gaps in concert with external partners and other institutions over the next 5-years, and outline the expected benefits of filling the gaps."

An interagency program committee was formed. It selected the following overarching focus:

"Understanding and predicting conditions associated with either too much or too little water."

The program committee consisted of experts from several agencies and academia, with an emphasis on representing the spectrum of scientific and engineering knowledge required, and spanning weather and climate, as well as meteorology and hydrology. Ultimately 60 people participated in a 3-day workshop (Fig. 3; Appendix 1), roughly 30% of who were atmospheric-science oriented, 60% hydrology, and 10% other. Roughly 1/3 of participants were from other agencies, 1/3 from academia, and 1/3 from NOAA. Input was gathered through invited plenary presentations by experts, break-out sessions, and panel discussions (see Appendix 2 for the detailed agenda and Appendix 3 for findings from the breakout sessions). Relevant outputs of earlier planning efforts led by USGS, USBR, USACE, WGA, and WUCA were considered (e.g., Brekke et al. 2009; WSWC 2008; WUCA 2010; Reclamation & USACE 2011; Fig. 4), and a brief synopsis of these is provided in Appendix 4.

The Program Committee identified the following four themes for the workshop and organized the meeting and this report around these themes:

- Next generation hydrologic modeling
- Hydrometeorological forcings for hydrologic models
- Physical processes underlying the water cycle, and
- Climate dimensions

C. Goals and Recommendations

- Increase hydrologic forecasting skill for low-to-high stream flow conditions to be as good as the skill afforded by weather and climate predictions

Fig. 1. Examples of several key drivers for improved understanding and prediction of the water cycle. (Courtesy of Don Cline, NOAA)

    - Develop systems using strengths of both “lumped” & “physically-based” hydrologic models
    - Develop a unified large-scale hydrological modeling system allowing integrated and multi-scale predictions, projections and analyses
    - Foster efforts to bridge the historical disconnect between hydrology and meteorology
- Improve representations, understanding and forecasting of key hydrometeorological forcings to rival those of other non-water-cycle variables and forcings in the weather-climate system
    - Develop a National water cycle reanalysis, including key components and fluxes that close the water balance
    - Fill major gaps in observations of water cycle parameters (water vapor transport, precipitation, snow, surface energy budget terms including evapotranspiration, aerosols)
    - Integrate in situ, radar, satellite and numerical model guidance to construct high-resolution data-assimilation products that directly link atmosphere and land-surface processes and depict the full water cycle over the US with high fidelity
    - Implement a “moon-shot” style effort to improve extreme precipitation information
- Identify and diagnose physical processes key to extreme events (storms and floods) and document their roles in forecast errors
    - Identify “emergent” behavior in watershed dynamics and quantify associated thresholds
    - Understand and diagnose variability of water vapor transport, including atmospheric rivers which conduct >90% of the water vapor transport in mid-latitudes
    - Explore the role of aerosol variability in modulating cloud microphysics and precipitation
    - Diagnose, understand and quantify the characteristics of extreme precipitation and precursor land surface conditions that amplify or reduce drought and flood severity.
- Explicitly characterize key uncertainties in climate and hydrologic models (and their couplings)

- Establish NOAA "tiger teams" to evaluate selected real-world extreme events aiming to dissect causes and antecedents, assessing forecast skill and utility from hours to weeks
- Understand and describe the distributions of seasonal-to-interannual climate oscillations and their impacts on drought and flood risks
- Develop a global water cycle reanalysis and applications tools to better quantify uncertainties in water cycle trends in climate models and to meet user needs, e.g., for long-term infrastructure decisions for flood control, water supply, endangered species, etc.
- Analyze and identify landscape changes and water scape changes (e.g., irrigation, ice cover, lake levels), including human-caused, that must be factored into hydroclimate projections.

Fig. 2. Examples of recent flooding impacts associated with extreme precipitation, and a recommendation after a formal service assessment. (Courtesy of Don Cline (top) and Dave Novak (bottom); both of NOAA)

D. Proposed Implementation Strategies

- Elevate the priority of water cycle science and services in NOAA to levels comparable to that of weather and climate, building on MOUs between USGS, USACE & NOAA and between WGA & NOAA.
- Fully support the "National Water Center" (NWC) in the NWS to advance hydrologic services.
- Fully support NOAA's HMT in OAR to develop innovative solutions to providing the necessary hydrometeorological "forcings" to drive future hydrologic prediction systems across agencies.
- Implement the "Western US Observing Systems Vision for Extreme Events" requested by the WSWC to improve monitoring, prediction and climate trend detection of extreme events.
- Carry out and coordinate hydrological (e.g., via CUAHSI) and hydrometeorological (e.g., HMT) field studies.
- Develop a Hydroclimate Testbed building on NIDIS, HMT, RISAs, Laboratories and CUAHSI that would link hydroclimate science to services and user needs, and would emphasize extremes.

The following quote from a resolution passed in July 2011 by the Western States Water Council as a recommendation to the Western Governors Association (WGA) illustrates the existence of policy-maker support to move forward on implementation of key elements of this report's recommendations.

- "BE IT FURTHER RESOLVED, that the Western States Water Council (WSWC) supports development of an improved observing system for Western extreme precipitation events, to aid in monitoring, prediction, and climate trend analysis associated with extreme weather events; and, … urges the federal government to support and place a priority on research related to extreme events, including research on better understanding of hydroclimate processes, paleoflood analysis, design of monitoring and change detection networks, and probabilistic outlooks of climate extremes; and … the WSWC will work with NOAA in supporting efforts on climate extremes, variability, and future trends as called for in the WGA-NOAA memorandum of understanding.

Understanding the Water Cycle

1. Introduction

A. Background and Organizational Context

This Workshop was a follow-up to a 2010 NOAA report "Strengthening NOAA Science" sponsored by Dr. Jane Lubchenco (Sandifer and Dole 2010) that identified the following NOAA Science Grand Challenge: "***Improve understanding of the water cycle*** *at global to local scales to improve our ability to forecast weather, climate, water resources and ecosystem health.*" The topic was selected by the NOAA Research Council (RC) for further development through engagement of external partners and stakeholders via this Workshop. The RC first identified five internal NOAA experts to start the planning. This group then identified eight external experts to join in the planning committee, and selected Drs. F. Martin Ralph (NOAA) and Robert Davis (USACE) to co-chair the Workshop. This committee then developed the workshop objectives, plan and invitation list, which were reviewed and approved by the RC prior to conducting the Workshop. Formally, this document is a report to the NOAA Research Council.

NOAA Science Grand Challenge:

Improve understanding of the water cycle at global to local scales to improve our ability to forecast weather, climate, water resources and ecosystem health.

Between roughly 2005 and 2010 NOAA organized its planning around four overarching goals, one of which was termed "Weather and Water." This reflected the increased recognition of NOAA's role in providing science and services to a broad range of stakeholders and users of water information, and that this required special internal capabilities and healthy external partnerships. Not only did NOAA see this as important, so too did USGS and USACE, who, with NOAA, entered into a formal MOU in May 2011 (Fig. 5; a copy is provided in Appendix 5) to address Integrated Water Resources Science and Services (IWRSS). Additionally, a key strategy that has emerged in NOAA was to better link research and forecast services through "Testbeds," including NOAA's

A key purpose of the workshop was to discuss and develop recommendations...that can be integrated into the next NOAA 5-Year Research Plan and into other NOAA science planning activities.

Hydrometeorology Testbed (HMT; Fig. 6; hmt.noaa.gov) that also strives to bridge the disciplines of meteorology and hydrology, and is especially germane to this Workshop (Ralph et al. 2005, 2012). While linking research and operations is a key challenge, so too is establishing close coordination between information user needs, monitoring and predictive services, and the enabling science and technology. While NWS, OAR and Testbeds do this in many ways, the National Integrated drought Information System (NIDIS 2007) provides an example of a robust, fully integrated strategy (Fig. 7) that was used to help inform the workshop.

NOAA's water-related services support many needs, but performance is tracked at high levels through a select few GPRA requirements. These requirements represent the service "pull" for better products and information, while often it is innovation in the science and technology (S&T) arenas that provide the foundation for improved services, i.e., the "S&T push." The list in Table 1.1 captures a few of the relevant performance measures as reflected in HMT's Implementation Plan. A number of other NOAA "requirements" not listed explicitly here are reflected in goals in OAR, NWS, NESDIS and NMFS (including those related to endangered species dependent on streamflow), many of which are captured in NOAA's 5-year research plan.

While this workshop is a key step for NOAA, it is by no means the only workshop to address requirements in water resources and flood protection (e.g., Brekke et al. 2009; WSWC 2008; WUCA 2010; Reclamation & USACE 2011; Fig. 4). Several key earlier workshops are summarized briefly in Appendix 4. One of the strategies employed was to weave into the presentations and discussions relevant information from these earlier planning efforts, including ones led by USGS, USACE, the Western States Water Council (which supports the Western Governors Association) and the Water Utility Climate Alliance.

Table 1.1 GPRA and Demonstration Performance Measures for Forecasts and Warnings Addressed by HMT

Type	Forecast or Warning	Statistical Form	Issuing Offices	Major R&D Activities Required
GPRA	1 inch precipitation	Threat score	NCEP HPC	A, F, G
GPRA	River flood warning	Lead time, accuracy	RFCs, WFOs	A, B, C, D, F, G
Demo	Extreme precipitation	POD/FAR/CSI/MAE	NCEP, RFCs	A, B, E, F, G
Demo	Snow level	Altitude error	RFCs	A, D, F.

HMT's Major Activitiy Areas for R&D and Service Improvements	
A	Quantitative precipitation forecasting (QPF)
B	Quantitative precipitation estimation (QPE)
C	Snow information (snow level and snow on ground)
D	Hydrology (flooding, soil moisture, runoff, and streamflow)
E	Debris Flow
F	Verification
G	Forecaster decision support tools

Workshop Purpose

To discuss and develop recommendations to NOAA Leadership, including the NOAA Research Council, that will inform a subsequent "NOAA Science Conference" and the next NOAA 5-Year Research Plan on the topic of: **"Understanding and predicting conditions associated with either too much or too little water"**

To fulfill this purpose the Water Cycle Science Challenge Workshop:

- Encompassed the current state of understanding;
- Identified gaps that can be addressed over the next 5-years;
- Identified NOAA's role in filling those gaps in concert with external partners and other institutions over the next 5-years;
- Outlined the expected benefits of filling the gaps.

The Workshop also

- Considered implications for relevant observing systems
- Characterized uncertainties associated with water cycle science information
- Discussed how best to communicate water cycle science information and associated uncertainties accurately and effectively to policy makers, the media, and the public at large.

B. Key Socioeconomic Drivers

Highlights from the invited Keynote presentation by Brad Udall, Director of NOAA's "Western Water Assessment" RISA summarize many of the reasons to pursue scientific and predictive challenges representing the earth's water cycle.

- "Too much water, too little water, and water of the wrong quality is a major world-wide problem right now, independent of climate change."
- "To many, 'Climate Change' really means 'Water Change'."
- "Water Solutions are Almost Always Zero-Sum Games."
- "Chesapeake Bay Dead Zone - There are 400 zones like this around the world (usually related to runoff) and the problem is growing exponentially. The nitrogen cycle is more broken that the carbon cycle."
- "Our largest river (in the southwest US), the Colorado, has failed to reach the sea for over 20 years."
- "Solve the disconnect between Hydrology and Meteorology"
- "There is a collision in the West between
    - 19th Century water law
    - 20th Century infrastructure
    - 21st Century population growth & climate change." (Fig. 1)

From the prediction perspective, Don Cline, Director of the NWS' Hydrology Laboratory, noted "Flood losses nationally have risen dramatically, even after being adjusted for inflation Flood losses averaged $4.7 B/year in the 1980s, $7.9 B/year in the 1990s and $10.2 B/year in the 2000s." Dave Novak, Chief of the forecast branch of the NWS' NCEP/HPC, noted that the rate of improvement in forecasting of extreme precipitation has lagged that of more common events and remarked that "Extreme precipitation events are a major gap, and Test beds are key to addressing this." (Fig. 3)

From a climate perspective, and based on experience as the developer of NIDIS (Fig. 7; NIDIS 2007) and current manager of key elements of NOAA's Climate portfolio, Roger Pulwarty noted that "Integrated approaches are what are needed but are notoriously difficult to carry out." Taking this even a step further, Murugesu Sivapalan noted that "Hydrology is not just about water. Human activities are part of the landscape, and human choices are conditioned on environmental change." This is especially true from a climate perspective.

C. Workshop Organization and Process

Agenda Strategy

(See Appendix 1 for the participant list and Appendix 2 for the detailed agenda)

Day 1: Overview of emerging user needs and science directions (Plenary)

Introductions, overview of requirements, plus for each of 4 major breakout topics there was a 75 min session to provide background and to stimulate ideas

- A 15-minute summary of emerging needs
- Three 15-minute presentations of emerging science
- A 15-minute period for discussion

Day 2: Feedback and brainstorming in breakout groups (Breakout sessions)

There were four topics with four participant groups rotating through each topic. Breakout group co-leads (drawn from the Program Committee) stimulated discussion using the relevant "questions" identified by the Program Committee plus any new questions that may have arisen on Day 1, and rapporteurs recorded the results. Each workshop participant, excluding two co-leads and two rapporteurs for each breakout topic, were randomly assigned a number 1, 2, 3 or 4, that defined which participant group they were in. Each participant group spent 80 min on each breakout topic. Co-leads and rapporteurs prepared their reports for presentation in plenary the next morning.

Day 3: Discussion and Synthesis into Future Science Directions (Plenary)

- Report outs by breakout session leads (1.5 h), one breakout co-lead handled the background session on Day 1, while the other co-lead presented the breakout report on Day 3
- Two panel discussions were held on key questions regarding future science directions (3 h)
    - Science directions for hydrologic predictions
    - Science directions for climate applications
- Wrap up (0.5 h)

There were roughly 60 attendees (Fig. 3), of which about one-half were either presenters or panelists (Day 1: 20 speakers, Day 2: breakouts, Day 3: 4 speakers plus 10 panelists). Plenty of time was allowed for discussion and an entire day was committed to breakout sessions, thus allowing all participants multiple opportunities to communicate their perspectives and ideas.

All presentations are available online at the Workshop website: www.esrl.noaa.gov/psd/events/2011/water-cycle-science.html

Fig. 3. Photo of participants at the NOAA Water Cycle Science Challenge Workshop at NOAA's Earth System Research Laboratory, Boulder, CO held from 30 August to 1 September 2011. Another 10 attendees are not shown, and several more planned attendees had to cancel due to flooding from hurricane Irene. (Photo by Will VonDauster, NOAA)

Pictured in the Group Photo:

1. Mike Dettinger (USGS/Scripps) – Program Committee
2. Jeff Arnold (USACE)
3. Larry Band (Univ. of North Carolina)
4. Pedro Restrepo (NOAA/NWS/OHD) – Program Committee
5. Eric Danner (NOAA/NMFS)
6. Drew Gronewald (NOAA/OAR/GLERL)
7. Bert Davis (US Army Engineer R&D Center) – Workshop Co-Chair
8. Brad Udal (NOAA/WWA/PSD) – Keynote Speaker
9. Glen Liston (CIRA/Colorado State University)
10. Paul Dirmeyer (COLA/IGES)
11. Dennis Lettenmaier (Univ. of Washington)
12. Allen White (NOAA/OAR/PSD)
13. Dave Novak (NOAA/NWS/NCEP)
14. Valeriy Ivanov (Univ. of Michigan)
15. Rick Rosen (NOAA/OAR/CPO)
16. Soroosh Sorooshian (Univ. California Irvine)
17. Siva Sivapalan (Univ. of Illinois Urbana-Champagne)
18. Robin Webb (NOAA/OAR/PSD) – Program Committee
19. Juan Valdes (Univ. of Arizona)
20. Mimi Hughes (NOAA/CIRES/PSD)
21. Jim McNamara (Boise State Univ.) – Program Committee
22. George Smith (Riverside Technologies)
23. Dave Jorgensen (NOAA/OAR/NSSL) – Program Committee
24. Judy Curry (Georgia Inst. of Technology)
25. Andy Wood (NOAA/NWS/CBRFC)
26. Jonathan Gourley (NOAA/OAR/NSSL)
27. Harold Optiz (NOAA/NWS/NWRFC)
28. Lynn Johnson (NOAA/OAR/PSD)
29. Scott Lindsey (NOAA/NWS)
30. Peter Webster (Georgia Inst. of Technology)
31. Chris Milly (USGS/GFDL)
32. Martyn Clark (NCAR)
33. Cary Talbot (US Army ERDC)
34. Levi Brekke (USBurRecl) – Program Committee
35. Mike Ek (NOAA/NWS/NCEP)
36. Casey Brown (Univ. of Massachusettes)
37. Witold Krajewski (Univ. of Iowa)
38. Marty Ralph (NOAA/OAR/PSD) – Workshop Co-Chair
39. Kevin Knuuti (US Army Engineer R&D Center)
40. Lauren Hay (USGS)
41. John Forsythe (CIRA/Colorado State Univ.)
42. Jerad Bales (USGS)
43. Huan Meng (NOAA/NESDIS/STAR)
44. Rob Cifelli (CIRA/Colorado State Univ./PSD)
45. Christa Peters-Lidard (NASA/GSFC) – Program Committee
46. Peter Troch (Univ. of Arizona)
47. Tim Schneider (NOAA/NWS/OHD)
48. Brian Nelson (NOAA/NESDIS/NCDC)
49. Kelly Mahoney (NRC/NOAA/PSD)
50. Jessica Lundquist (Univ. of Washington)

Attended but not in Group Photo

51. Sandy MacDonald (NOAA/OAR/ESRL)
52. Bill Neff (NOAA/OAR/PSD)
53. Don Cline (NOAA/NWS/OHD)
54. Lidia Cucurull (NOAA/NWS/NCEP)
55. David Gochis (NCAR)
56. Marty Hoerling (NOAA/OAR/PSD)
57. Roger Pulwarty (NOAA/OAR/CPO)
58. Jim Verdin (USGS)
59. Jorge Ramirez (Colorado State Univ)

Could not attend (travel or last-minute issues, e.g. hurricane Irene)

60. Ralph Ferraro (NOAA/NESDIS/STAR) – Program Committee
61. Ana Barros (Duke University)
62. Kingtse Mo (NOAA/NWS/NCEP)
63. Christina Tague (Univ. of California Santa Barbara)
64. Gary Bardini (California Dept. of Water Resources) – Prog. Cmte.
65. Mike Anderson (California Dept. of Water Resources)
66. Kurt Brown (US Bur. Recl.) – Program Committee

2. Priority Topics and Key Science Questions

"There is a collision in the Western US between 19th Century water law, 20th Century water infrastructure, and 21st Century population growth & climate change."

Brad Udall – WWA, Keynote

As part of the planning process, the Program Committee identified the following areas of interest from a technical perspective.

Primary Technical Topics

1. What are the "forcings" needed for NOAA hydrologic prediction services of the future, and for external partners? "Forcings" here refers to those inputs needed to drive explicit stream flow prediction models typically forecasting out hours to days or weeks, e.g., precipitation, soil moisture, snow pack, evapotranspiration, base flow.
2. What methods and basis are best for estimating extreme meteorological and hydrological event possibilities, deterministically or probabilistically, in a changing climate?
3. How to jointly utilize the longer-term climate variability from observed records, paleoclimate, and projected climate information when portraying drought and surplus possibilities in planning?
4. What will NOAA's future hydrologic models consist of and how can they be developed under the Integrated Water Resources Science and Services (IWRSS) interagency framework?
5. What scientific inputs are needed on water cycle extremes, normals, predictability, climate trends and uncertainty information for policy makers dealing with major infrastructure planning, typically for decades into the future (e.g., water supply and flood control) and/or endangered species (e.g., salmon)?
6. How to make better use of existing and future weather & seasonal/annual climate predictions related to the water cycle?

The agenda (Appendix 2) was organized around 4 overarching technical subjects, which are also used in this report to organize the workshop outputs, including reports from the breakout sessions (Appendix 3):

- Next generation hydrologic modeling
- Hydrometeorological forcings for hydrologic models
- Physical processes underlying the water cycle
- Climate dimensions

The following topics were identified as cross-cutting and were reflected in the guidance to presenters, panelists and participants to help solicit input:

- User needs
- Extreme events (drought, flood)
- Observations
- Communication
- Ecosystem health

The following questions were developed by the Program Committee to help stimulate input, especially during the breakout sessions:

- What are the major deficiencies in our understanding of the physics of heavy rain systems and what does it imply about uncertainties in prediction? Are these gaps primarily in our understanding of cloud microphysics?

- What are the major gaps in our understanding of the meteorological and climatic underpinnings of droughts? What do we need to know in order to predict the onset, persistence, depth, and cessations of droughts? How well do we forecast these aspects of meteorological drought?

- What are the implications for needs for observing systems? What are the gaps? What could be the path to closing the gaps (both near and long term)? What interagency opportunities exist?

- What are needs for process understanding and model development, including NOAA's models for weather, climate and hydrology, especially factors affecting precipitation and steam flow?

- What field observations and modeling experiments might be useful for addressing key questions, and what are their requirements?

- What computing and information systems are required for high-resolution hydrologic and water resources monitoring, predictions and understanding nationwide and for their associated meteorological inputs, e.g., surface, profiles, radar, satellite, numerical weather predictions?

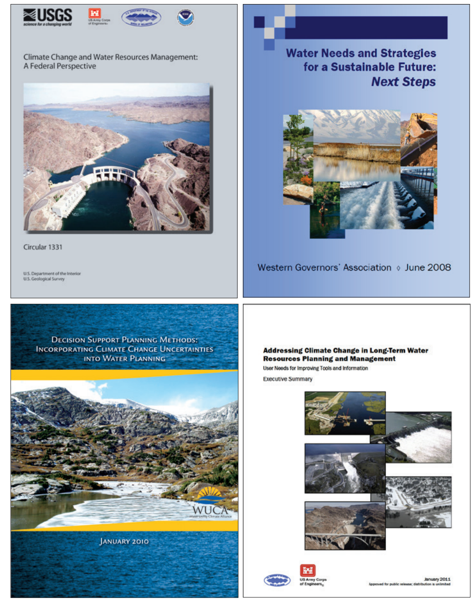


Fig. 4. Several recent interagency reports that provided background for this workshop (Brekke et al. 2009 – upper left; WSWC 2006 – upper right; WUCA 2010 – lower left; Reclamation and USACE – 2011). See Appendix 4 for additional information on these earlier requirements surveys. (Courtesy of Dr. Levi Brekke, U.S. Bureau of Reclamation)

"Flood losses nationally have risen dramatically, even after being adjusted for inflation (Fig. 2). Flood losses averaged $4.7 billion/year in the 1980s, $7.9 billion/year in the 1990s and $10.2 billion/year in the 2000s."

Don Cline – NWS, Invited

- What are the primary mechanisms by which water-cycle variations on meteorological time scales establish climatic variations and changes? What are the influences of climate-scale variations and changes on the water cycle at meteorological time scales? That is, what do we need to know to better understand (and ultimately predict) the weather-climate interface?

- Water yields and the demand side of the water cycle question: Do we have the instrumentation to adequately measure and have the observing networks to monitor evapotranspiration and evaluate predictions of water demand? Looking beyond just temperature and precipitation, how well do model forecasts and projections represent the full complement of surface water/energy budget variables (e.g., the variables used in Penman Montheith or Priestly Taylor calculations) for use in hydrologic modeling? Can these weather/climate/atmospheric model calculated variables be effectively downscaled and/or bias correct.

3. Synthesis Reports on Major Themes

"We have the computing power for physically-based, distributed models, but not the observations to support them."

Jessica Lundquist – Univ. Washington

A. Hydrologic Modeling

Goal: "Increase hydrologic forecasting skill for low-to-high stream flow conditions to be as good as the skill afforded by weather and climate predictions."

Overarching Recommendations

- Develop systems using strengths of both "lumped" and "physically-based" hydrologic models
- Develop a unified large-scale hydrological modeling system allowing integrated and multi-scale predictions, projections and analyses
- Foster efforts, such as NOAA's Hydrometeorology Testbed (HMT), to bridge the historical disconnect between hydrology and meteorology

Motivations for advancing hydrologic modeling and forecasting services are diverse and depend critically on exactly what hydrologic predictions are needed, e.g., flash flood peak flow, river flood peak timing, flow and duration, flood inundation area and depth, low stream flow, seasonal runoff volume, and decadal runoff variability. They also depend upon region, season and associated hydrometeorological conditions that lead to them (Fig. 8).

As background, current NOAA water cycle prediction services include:

- Streamflow (provided by River Forecast Centers): lumped, conceptual (SAC/Snow17) with prescribed potential evapotranspiration (PET) and temperature (T); snowmelt is key in the mountainous west
- Tides/Salinity/Currents/Temperatures (OFS): ROMS

"This Memorandum of Understanding is a commitment by our agencies to work together and closely coordinate our efforts in water management to provide the national with critically needed water resources information and support for better and smarter water planning and management." *—Rock Salt (for Joellen Darcy), US Army Civil Works*

"This initiative will leverage each agency's expertise to improve water resource forecasts and facilitate informed decisions, all utilizing the best available science. This marks a step forward in providing tailored, easily accessible and usable water information services to the people who need it." *—Jane Lubchenco, NOAA*

"This partnership is a great example of how forward-thinking government agencies can enhance their complementary resources while providing great service to the nation on issues of critical importance. We built upon a successful collaboration developed during times of extreme events, and we are extending it to a stronger, enduring relationship through the MOU." *—Marcia McNutt, USGS*

Fig. 5. Comments from agency leadership upon the signing of a Memorandum of Understanding (MOU) between USACE, USGS and NOAA on development of Integrated Water Resources Science and Services (IWRSS) in May 2011. (Courtesy of Dr. Jeff Arnold, USACE)

- Drought (provided by CPC): leaky bucket model → Palmer Drought Severity Index (PDSI)
- Regional NWP (NCEP/EMC): NAM
- Global NWP/Seasonal (NCEP/EMC): GFS/CFS
- Long - term Climate (GFDL): AM3

The workshop envisioned the following future services:

- Streamflow: distributed and lumped, physically-based water and energy balances for large and small (urban) watersheds
- Tides/Salinity/Currents/Temperatures: NEMS+ROMS
- Drought: distributed, physically-based water and energy balance
- Regional Numerical Weather Prediction (NWP): NEMS
- Global NWP/Seasonal: NEMS
- Long - term Climate: ESM
- For all future services, linkages to water quality, ecology and groundwater

Observations, watershed data and procedures for assimilation of hydrometeorological forcing data for hydrologic modeling have advanced at an increasing rate since implementation of the NWS River Forecast System (NWSRFS) in the 1960s. The NWSRFS has been applied nationwide in a "lumped" mode for some 4000 forecast points on the major rivers of the US. Deployment of the NEXRAD system and associated precipitation estimation algorithms have provided better definition of the spatial and temporal distribution of rainfall in many regions, at least where beam blockage by variable terrain is not a factor. Other sensors, such as "gap-filling' radars, satellite, GPS-met, and vertical profilers now can provide even higher resolution quantitative precipitation estimation (QPE) mapping of precipitation type and distribution. Further, numerical weather prediction models (NWP) have been advanced to assimilate these data and to provide high resolution quantitative precipitation forecasts (QPF). These hydrometeorological observations networks and modeling capabilities provide a "supply push" scenario whereby monitoring and forecasting can be accomplished at higher spatial and temporal resolutions. This, in turn, motivates the need for hydrological models and forecasting procedures to take advantage of these data. And this increase in this monitoring and prediction potential is being met with wide acceptance by the user community to meet public safety (e.g. flash floods) and support optimal water management strategies.

However, the workshop identified a number of issues associated with the monitoring and hydrometeorological forecasting systems that need to be addressed to fully realize the potential:

- Hydro forecasts are only as good as precipitation forecasts. Uncertainties of multi-sensor, gridded, precipitation products can be large and propagate in a non-linear manner when input to hydrologic models. More research is required to reduce these uncertainties and to characterize the impact of variations on the hydrologic predictions.

- Streamflow monitoring is a fundamental requirement for calibrating and validating hydrologic models, both for retrospective studies and in real time operations. There is a continuing trend towards reductions of streamflow gaging due to budget constraints. Long-term gaging of "natural" watersheds is important for climate change assessments.
- Soil moisture (SM) plays a significant role in land surface water balance and flood runoff modeling. It is difficult to measure and the representativeness of in situ measurements is limited due to high spatial variability of soil characteristics. There are also issues on how to assimilate the SM measurements into hydrologic models.
- Groundwater systems are linked to surface flows through complex dynamics, especially for lower flow and longer-term conditions. Groundwater systems and the surface-groundwater interaction dynamics are difficult to monitor given the expense of subsurface observations and geologic materials variability.
- Monitoring of land surface energy exchanges is required to close the water balance (e.g. evapotranspiration losses) and instruments and techniques to accomplish are needed.
- Establishing "Testbed" watersheds having high density hydrometeorological monitoring networks are required to provide the means to quantify the value added of specific instrumentation network components and hydrologic modeling methods.
- Many of these characteristics of a watershed depend on the surface and subsurface conditions including the geomorphology, catchment hydrology and biomass characteristics above and below ground (Fig. 9).

  Advancements of hydrologic modeling science are in part motivated by the advancements in hydrometeorological forcings monitoring and data assimilation procedures. Issues associated with advancing the science of hydrologic predictability were identified at the workshop.

- There have been strong calls at the workshop and otherwise for moving from the NWSRFS lumped-conceptual modeling paradigm to a higher-resolution distributed and physically-based approach. A distributed approach being examined by the NWS-OHD and other researchers (Fig. 8) is based on a gridded data structure (e.g. 1 km^2); this scale could address much of the flash flood problem for example.

Fig. 6. NOAA's Hydrometeorology Testbed (HMT; hmt.noaa.gov) focuses on hydrometeorological "forcings," including extreme precipitation , connects researchers, forecasters and forecast users. It has been researching and developing prototypes on extreme precipitation in California since 2003, and has expanded to the Pacific Northwest and Arizona. A regional implementation HMT in the Southeast US is slated for 2013-2015 in close partnership with NASA. Lessons learned from HMT have been documented in over 50 formal peer-reviewed technical publications and have generated new tools now in use at NWS and elsewhere. (Courtesy of Tim Schneider, NOAA)

- Also, the grids could be "intelligent" in the sense that the fundamental physical processes can be represented for each grid.
- Some envision that hydrologic models based on such a structure would require little or no calibration. Calibration is a complicated and labor intensive process and current operational models benefit from years of calibration activities. A suggestion was made that calibrations might be made which target different operational forecasting purposes.
- There are concerns that higher resolution computational structures can lead to "numerical dispersion" effects and do not lead to better predictions. For example, the NWS-OHD Distributed Model Intercomparison Project (DMIP) demonstrated that the distributed approach did not always produce better results in comparison to the lumped approach.

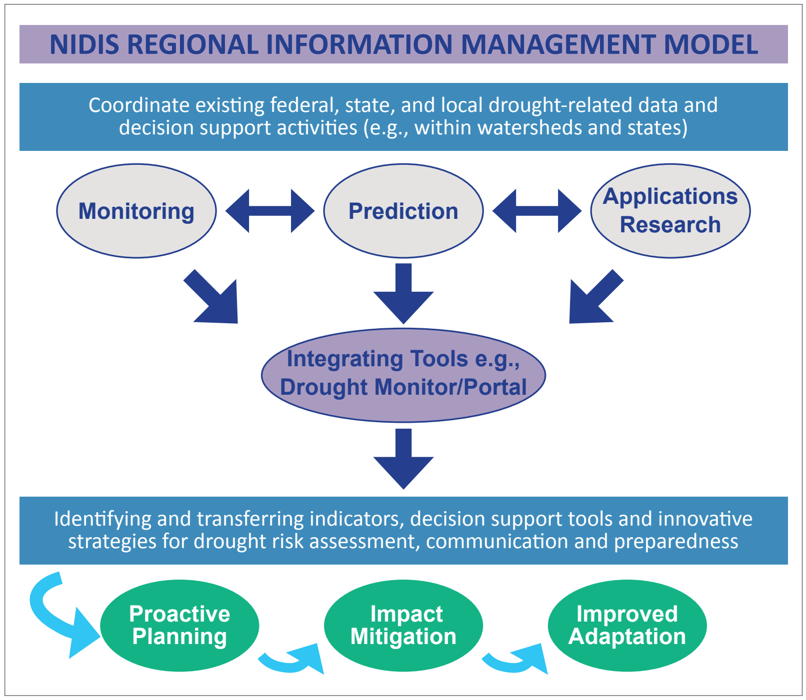


Fig. 7. Example from the National Integrated Drought Information System of effective strategies linking science to predictive services to user needs in the case of too little water. (Courtesy of Dr. Roger Pulwarty, NOAA)

- A call was made to establish a single unified hydrologic community modeling structure similar to that accomplished by the atmospheric modelers. Such a model structure could support multiple process hypotheses and process interactions so that comparisons can be made.
- Hydrologic forecasts need to address the full spectrum of flow conditions in addition to flood peaks and storm surge levels. Hydrologic prediction service demands vary by scale. It is desired to "warn on forecast" for flash floods. And it is required to better represent low flows during droughts as well.
- The scope of the hydrologic process models needs to be increased to represent water, energy and chemical balances. Forecasts for other variables besides streamflow are needed.
- Testbed watersheds are needed which are highly instrumented in order to advance understanding of basic hydrologic, energy and mass balance processes. These need to be operated for longer terms in order to capture adequate record lengths to represent the hydrologic extremes.

Integration of hydrologic models for forecast operations and decision support was a third theme identified at the workshop.

- Procedures for assessing the skill of hydrologic forecasts are needed. New threat scores that that address the skill in predicting high impact events can provide the means for tracking performance and identify areas for improvement.
- Establishment of data standards is required to maximize transferability of the observations and derived products between agencies and stakeholders at all levels.
- Better communications are required on the uncertainty associated with hydrologic forecasts. And training in how the uncertainty information can be used to best effect is required to obtain maximum benefits.
- There is a need for a co-conceived operational model and data Infrastructure that takes full advantage of existing and anticipated monitoring systems. The NWS CHPS is a step in the right direction for a modernized hydrologic model infrastructure that supports predictions services.

- Need a formal mechanism to bring operations into the same room with "the geeks". NOAA must have operators at the NWC.
- There is a need to integrate the forecasts into water management information systems so that forecast benefits are maximized, and to obtain feedback on the managed flows so that forecast products reflect flow regulation procedures. This is a goal of the IWRSS and the National Water Center. Whether it is achieved using a unified water modeling structure or through interoperability between agencies, or both, remains to be determined.
- It is advantageous to leverage academic innovation. The NOAA Cooperative Institutes could be more involved and focused on hydrology.

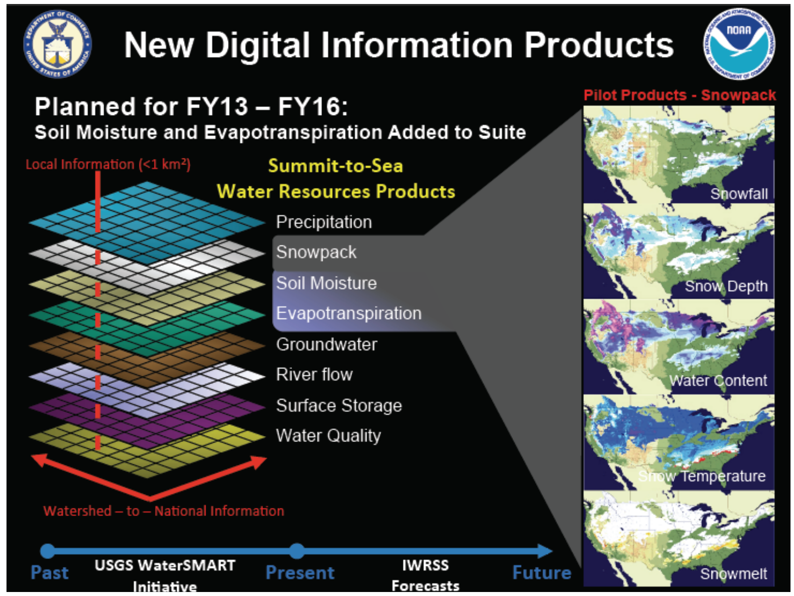


Fig. 8. Schematic of gridded hydrologic model inputs and outputs related to distributed, physically based hydrologic modeling. (Courtesy of Don Cline, NOAA)

B. Hydrometeorological Forcings

Goal: Improve representations, understanding and forecasting of key hydrometeorological forcings to rival those of other non-water-cycle variables and forcings in the weather-climate system

Overarching Recommendations

- Develop a National water cycle reanalysis, including key components and fluxes that close the water cycle
- Fill major gaps in observations of water cycle parameters (water vapor transport, precipitation, snow, surface energy budget terms including evapotranspiration, aerosols)
- Integrate in situ, radar, satellite and numerical model guidance to construct high-resolution data-assimilation products that directly link atmosphere and land-surface processes and depict the full water cycle over the US with high fidelity

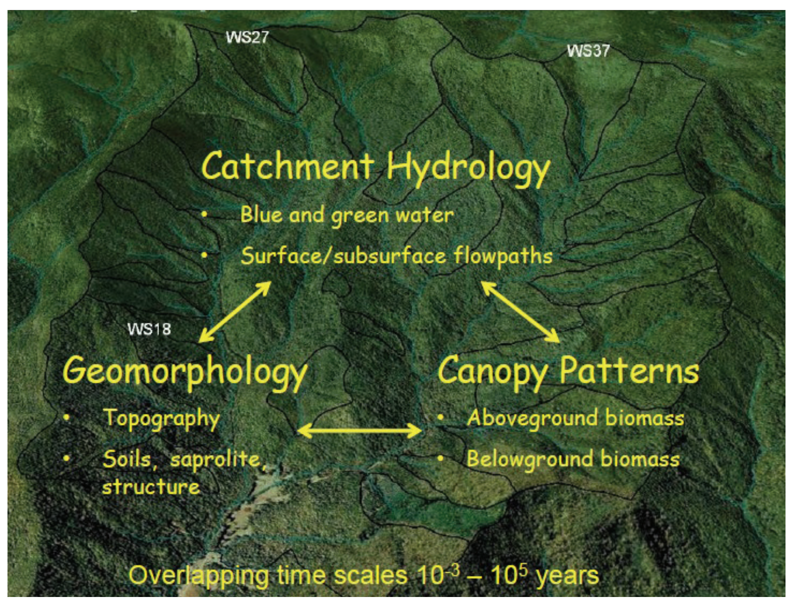


Fig. 9. Surface and ecosystem characteristics that strongly influence hydrologic behavior that physically based hydrologic models must represent or parameterize. Some of these characteristics change significantly over time scales ranging from hours to 10,000 years or more. (Courtesy of Larry Band, Univ. of North Carolina/Institute for the Environment)

- Implement a "moon-shot" style effort to improve extreme precipitation information building on HMT's foundation of innovation

During the workshop three fundamentally different types of forcings were described and discussed in terms of current and potential future needs, i.e., forcing parameters provided from outside of the hydrologic model and imposed on the simulations, hydrological state variables that are initialized and assimilated, and model static fields that are fixed, such as topography. Currently hydrologic models use primarily precipitation (QPE/QPF), air temperature, freezing level, surface snow distribution, prescribed land-cover, vegetation and potential evapotranspiration (PET). Future hydrologic modeling will require these, plus forcing terms critical to the surface energy balance (as an upper boundary condition to the hydrologic model), such as surface wind, humidity, solar and long wave radiation (e.g., clouds) and pressure. They will also require internal conditions that factor in ecological and human influences, including irrigation, reservoirs and land-cover change. Forcings at the lower boundary are also crucial, including ground water conditions (especially key for low stream flow conditions) and permafrost active layer. Given the importance of coastal inundation risks it also key that lateral boundary conditions associated with tides and "storm surge" be provided. In the case of fully coupled climate-scale modeling (e.g., in an earth system model framework), it will also be important to include greenhouse gases, aerosols, sea surface temperatures and human/social-influences on land-cover etc.

Given that precipitation is a primary forcing for hydrologic prediction and the fact that it is one of the most challenging parameter to predict (Fig. 10), special efforts are required to improve on these forecasts. It is this challenge that gave rise to the development of NOAA's HMT, which identified QPF is one of its "Major activity areas" (Fig. 7), for which detailed research strategies have been developed (see hmt.noaa.gov). Results from HMT to date were described at the workshop, including:

- Determining that extreme precipitation from strong, stalled atmospheric rivers (see Physical processes section) are responsible for generating extreme precipitation that cause most West Coast floods and creation of specialized tools to monitor and predict these features
- Documenting a shallow precipitation process that represents roughly 30% of West Coast precipitation, but is not well represented in weather prediction models and usually occurs beneath the lowest beam of scanning radars (which are often either on top of mountains scanning above the rain or are blocked by mountains due to the complex terrain)
- Quantified the key role of snow-level, measured forecast performance and developed a new remote sensing system for monitoring snow level
- Explored the role of precursor soil moisture and snowpack conditions (Fig. 11) in modulating stream flow
- Developed new model diagnostic tools to quantify AR conditions, and created a "water vapor flux tool" that integrates unique observations with high-resolution regional model output and scientifically based thresholds that are both used operationally.

Based on these findings, a 21st Century observing system is being implemented in California to better monitor and predict atmospheric rivers, shallow rain and the snow level (Fig. 12; White et al. 2012). This project is a legacy of HMT-West and is entitled "Enhanced Flood Response and Emergency Preparedness" (EFREP), which emphasizes developing and implementing new observations tailored to water-cycle-related predictions. The EFREP project serves as a useful example of what can be done on a regional basis by combining science, forecasting and user needs in a testbed. This experience led the Western States Water Council to request a vision be developed following this methodology but for the entire western US. This was formalized in a Resolution passed by the WSWC and formally submitted to the Western Governors Association (WGA). The resulting Vision document is summarized in a sidebar and is the focus of outreach efforts by WSWC to pursue implementation of the vision, which would address a number of key gaps identified in the NOAA Water Cycle Science Challenge Workshop report (as well as earlier related interagency reports noted earlier and discussed at the workshop). This also highlights a major cross-cutting theme at the workshop, i.e., the importance of modern, integrated observing systems.

Supporting Recommendations from the Breakout Session

i. Measure QPE/QPF skill with respect to stream flow/hydrometeorological forecast skill
    - Forecast of extreme events (e.g., 4 inches in 4 h with 1-day lead time) lags that of smaller events at HPC
    - Accurate QPF and QPE are necessary but not sufficient for hydromet forecast skill
    - QPE improvement strategies:
        - Dual-pol and gap-filling radars
        - Incorporate regional networks, satellites (especially in terrain)
    - QPF improvement strategies:
        - Higher spatial resolution
        - More accurate microphysics parameterizations

- Add aerosols (direct and indirect effects)
- Improve water vapor transport (atmospheric rivers and low-level jets)

ii. Provide continuous, seamless retrospective and forecast multi-sensor forcing analysis including uncertainties (note that uncertainty increases both backward and forward in time)

- Probabilistic forcing analysis including analysis of record and ensemble forecasts needed for:
- Uncertainty analysis and error propagation studies
  - Data assimilation (EnKF)
- Co-variation among forcing fields (e.g., radiation/precipitation or rainfall/pressure) must be preserved in forcing analysis
- Need access to raw data and methods used in Analysis of Record (AOR) to support reproduction of different spatial and temporal resolution products
  - Hyper-resolution nested model-based forcing analysis for urban/orographic areas

iii. Quality control, stewardship, and access to multi-agency, state, local, private, international forcing datasets

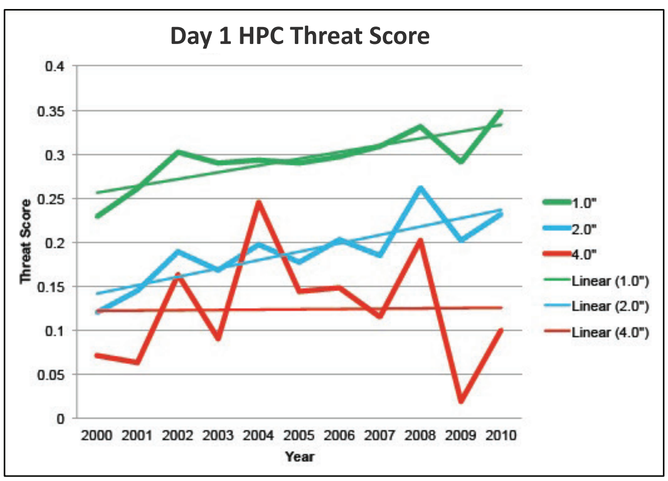


Fig. 10. Trends in HPC Quantitative Precipitation Forecast (QPF) skill (threat score) from 2000-2010 highlighting the challenge of predicting 24-hour precipitation accumulation in extreme events with 0-24 hours lead time. Larger values of the threat score represent a better forecast. The threat score is effectively the percentage of overlap between predicted and observed areas of precipitation accumulation exceeding a prescribed threshold. Thresholds of 1, 2 and 4 inch 1-day accumulations are shown. (Courtesy of Dave Novak, NOAA)

- Quantify uncertainty of individual inputs (station, radar, satellite, model)
- Develop integrated, regionally optimized observing networks including in situ, remote sensor and satellite systems (e.g., HMT, CASA)
- Pursue interagency and international partnering for access to satellite data (especially geostationary visible and infrared imagery and microwave data from polar orbiting satellites)
- OCONUS forcing should be similar latency and quality to CONUS forcing

C. Physical Processes

Goal: Identify and diagnose physical processes key to extreme events (storms and floods) and document their roles in forecast errors

Overarching Recommendations

- Identify "emergent" behavior in watershed dynamics and quantify associated thresholds
- Understand and diagnose variability in water vapor transport, including atmospheric rivers, which conduct >90% of the water vapor transport in mid-latitudes
- Explore the role of aerosol variability in modulating cloud microphysics and precipitation
- Diagnose, understand and quantify the characteristics of extreme precipitation and precursor land surface conditions that amplify or reduce drought and flood severity.

NOAA has statutory responsibility for providing water forecasts, warnings and outlooks over a wide variety of spatial and temporal scales. Of primary importance are the main stem river water level forecasts, flash flood warnings, and precipitation outlooks from weekly to seasonal trends to inform various decision makers. The tools that NOAA forecasters use to assist with delivery of these services vary according to the time and special scales of the forecasts. The National Weather Service's (NWS) River Forecast Centers (RFCs) utilize several "lumped" hydrologic prediction models, many of which were developed back in the 1950s, to forecast the river water levels and flood plain inundation from excessive water rises. Time scales of importance to RFCs are greater than 6 hours with basin spatial scales of thousands of square kilometers. Protection of life and property from "flash floods" falls to the local NWS Weather Forecast Office (WSFO). The drainage basins are much smaller than those of concern to the RFC, ranging from less than ten to a few hundred square kilometers. Similarly, the temporal scales are less than 6 hours. Seasonal outlooks of the probability of precipitation departure from normal (including drought outlooks) are prepared by NWS Climate Prediction Service.

The majority of the forecasts are within acceptable bounds of accuracy and timeliness, although less-so for extreme events. For some extreme hydrological "high impact" events, however, there have been notable shortcomings. For example, an unusually warm spring thaw in Alaska in 2009 caused some of the state's worst flooding in decades, with rising rivers wiping out an entire village. The magnitude of this event was not caught by the largely empirical runoff models because of shortcomings in the modeled melting processes. Similarly, there have been cases of rapid melting due to rain-on-snow that have not been handled well by these models.

These dramatic hydrologic model prediction "failures" point to the urgent need to move toward a new paradigm of forecasts, for some events, based on "physical" parameters rather than statistical empirically determined models to predict runoff. These physical models are not completely devoid of "calibration" or parameterized processes that dominate the statistical model approach, but they will be much less reliant on them and would respond to events outside the training experience of statistical models. Moreover, the changing global environment makes it more likely that future events will fall outside the historical envelope of the statistical models making more uncertain hydrologic forecasts of extreme events. Lastly, hydrologic predictions are mostly driven by their inputs of precipitation, either observed by gages or radars (QPE or quantitative precipitation estimates), or from atmospheric models (QPF or quantitative precipitation forecasts). QPE is notably inaccurate in the western US due to difficulties in siting rain and snow gages and radar deficiencies due to beam blocking by terrain, the generally less-dense radar network, dominance of orographic effects and the presence of melting levels. The skill at QPF, especially at high thresholds and in the summer season, is virtually non-existent beyond about a day. Until QPE and QPF skill improves, skillful hydrologic prediction will lag.

Key Physical Processes Themes from the Workshop

The workshop participants identified key areas where lack of knowledge about the physical processes could yield hy-

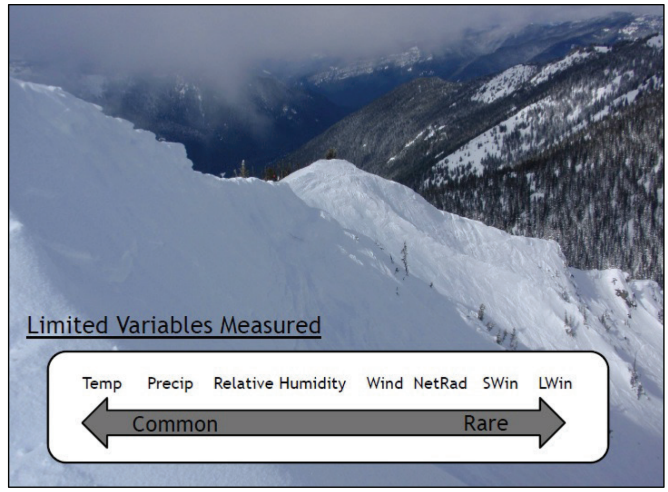


Fig. 11. Summary illustrating the relative lack of key parameters in the surface energy balance that are crucial as forcings for snow-melt related hydrologic predictions. Surface air temperature (Temp), precipitation (Precip), relative humidity, near-surface wind, net radiation (NetRad), short-wave (solar) radiation (SWin) and long-wave (essentially emissions from the atmosphere and clouds) radiation (LWin) are noted on a scale subjectively defining how common it is for that variable to be observed. Courtesy of Dr. Jessica Lundquist (Univ. of Washington).

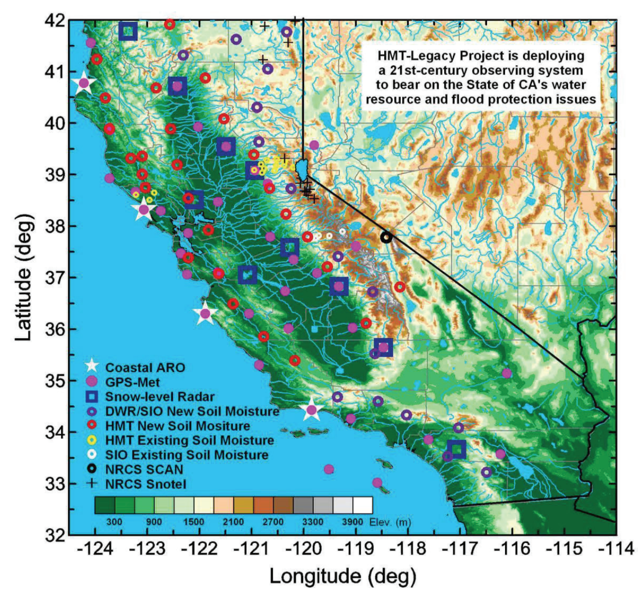


Fig. 12. State-of-the-art, water-cycle-focused mesonet being deployed for the State of California based on findings from NOAA's Hydrometeorological Testbed to support enhanced flood response and emergency preparedness. There are 94 new stations being deployed between 2009-2013, including 4 atmospheric river observatories, 10 snow-level radars, 43 soil moisture sites at 10 cm depth and 37 GPS-met sites (White et al. 2012). Courtesy of Allen White (NOAA/ESRL/PSD).

Snow Water Equivalent Anomalies

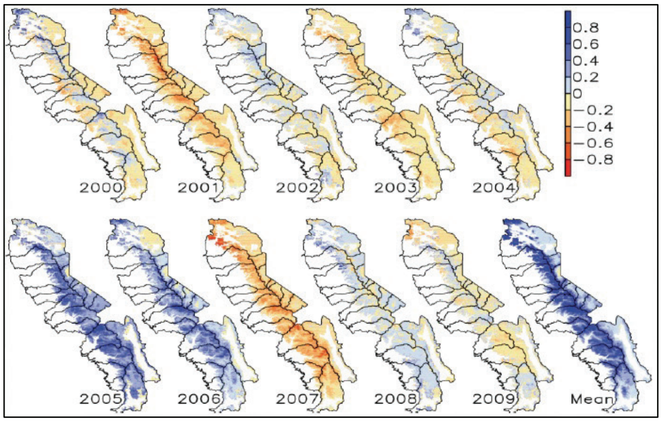


Fig. 13. Anomalies of snow-water equivalent in the Sierra Nevada from 2000-2009 highlighting large interannual variability. From B. Guan, N. Molotch, J. Dozier and T. Painter. (Courtesy of Bert Davis, USACE/CRREL)

drologic model failures. Some of these processes include (no ranking as to importance):

- Exploration of thresholds related to "emergent" behaviors in watershed responses to forcings
- Determining the scale dependencies of key physical processes
- Snow processes (e.g., rain/snow transitions) and cold region physics (e.g., Fig. 13; Guan et al. 2012)
- Ground water, including connection to surface, flow rates to deep aquifers, water quality (e.g., Fig. 14; Jencso et al. 2009)
- Over-lake evaporation
- Multi-physics thermal/moisture packages and vegetation phenology
- Sensitivity of hydrologic model to atmospheric persistence
- Atmospheric river duration and movement – better characterization of water vapor transport (e.g., Fig. 15; Neiman et al. 2008)
- Cloud microphysics and aerosol impact on QPF
- Land surface heat fluxes feedback to atmosphere, land use changes
- Drought and low stream flow issues
- Sensitivity of hydrologic models to uncertainties in input forcing (QPE/QPF)
- Human actions that restrict water flow (e.g., dam operations)

Scientists in academia, government agencies and laboratories are studying many, if not most, of these topics. But they largely are in isolation and not directly focused toward improving NOAA services. Even the most promising research results are slow to be brought to the prototype level because NOAA lacks a central mechanism for accelerating transition of research to operations. A key theme from the physical processes breakout involved facilitating research to operations toward development of the next generation hydrologic prediction tools involving more physically based parameters.

Specific Recommendations

- Establish integrated long-term observatories featuring regional implementations of NOAA's Hydrometeorological Testbed (HMT) within experimental watersheds, spanning arid to humid, warm to arctic basins, in all seasons to gather *integrated* atmospheric and hydrologic data sets to test hypotheses that extend knowledge of the hydro-meteorological physical processes that can be tested in physically based models.
- Establish a repository of high-impact hydrological cases with which to evaluate next generation hydrologic prediction models.
- Support a move toward a unified community hydrologic prediction model, similar to the atmospheric

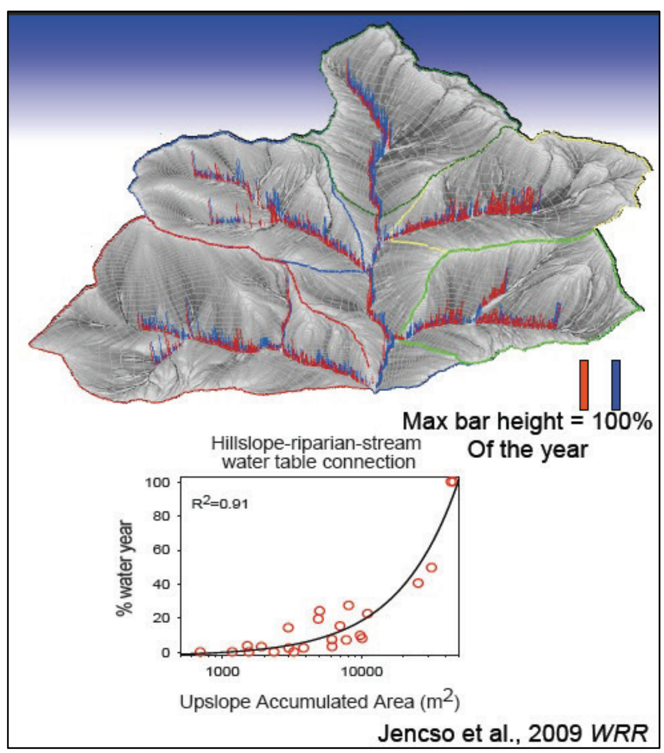


Fig. 14. Example illustration of "emergent behavior" linking hill slope area and vegetation to flow in the channel of an experimental watershed with shallow soils based on 84 wells. (Courtesy of Jim McNamara, Boise State Univ.)

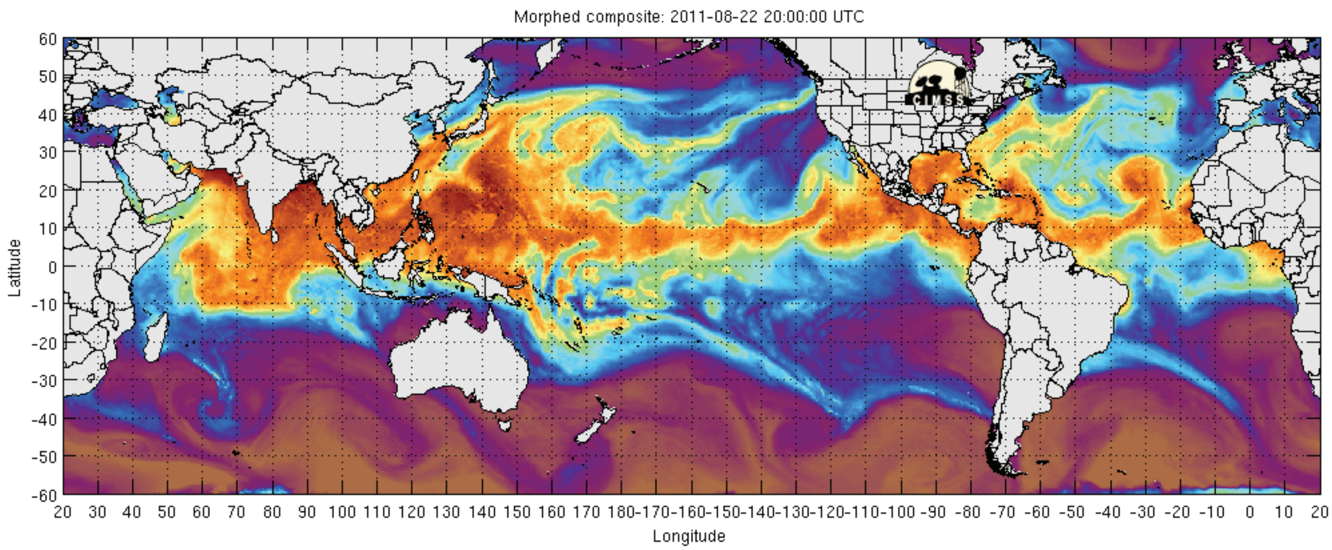


Fig. 15. "Atmospheric Rivers (AR) contain 95% of the poleward water vapor flux outside the Tropics, in < 10% of the zonal circumference," (e.g., Zhu and Newell 1998; Neiman et al. 2008). ARs are seen in this composite satellite image of vertically integrated water vapor (IWV). They appear as elongated, narrow regions of large IWV that are mostly oriented with a slope from west to east and toward the pole (e.g., off the US West coast and in the South Atlantic and South Pacific). Panel discussion on climate. (Courtesy of Mike Dettinger, USGS)

Weather Research and Forecasting (WRF) mesoscale prediction model that would accelerate research results into operations.

- Conduct focused integrated field experiments to test new instrumentation and new concepts.
- Foster hydrometeorological forecaster/researcher exchange, perhaps in the context of NOAA's National Water Center and HMT, to provide a place for prototype evaluation to accelerate research results to operations.
- Provide a mechanism to allow research hydrometeorologists to work closely with atmospheric modelers (e.g., Development Test Center at NCAR) to improve short range QPF of high impact weather events.
- Evaluate QPF skill improvements in terms of hydrologic prediction skill rather than the traditional measures of QPF skill (e.g., equitable threat scores, probability of detection and false alarm rates) and assess performance of QPF for extreme events.
- Establish a process to extend NOAA products and services to the entire flow duration curve, especially low-stream flow events. This will entail incorporating new processes within hydrologic prediction models including such processes as vegetation dynamics, hill slope and riparian evapotranspiration, and channel geomorphology.

D. Climate Dimensions - *Getting climate dimensions of the water cycle right*

Goal: Explicitly characterize key uncertainties in climate and hydrologic models (and their couplings)

Overarching Recommendations

- Establish NOAA "tiger teams" to evaluate selected real-world extreme events aiming to dissect causes and antecedents, assessing forecast skill and utility from hours to weeks
- Understand and describe the distributions of seasonal-to-interannual climate oscillations and their impacts on drought (Fig. 16; Burke et al. 2006) and flood risks
- Develop a global water cycle reanalysis and applications tools to better quantify uncertainties in water cycle trends in climate models and to meet user needs, e.g., for long-term infrastructure decisions for flood control, water supply, endangered species, etc…
- Analyze and identify landscape changes and water scape changes (e.g., irrigation, ice cover, lake levels), including human-caused, that must be factored into hydroclimate projections.

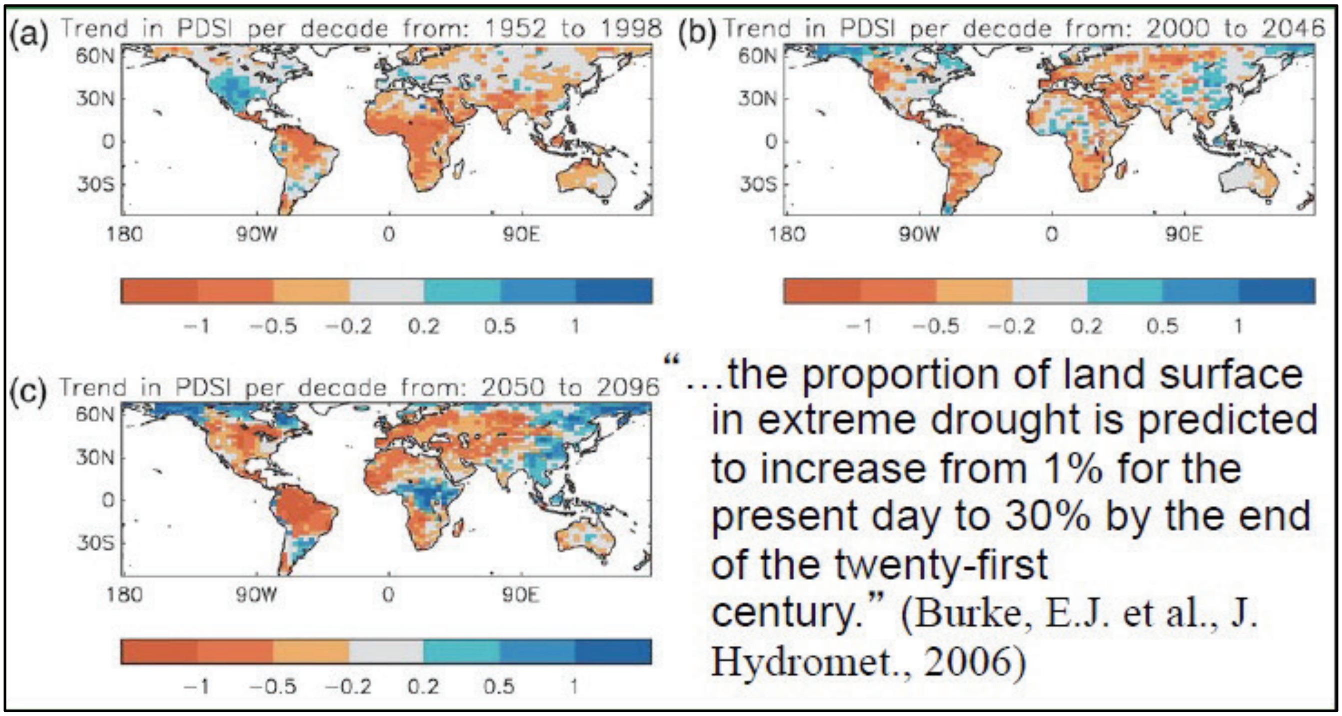


Fig. 16. Projected trends in the distribution of drought from the late 20th century to the late 21st century. (Courtesy of Chris Milly, USGS)

Water and the water cycle are important players in the climate system at global to local scales. As such, our understanding of, and ability to predict and project, water and the water cycle are key to our ability to forecast climate and hydrology at all geographic scales and at time scales from variations lasting a week or so to century-scale changes. One of the most challenging aspects of the climate system on these space and time scales is the bewildering array and range of scales, processes and conditions that continually interact and feedback on each other to yield what we call "climate" and, in turn, hydrology. At the heart of many of these interactions and feedbacks is water in its many forms and reservoirs, on land, in the oceans, and in the atmosphere. Current climate models do not yet simulate many of these interactions, feedbacks and even some of the reservoirs. Examples of coupling mechanisms that are not currently included in climate models, both operational and for the most part research, are the buffering effects of groundwater reservoirs on land-surface evaporation and water balances, the variability and predictability of vegetation and water vapor that it takes from the land to add to the atmosphere, and the impacts of human activities and disturbances on landscapes at time scales ranging from irrigation seasons to the lifetimes of sprawling expanses of pavement. Examples of coupling mechanisms that are not currently included in operational and (most) research models of rivers and streams are all of the above plus the ways that land surface conditions, especially associated with soil moisture and water bodies, have on the local to regional weather and climate conditions that ultimately determine the amounts of water escaping from precipitation to run into reservoirs or streams.

Given the central role that these interactions or "couplings" play in establishing climate, hydrology, and the variations and changes of both, a major goal of modern climate and hydrologic science is to understand and ultimately to simulate and predict the workings of the water cycle (at many scales) including the most important of these coupling mechanisms. Including more of these coupled processes and influences into climate models as well as into hydrologic models will provide a clearer understanding of how and why climate and hydrology vary and change, and should allow more complete and accurate predictions and projections of the Nation's water supplies and hazards. At present, most seasonal to longer term forecasts reflect future conditions "in the absence of other influences not yet incorporated" (see examples of missing coupling processes above) or "all other things being equal". This is especially true of multidecadal to century-scale climate-change projections, and is why they are generally referred to as projections rather than predictions or forecasts. That is, current climate-change projections are almost always illustrations of future climates if certain changes in atmospheric chemistry occur BUT human land uses and land cover don't change or change in prescribed ways, if long-term influences of groundwater and lakes are not important, and in the absence of other competing long-term changes to elements of the climate system. Current projections of hydrologic change in response to the climate projections are, in turn, reflections of the climate changes simulated for those carefully circumscribed future conditions (chemistry changes but not the others). A new generation of climatic and hydrologic models that incorporates the most important of these coupling processes and conditions could greatly reduce current limitations on the range of possible future climates and hydrologies included in current forecasts and projections on seasonal to climate-change time scales.

"Progress on predicting extreme precipitation seriously lags progress of other forecasts, and represents a major current gap."

Dave Novak – NOAA, Invited

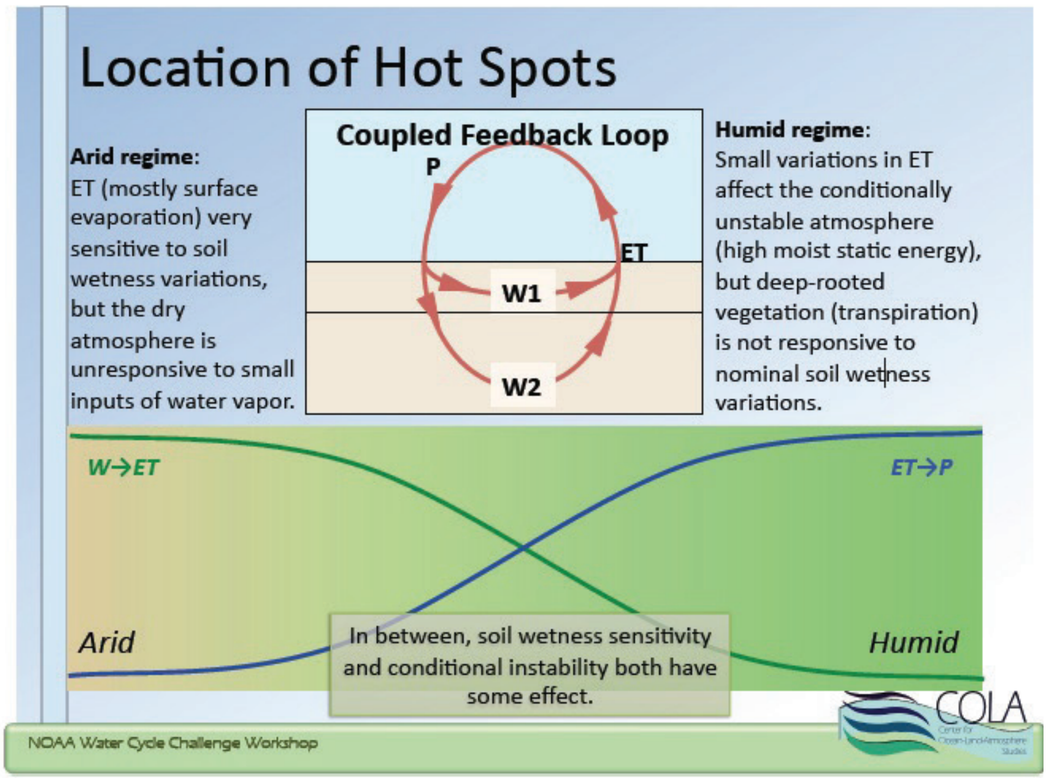


Fig. 17. Example illustration of land-air coupling "hotspots" where soil wetness sensitivity and conditional atmospheric static stability are present. These conditions and the locations where they are present could be affected by changing climate . (Courtesy of Paul Dirmeyer, COLA)

Developing such coupled climate and hydrologic models for research and, especially, for operational uses, is not expected to be the work of a short time or a single effort. Rather this is a long-term goal of much of modern climate and hydrologic science. However, so-called "earth system models (ESMs)"—which mark important strides towards fully coupled climate models including a wide (albeit still incomplete) range of coupling processes (e.g., air-land coupling "hotspots," Fig. 17) –are already being developed and used for parts of the current IPCC assessments, and these models are demonstrating that more fully coupled models will be quite possible, in time. Challenges still to be overcome include perfection and validation of the very preliminary ESMs that now exist, observation-understanding-and-eventually-inclusion of even more of the confounding coupling processes, validation of coupled models in historical and forecast modes, development of corresponding (parallel) coupled hydrologic models, and development of systems that allow/warrant bringing such models into operational-forecast and scenario-projection uses.

"To many, 'Climate Change' really means 'Water Change'."

Brad Udall – WWA, Keynote

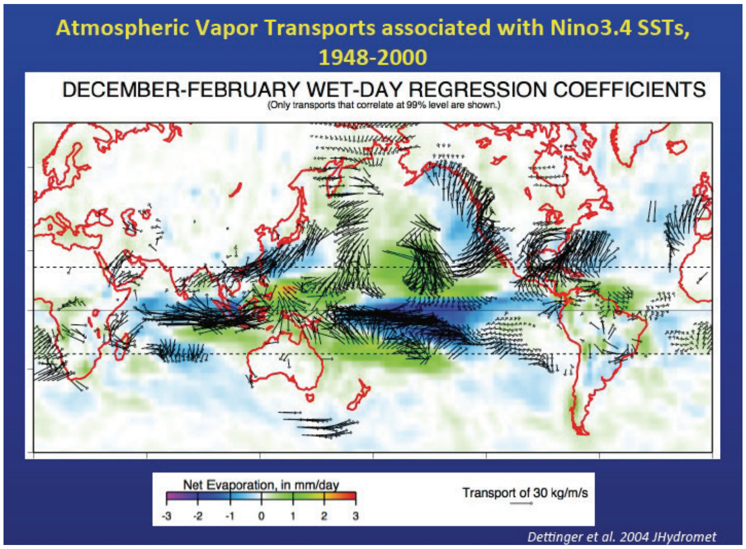


Fig. 18. Water vapor transport behavior in relation to ENSO and net evaporation. (Dettinger et al. 2004).

Two important steps that NOAA could undertake that would move its capabilities to address these coupled processes, and that would also directly provide a basis for strengthening the scientific foundations used in its seasonal-to-interannual forecasts and longer-term forecasts and projections of climate and hydrology, are:

1. Establishing a firmer scientific foundation for water cycle science, forecasts and projections by focusing NOAA's data- and modeling capacities specifically on the water cycle, with a global water-cycle reanalysis, water-cycle (and water-vapor) focused model data assimilations and initializations, and water-cycle-focused climate model and forecast validations. Not only does a global water cycle reanalysis differ from a traditional atmospheric reanalysis in terms of spatio-temporal resolutions, but it would also require assimilation of both the atmosphere and land/water surface dimensions of the water cycle, including soil moisture, vegetation, snowpack, runoff, etc.

2. Current global atmospheric reanalyses (which provide high quality, long-term, detailed, multivariate and dynamically consistent histories of past weather across the globe at time scales greater than a few hours and on spatial grids commensurate with current climate models) are produced by a number of centers including NOAA/NCEP. Originating with weather forecast models, they use essentially the same data assimilation system used for initializing numerical weather predictions, incorporating meteorological observations to nudge model variables to a state close to observations but maintaining internal consistency with ongoing simulation of the atmospheric conditions. The reanalysis processes add "analysis increments" to the model variables to accomplish this nudging, and these increments are not constrained in ways that ensure that water is conserved in the modeled atmosphere; the conservation of water (and, by extension, energy) is violated. This hampers the usefulness of reanalyses for studies of the water cycle and other hydrologic applications. Methods of data assimilation that do not severely violate these conservation principles should be implemented in a new set of future reanalyses targeted for water-cycle uses. There are various numerical methods that could improve upon standard methods (e.g., Kalman filter-based approaches) in reducing the size of the analysis increments. Even more beneficial would be application of the increments as nudging to specific terms of the model equations (specifically the flux or advection terms) rather than as extra model forcing terms.

   Similarly, the validation of climate model simulations and forecasts has traditionally focused on variables like temperatures, precipitation and geopotential heights. Improvements in the performance of the models in terms of all components of the water cycle (including precipitation) may be accrued if future model developments (including data assimilation and model initialization procedures) and model validations are specifically targeted upon model performances in terms of water cycle components and water-vapor transports. Resulting forecasts and projections would more faithfully represent the water–cycle and attendant hydrologic events, by improving the use of observations in initialization of the model forecasts and simulations, by ensuring closer adherence to water and energy conservation, and eventually better representations and parameterizations of the processes that are most important to getting the water cycle right.

3. Deploy a network of hydroclimatic testbeds, with significant field, modeling, reforecast, and forecast prototyping components.

   Climate and hydrologic forecasts and projections are both still relatively new ground for NOAA science and operations (as for everyone else). Forecast skills are still relatively modest. Progress in improving these skills may be offered by establishment of programs and testbeds where historical climate variations, recent forecast experiences, and on-the-ground process studies and methodological improvements can be analyzed. In the climate arena, the scale of these testbeds may need to be larger (closer to standard climate regionalizations) to yield reliable results; in the hydrological arena, an important question will be whether or not standard operational hydrologic models of the kind used in current, shorter term hydrologic forecasts are also the best vehicles for making climate-scale hydrological forecasts and projections. Baseline forecast skills as well as forecast skills that vary through time in predictable ways depending on the status of important climate modes and changes (e.g., ENSO or AMO status, or longer term changes in seasonal skills that may result from warming trends) will need to be identified and quantified to provide useful products. An example would be better understanding and predicting the changes in evaporations and water vapor transport in relation to ENSO and atmospheric rivers (Fig. 18; Dettinger et al. 2004, 2011). These and other challenges can best be met with field evaluations and observational campaigns, closely associated modeling experiments, and historical data analyses of determinants of climate-forecast skills in selected regions. The required Hydroclimatic Testbed program can draw much, programmatically and scientifically, from the existing HMT program, but will need to have its own resources, foci, and probably its own field areas (due to differences in relevant time and space scales).

Photo credit: ©2011 Paul Neiman

4. Summary

Goal:
Increase hydrologic forecasting skill for low-to-high stream flow conditions to be as good as the skill afforded by weather and climate predictions

Input from a wide range of participants representing differing disciplines, agencies, academic institutions and information users was collected in this workshop. It is in some sense apropos that just prior to the workshop a moderate intensity hurricane made landfall on the US East Coast, causing extreme precipitation and flooding (Fig. 19) in an already severe year for U.S. natural disasters (more than 10 events each exceeded $1 billion in damages, most related to flooding). The adverse impacts of the storm included cancelation of flights for several expected participants who were thus unable to attend. Nonetheless, the meeting took place with roughly 60 participants over 3 days in Boulder Colorado and yielded information and recommendations organized around four themes:

- Next generation hydrologic modeling
- Hydrometeorological forcings for hydrologic models
- Physical processes underlying the water cycle, and
- Climate dimensions.

A. Goals and Recommendations

- Increase hydrologic forecasting skill for low-to-high stream flow conditions to be as good as the skill afforded by weather and climate predictions
    - Develop systems using strengths of both “lumped” & “physically-based” hydrologic models
    - Develop a unified large-scale hydrological modeling system allowing integrated and multi-scale predictions, projections and analyses

- Foster efforts to bridge the historical disconnect between hydrology and meteorology

- Improve representations, understanding and forecasting of key hydrometeorological forcings to rival those of other non-water-cycle variables and forcings in the weather-climate system
  - Develop a National water cycle reanalysis, including key components and fluxes that close the water balance
  - Fill major gaps in observations of water cycle parameters (water vapor transport, precipitation, snow, surface energy budget terms including evapotranspiration, aerosols)
  - Integrate in situ, radar, satellite and numerical model guidance to construct high-resolution data-assimilation products that directly link atmosphere and land-surface processes and depict the full water cycle over the US with high fidelity
  - Implement a "moon-shot" style effort to improve extreme precipitation information

- Identify and diagnose physical processes key to extreme events (storms and floods) and document their roles in forecast errors
  - Identify "emergent" behavior in watershed dynamics and quantify associated thresholds
  - Understand and diagnose variability of water vapor transport, including atmospheric rivers which conduct >90% of the water vapor transport in mid-latitudes
  - Explore the role of aerosol variability in modulating cloud microphysics and precipitation Diagnose, understand and quantify the characteristics of extreme precipitation and precursor land surface conditions that amplify or reduce drought and flood severity.

- Explicitly characterize key uncertainties in climate and hydrologic models (and their couplings)
  - Establish NOAA "tiger teams" to evaluate selected real-world extreme events aiming to dissect causes and antecedents, assessing forecast skill and utility from hours to weeks
  - Understand and describe the distributions of seasonal-to-interannual climate oscillations and their impacts on drought and flood risks
  - Develop a global water cycle reanalysis and applications tools to better quantify uncertainties in water cycle trends in climate models and to meet user needs, e.g., for long-term infrastructure decisions for flood control, water supply, endangered species, etc.
  - Analyze and identify landscape changes and water scape changes (e.g., irrigation, ice cover, lake levels), including human-caused, that must be factored into hydroclimate projections.

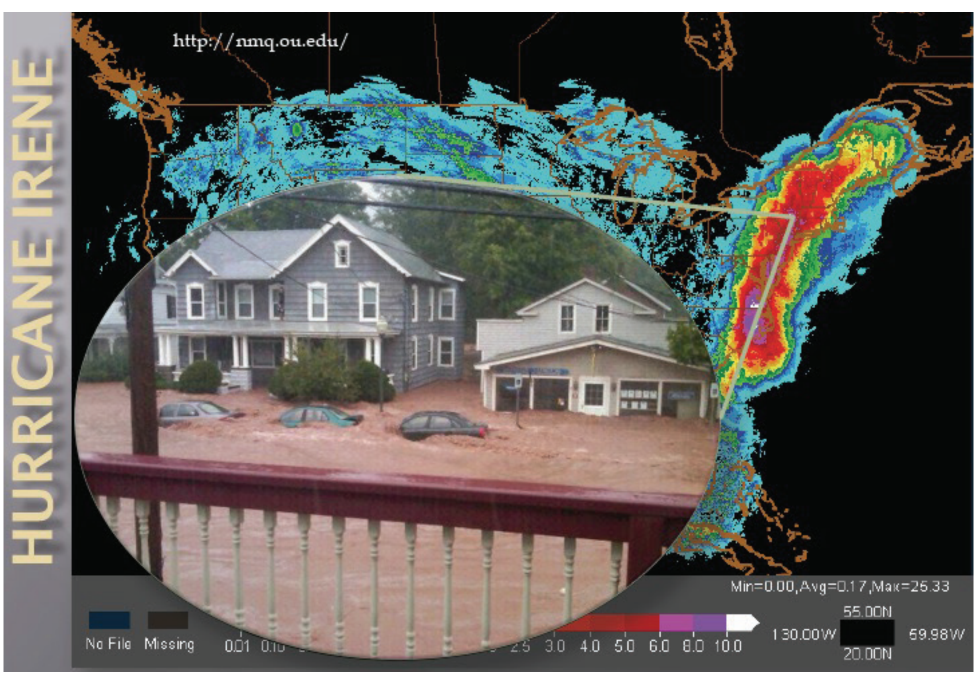
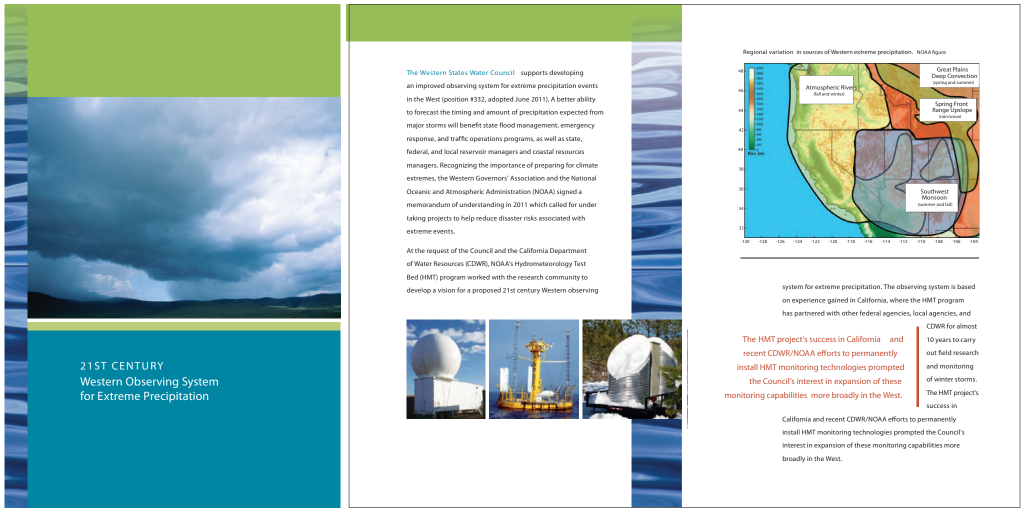


Fig. 19. extreme precipitation and inland flooding associated with land-falling tropical storms or hurricanes is a major cause of damage and loss of life in hurricanes as is illustrated with this example from hurricane Irene that struck the Eastern U.S. at nearly the same time as this workshop was being held. Several expected participants of the workshop from the region struck by Irene were unable to attend due to flight cancelations and other impacts. The color-filled areas represent estimated one-day precipitation totals, which exceeded 10 inches in some areas. (Courtesy of Tim Schneider, NOAA)

"A Vision for a Western Observing System for Extreme Precipitation" developed at the request of the Western States Water Council (WSWC) by Ralph et al. with input from 26 contributors representing 21 organizations. (Brochure courtesy of WSWC.)



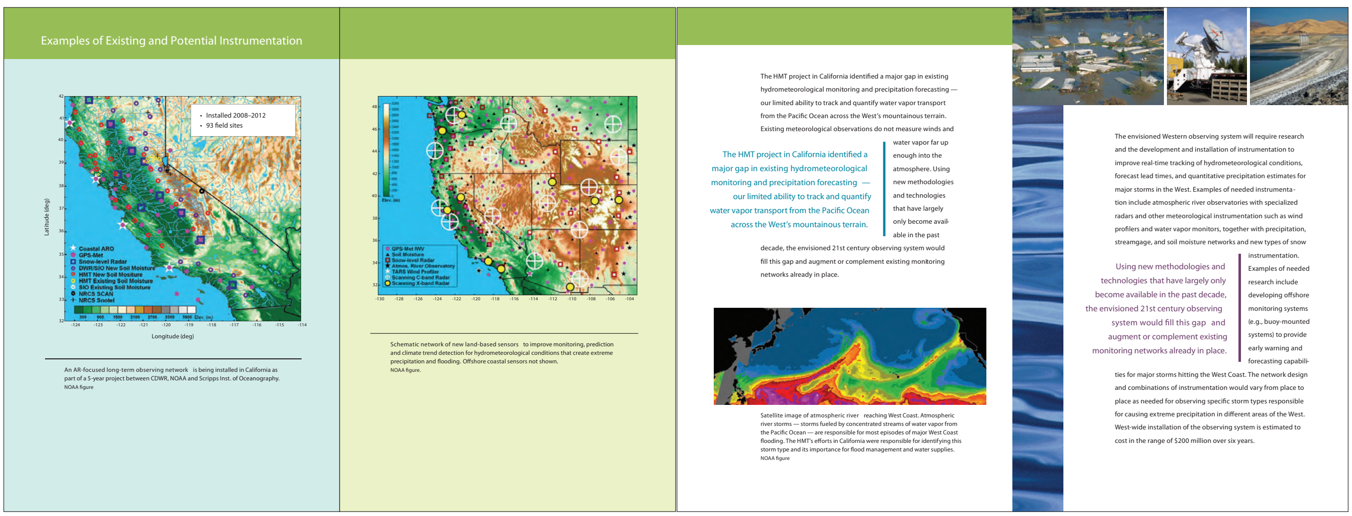


Fig. 20. A brochure from WSWC describing a vision for a 21st century set of observations for the Western U.S. for extreme precipitation, water supply, flood, and climate trend detection. To download brochure, go to: http://www.westgov.org/wswc/167%20council%20meeting%20-%20id/WSWC%20HMT%20brochure%20june%202012.pdf

Goal: *Improve representations, understanding and forecasting of key hydrometeorological forcings to rival those of other non-water-cycle variables and forcings in the weather-climate system*

B. Proposed Implementation Strategies

- Elevate the priority of water cycle science and services in NOAA to levels comparable to that of weather and climate, building on MOUs between USGS, USACE & NOAA and between WGA & NOAA.
- Fully support the "National Water Center" (NWC) in the NWS to advance hydrologic services.
- Fully support NOAA's HMT in OAR to develop innovative solutions to providing the necessary hydrometeorological "forcings" to drive future hydrologic prediction systems across agencies.
- Implement the "Western US Observing Systems Vision for Extreme Events" requested by the WSWC to improve monitoring, prediction and climate trend detection of extreme events (Figure 20).

***Goal:** Identify and diagnose physical processes key to extreme events (storms and floods) and document their roles in forecast errors.*

- Carry out and coordinate hydrological (e.g., via CUAHSI) and hydrometeorological (e.g., HMT) field studies.
- Develop a Hydroclimate Testbed building on NIDIS, HMT, RISAs, Laboratories and CUAHSI that would link hydroclimate science to services and user needs, and would emphasize extremes.

The following quote from a resolution passed in July 2011 by the Western States Water Council as a recommendation to the Western Governors Association (WGA) illustrates the existence of policy-maker support to move forward on implementation of key elements of this report's recommendations.

- "BE IT FURTHER RESOLVED, that the **Western States Water Council (WSWC) supports** development of an improved observing system for Western extreme precipitation events, to aid in monitoring, prediction, and climate trend analysis associated with extreme weather events; and, … urges the federal government to support and place a priority on research related to extreme events, including research on better understanding of hydroclimate processes, paleoflood analysis, design of monitoring and change detection networks, and probabilistic outlooks of climate extremes; and … the WSWC will work with NOAA in supporting efforts on climate extremes, variability, and future trends as called for in the WGA-NOAA memorandum of understanding.

  This policy-maker support has continued to grow since the workshop was conducted, as manifested by the adoption of a "Vision for Western U.S. Observations for Extreme Precipitation." After receiving the vision document that was developed at their request (Ralph et al. 2011), they have begun outreach to the WGA and elsewhere to make the case for implementation. As part of this outreach, WSWC developed a brochure that is included in this Workshop report.

  IWRSS continues to be implemented, as does the National Water Center. However HMT received a significant budget reduction from NOAA in FY12. Efforts to build the capacity in NOAA to address the societal needs, forecast and other service gaps, and advance the science, requires that the recommendations and existing capabilities in NOAA be given a higher priority if NOAA is to meet the nation's needs for services related to drought, flood, water supply, water quality and environmentally vulnerable systems including endangered species. Other agencies, scientists, stakeholders and key water policy makers have voiced their opinions strongly on this.

  This report provides a scientific foundation upon which pursue the NOAA Science Grand Challenge on Understanding and Predicting the Water Cycle.

***Goal:** Explicitly characterize key uncertainties in climate and hydrologic models (and their couplings)*

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Appendix 1

Workshop Participants

Name	Affiliation
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Jerad Bales	U.S. Geological Survey
Band, Lawrence	Institute for the Environment/Univ. of North Carolina
Ana Barros	Duke University
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Mike Ek	NOAA/NWS
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Andrew Gronewold	NOAA/OAR/GLERL
Lauren Hay	USGS
Martin Hoerling	NOAA/OAR/ESRL
Mimi Hughes	CIRES
Valeriy Ivanov	University of Michigan
Lynn Johnson	NOAA/OAR/ESRL
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Jim Verdin	USGS
Robert Webb	NOAA/OAR/ESRL
Peter Webster	Georgia Institute of Technology
Allen White	NOAA/OAR/ESRL
Andy Wood	NOAA/NWS/CBRFC

Appendix 2

Agenda

NOAA Water Cycle Science Challenge Workshop

30 August – 1 September 2011
NOAA Earth System Research Laboratory
Boulder, Colorado

Day 1 – Introduction, Plus Overview of Emerging User Needs and Science Directions

07:30 – 8:15 Breakfast and Sign-in

Session Chair: Robert Webb

08:15 - 08:30 Welcome, Introductions and Overview – Bert Davis

08:30 - 08:40 Strengthening NOAA Science – Sandy MacDonald

08:40 - 08:50 Purpose of this Workshop – Marty Ralph

08:50 - 09:20 Keynote Address – Brad Udall

09:20 - 09:40 Interagency Coordination - IWRSS – Don Cline

09:40 - 10:00 Drought - NIDIS – Roger Pulwarty

10:00 - 10:20 Summary of past "requirements" surveys – Levi Brekke

10:20 - 10:45 Break

Session Chair: Pedro Restrepo

10:45 - 11:00 Hydrologic Modeling – Emerging needs – Harold Optiz

11:00 - 11:15 New Features of the "LM3" Land Model with Rationale and Evaluation – Chris Milly

11:15 - 11:30 Structure, Function and Dynamics of Watersheds – Larry Band

11:30 - 11:45 Predictions under Change (PUC): Water, Earth and Biota in the Anthropocene – M. Sivapalan

11:45 - 12:00 Hydrologic Modeling – Discussion

12:00 - 01:00 Lunch

Session Chair: Christa Peters and Lidard

01:00 - 01:15 Hydrometeorological forcings – Emerging needs Tim Schneider

01:15 - 01:30 Quantitative Precipitation Estimation (QPE) Rob Cifelli

01:30 - 01:45 Quantitative Precipitation Forecasting (QPF) Dave Novak

01:45 - 02:00 Snow information Jessica Lundquist

02:00 - 02:15 Hydrometeorological Forcings – Discussion

Session Chair: Dave Jorgensen

02:15 - 02:30 Moving to Spatially-Distributed Modeling; Snow as a Surrogate for Some Key Challenges – Bert Davis

02:30 - 02:45 Precipitation and Clouds - Modeling – Dave Gochis

02:45 - 03:00 Precipitation Processes - Observations – Allen White

03:00 - 03:15 Land Surface Hydrology and Watershed Dynamics – Jim McNamara

03:15 - 03:30 Water Cycle Physical Processes – Discussion

03:00 - 03:30 Break

Session Chair: Mike Dettinger

03:30 - 03:45 Climate Dimensions - Emerging Needs – Jeff Arnold

03:45 - 04:00 Climate - Emerging Science Topic 1 – Judy Curry

04:00 - 04:15 Climate - Emerging Science Topic 2 – Dennis Lettenmaier

04:15 - 04:30 Climate - Emerging Science Topic 3 – Paul Dirmeyer

04:30 - 04:45 Climate Dimensions – Discussion

04:45 - 05:00 Wrap-up Discussion from Day 1 – M. Ralph and B. Davis

Day 2 – Breakout Sessions

Four participant groups rotate through 4 breakout topics for 80 minutes per session. There will be two leads, plus a rapporteur for each breakout session.

Breakout Session Leads and Rapporteurs:

- Next Generation Hydrologic Models: P. Restrepo and L. Brekke (Leads), L. Johnson (Rapporteur)
- Hydrometeorological Forcings: C. Lidard and A. White (Leads), D. Novak (Rapporteur)
- Physical Processes: D. Jorgensen and J. McNamara (Leads), R. Cifelli (Rapporteur)
- Climate Dimensions: R. Webb and M. Dettinger (Leads), K. Mahoney (Rapporteur)

Breakout Group Program Representatives (B. Davis, M. Ralph, D. Cline, B. Udall)

07:30 - 08:00 Breakfast

08:00 - 08:20 Description of Process for Breakout Sessions – Marty Ralph

08:20 - 08:30 Transition to Breakout Session Rooms

08:30 - 09:50 Breakout Sessions – 1st Rotation Breakout

09:50 - 10:20 Break and Transition to New Breakout Rooms

10:20 - 11:40 Breakout Sessions – 2nd Rotation Breakout

11:40 - 12:00 Group Photo Before Lunch (Meet in Lobby)

12:00 - 12:50 Lunch

12:50 - 02:10 Breakout Sessions – 3rd Rotation Breakout

02:10 - 02:20 Transition Between Breakout Sessions

02:20 - 03:40 Breakout Sessions – 4th Rotation Breakout

03:40 - Adjourn for Day 2 (Except for Breakout Leads and Rapporteurs)

04:00 - 05:45 Session Leads and Rapporteurs Prepare Reports Writing

Day 3 – Discussion and Synthesis into Future Science Directions

07:30 - 08:00 BREAKFAST

Session Chair: Jim McNamara

08:30 - 08:45 Report from Hydrology Modeling Breakout – TBD

08:45 - 09:00	Report from Hydrometeorology Breakout – TBD
09:00 - 09:15	Report from Physical Processes Breakout – Dave Jorgensen
09:15 - 09:30	Report from Climate Dimensions breakout – Robert Webb
09:30 - 10:00	Discussion including inputs from Breakout Group and Program Representatives
10:00 - 10:30	Break

Panel Moderators: Levi Brekke and Pedro Restrepo

10:30 - 12:00	Panel 1: Science Directions for Hydrologic Predictions
	Panelists: W. Krajewski, V. Ivanov, L. Cucurull, S. Sorooshian, G. Smith
12:00 - 1:00	Lunch

Panel Moderator: Roger Pulwarty

1:00 - 2:30	Panel 2: Science Directions for Climate Applications
	Panelists: A. Wood, M. Dettinger, P. Webster, K. Mo, M. Hoerling
2:30 - 3:00	Wrap-up – M. Ralph and B. Davis
3:00 -	Workshop Adjourns
3:30 - 5:00	Program Committee Meets

Day 4 – Program Committee Only

08:30 - 12:00	Writing
12:00 - 1:00	Lunch
1:00 - 2:30	Writing
2:30 - 3:00	Wrap-up and Next Steps

Appendix 3

Breakout Session Notes

A. Next Generation Hydrologic Models

Breakout Session Report

Levi Brekke (Bureau of Reclamation), Pedro Restrepo (NOAA/NWS),
Lynn Johnson (NOAA/OAR; Rapporteur)

Framing Questions/Suggestions

- Hydrologic prediction service demands vary by scale
- Human dimensions
- Importance of education/training to support model deployment
- NOAA Cooperative Institutes focused on hydrology
- Quantification of uncertainty

Potential Modeling System Goal

- Develop models that require little or no calibration
- Apply system to develop hydrologic scenarios.
- Model structure that supports multiple process hypotheses & process interactions
- Simulation of water, energy and mass (nutrient) balances
- Support high spatial-resolution forecasting (~1km resolution)
- Calibration issues

Potential Modeling System Requirements

- Intelligent grids
- Use of existing observations and anticipate new developments
- Simulation of water management actions
- Scope of processes
- Simulate energy budget, not just water budget
- Support prediction on short- to long-time scales, from highest to lowest flows
- Forecast other variables in addition to streamflow

Possible Attributes of Next Generation Hydrologic Models

- Linked/nested system of models
- Single unified/community model?
- Multiple model calibrations, targeting different operational forecasting purposes?
- Geography
- Address processes not well-represented in current services

Data Requirements to Support Next generation Hydrologic Models

- Pursue field campaigns
- Reach out to other disciplines
- Soil moisture and groundwater monitoring
- Real-time verification information
- Radiation components
- Water management actions
- Data Integration
- Hydrologic data standards

B. Hydrometeorological Forcings

Breakout Session Report

Christa Peters-Lidard (NASA), Allen White (NOAA/OAR)
David Novak (NOAA/NWS; Rapporteur)

What "forcings" are needed for future NOAA hydrologic prediction services and for external partners?

Current NOAA Water Cycle Prediction Services

- Streamflow (RFCs): lumped, conceptual (SAC/Snow---17) with prescribed potential evapotranspiration (PET) and Temperature (T) - based snowmelt
- Tides/Salinity/Currents/Temperatures (OFS): ROMS
- Drought (CPC): leaky bucket model ---> Palmer Drought Severity Index (PDSI)
- Regional NWP (NCEP/EMC): NAM
- Global NWP/Seasonal (NCEP/EMC): GFS/CFS
- Long - term Climate (GFDL): AM3

Future NOAA Water Cycle Prediction Services

- Streamflow (RFCs??): distributed, physically – based water and energy balance + ecology + groundwater + water quality with data assimilation
- Tides/Salinity/Currents/Temperatures (OFS): NEMS+ROMS?
- Drought (CPC??): distributed, physically - based water and energy balance + Ecology + Groundwater + Water quality with data assimilation
- Regional NWP (NCEP/EMC): NEMS
- Global NWP/Seasonal (NCEP/EMC): NEMS
- Long - term Climate (GFDL): ESM

Definition: Hydrometeorological ("Hydromet") Forcings

- Definition of "forcing" depends on the problem, application, time-scale, and the model
- We separate three important inputs:
  - Forcing (outside of model and imposed on simulation)
  - State Variables (initialized, assimilated)
  - Model static fields (topography/bathymetry, soils, geology)
- Current Forcings: Precipitation (QPE/QPF), air temperature, freezing level with prescribe land-cover, vegetation and PET
- Future Forcings (Uncoupled):
  - Upper Boundary Condition (BC): Precipitation (QPE/QPF), Air Temperature, Freezing Level, Wind, Humidity, Radiation, Pressure
  - Internal: Ecological and human influences included (irrigation, land cover change, reservoirs/withdrawals)
  - Lower BC or prognostic: Ground water table, Permafrost Active Layer
  - Lateral BC: Tides
- Future Forcings (Coupled—NEMS, ESM): Sun, CO2, Aerosols, SST, Human/Social

Key Recommendation 1:

Measure QPE/QPF skill with respect to streamflow/hydromet forecast skill

- Accurate QPF and QPE are necessary but not sufficient for hydromet forecast skill

- QPE improvement strategies:
  - Dual-pol and gap-filling radars
  - Incorporate regional networks, satellites (especially in terrain)
- QPF improvement strategies:
  - Higher spatial resolution
  - More accurate microphysics parameterizations
  - Add aerosols (direct and indirect effects)
  - Improve water vapor transport (atmospheric rivers and low-level jets)

Key Recommendation 2:

Provide continuous, seamless retrospective and forecast multi-sensor forcing analysis including uncertainties

- Probabilistic forcing analysis including analysis of record and ensemble forecasts needed for:
  - Uncertainty analysis and error propagation studies
  - Data assimilation (EnKF)
- Co-variation among forcing fields (e.g., radiation/precipitation or rainfall/pressure) must be preserved in forcing analysis
- Need access to raw data and methods used in Analysis of record (AOR) to support reproduction of different spatial and temporal resolution products
  - Hyper-resolution nested model-based forcing analysis for urban/orographic areas

Key Recommendation 3:

Quality control, stewardship, and access to multi-agency, state, local, private, international forcing datasets

Insert Figure (slide 9 of ppt), collage of images of sensors

- Uncertainty of individual inputs (station, radar, satellite, model)
- Strategic network design and gap-filling radar (e.g., CASA)
- Interagency and international partnering for access to satellite data (especially geostationary visible and infrared imagery and microwave data from polar orbiting satellites)
- OCONUS forcing should be similar latency and quality to CONUS forcing

C. Physical Processes Underlying the Water Cycle

Breakout Session Report

Dave Jorgenson (NOAA/OAR), Allen White (NOAA/OAR)
Rob Cifelli (Colorado State University; Rapporteur)

Currently NOAA Water Services from RCs Differ from Those of WSFOs

- River Forecast Centers (RFC)
    - Main stem river stages
    - >6 hours to 3 days
    - Lumped runoff & snowmelt models (Sacramento, Snow---17)
- Weather Service Forecast Offices (WSFO)
    - Flash floods
    - <6 hours, small catchment or debris basins
    - Empirical statistics based on historical rain/event data
    - Growing need for seasonal to decadal outlooks for water

NOAA Forecast System Works Well Most of the Time

- Some (spectacular) failures related to extreme events (rain in dry basins, very heavy rain)
    - Outside experience of current models/stats
- New paradigm of physically---based models in some situations
    - New observations to support those models
- Changing world makes previous calibrations obsolete

Why do Hydro Prediction Models Have Larger Errors?

That is, what are the critical physical processes that aren't handled well?

- Rain/snow transitions
- Rain-on-snow events (rapid melt)
- Regional Effects (including human activities) and space/time scales drive the physics
- Ground water storage and proper handling of antecedent conditions (arid environments)
- Large errors in Quantitative Precipitation Forecasts (QPF) are a major source of hydrologic forecast errors

How to Facilitate Research Toward a Next Generation Paradigm of Hydrologic Forecasting?

- Academic researcher/forecaster exchange
- Inventory of model failures and historical data for quantitative evaluation of progress
- Testbed for hydrologic technique/model evaluation
    - RFC and WSFO problems differ
    - Not necessarily the same place (could be part of the National Water Center?)
- Focused integrated field experiments (could HMT be expanded?)

Improvements to quantitative precipitation forecasting (QPF) are needed

- Atmospheric model improvements
    - Microphysics
    - Radiation
    - Boundary layer process (e.g., evaporation)

- Coupled hydrologic/atmospheric models
    - Feedbacks
- Data assimilation systems
    - Dual-pol radar
    - Soil moisture
- Role of testbeds
    - Evaluation of process parameterizations (e.g., sub surface storage, fluxes)

Is it time to move toward a community hydrologic prediction model?

- NWS/CHIPS provides structure support
- More rapid transition from research results to operations
- “Modules” that fit within the framework, each of which could be evaluated within a testbed

Integration of physics, observations and models

- Improved physics must be guided by observations
- Integrated long-term observatories with advanced hydrometeorological observations (HMT) with experimental watersheds should be collocated

Key physical processes for which improved understanding is required

- Determine scale dependencies of otherwise well-knows physical processes
- Human actions are considered
- Snow processes and cold region physics
- Ground water (connection between surface flow rates and deep aquifers and to water quality)
- Over-lake evaporation
- Multi-physics thermal/moisture packages and vegetation phenology
- Sensitivity of hydrologic model to persistence of key atmospheric conditions
- Atmospheric river duration and movement
    - Better characterization of water vapor transport
- Cloud microphysics and aerosols
- Land surface heat fluxes feedback to atmosphere, land use changes
- Drought and low flow issues
- Sensitivity of hydrologic models to precipitation (QPE/QPF)
- Low stream flow conditions including droughts

Low Stream Flow Conditions

- Represents a new direction for NOAA
    - Predict the entire flow duration curve
- Models must incorporate new processes
    - Vegetation dynamics
    - Hill slope and riparian evapotranspiration
    - Gaining and losing channels
    - Human actions (e.g., nearby groundwater withdrawals)
    - Channel geomorphology
    - New flow routing techniques

D. Climate Dimensions

Report from Breakout Sessions

Mike Dettinger (USGS/Scripps Institution of Oceanography), Robin Webb (NOAA/OAR),
Kelly Mahoney (Univ. of Colorado; Rapporteur)

* No definite or consensus definition adopted, but for this report "climate" is defined mostly in terms of time scales

- Separated by the transition from near-deterministic timescale to those associated most with probabilistic considerations
- > 1 week to century time scales
- Two broad time frames included: Seasonal to interannual forecasts and Multidecadal/trend scales of climate change

Major Challenges and/or Considerations

What are the long-memory determinants/processes of climate variability and change? To what extent and how should these long-memory processes be incorporated into models (climate and hydrologic) and predictions?

- e.g., Land-air interactions (including soil moisture, groundwater, land uses and cover); ocean-air interactions; cryospheric variability and change
- e.g., internal climate modes (including MJO, PNA, ENSO, NAO, PDO, AMO, unnamed, etc…)
- e.g., external forcings (including greenhouse gases, anthropogenic land disturbance, solar, volcanoes, etc…)

Need to understand, initialize, simulate and project most of these at regional scales with uncertainty envelopes.

Consideration of these long-memory processes is part of a broad need to include more coupling of land-air and hydrology-climate processes in models and forecasts.

Long-range vision includes coupling of:

- soil moisture – atmosphere (at both climate time scales defined above)
- human disturbances and changes of land surface and cover and water availability (on both climate time scales but perhaps more so on climate-change scales), and
- coevolution of climate/hydrology/vegetation/landscape with society (climate change time scales) in climate and hydrologic models and forecasts

What is required to produce useful AND defensible predictions/projections and scenarios from climate projections and models?

- More resolution (human scale to basin scales), more processes, more coupling
- Better internal modes, especially at interdecadal time scales (requires >500-year-long records)
- Evapotranspiration and associated variables are of increasing importance (especially in extreme conditions)

Note that similar issues plague downscaling for seasonal forecasts but (a) downscaling is being done, and (b) seasonal forecasts are more limited by climate=forecast skill than by downscaling.

Future of Hydrologic Forecasts/Projections

- Distributed models/physically based are needed to capture extremes and unusual conditions, to accommodate change (including landscape change), for coupling of land-to-atmosphere
- Hydrologic initialization of climate models will be increasingly important
- Dynamic vegetation is important, phenology for forecasts, coevolution for projections
- Groundwater is important and NOAA is going to require help from outside
- Human management of water and land is important and NOAA is going to require help from outside
- Recalibration or dynamic-recovery parameterizations are needed for accommodation of land changes/disturbances in forecast models

- Permafrost change (along with other cryospheric change) at seasonal to century time scales needs to be tracked and included in Arctic (and in mountains)

What are appropriate scales for land-air coupling in models, for downscaling, for representing feedbacks?

- Need to close water (and energy) balances associated with land hydrology in climate models.
- How will storm tracks change? How will synoptic conditions contributing to climate-scale processes and outcomes change?
- Regional models could be a learning ground for inclusion of additional processes and land-air coupling, but similar inclusions should begin in global models too.
- Climate-change hydrologic projections are irrelevant until brought to local (basin?) scales.

Recommendation

Explicitly characterize ALL uncertainties in our climate and hydrologic models (and their couplings): disentangling different sources of uncertainty is VERY difficult but promising avenues include multiphysics experimentation and hierarchical Bayesian approaches.

Recommendation

Propose establishment of NOAA "tiger teams" to evaluate selected real-world extreme events (climate and hydrologic) aiming to dissect causes and antecedents; determine how much forecast skill was there and how much could or should it have been used, considering time scales from hours to weeks.

Drought Forecast and Characterization

How well can we define what state we are in (drought -wise)? Need initialization of soil moisture, groundwater, streamflow, snow, reservoir storage, irrigation, etc… at "HUC10-ish" scales.

NASA and other agencies can help. What can remote sensing add to weather-climate nowcasting?

More generally (in drought or not), WE DON'T KNOW WHERE THE WATER IS, or WHEN, from NOW AND INTO THE FUTURE.

Need full and continuous distributions of climate modes like North Atlantic Oscillation (NAO) or Arctic Oscillation (AO) and their drought impacts.

Other Questions

- On climate-change scale how does climate elasticity of runoff depend on model parameters and parameterizations?
- How to characterize (estimate) climate-change uncertainties and how to handle risk under nonstationary statistics?
- On both time scales, is a downscaled ensemble of mechanistic climate/hydrologic models actually better than statistical methods for things like flood frequencies?

Closing Questions

- Are forecasts of numbers and cumulative effects of synoptic-based extreme weather events possible? For example, the number of atmospheric events, and possibly cumulative hydrologic effects.
- Analysis of records of past and attribution are still extremely fruitful but face major challenges. Decadal forecasts are an important investment area for NOAA and its partners.
- Added processes/coupling/resolution all may run afoul of the challenge of piling on models that are already over-parameterized.

Programmatic Recommendation

Everything, everywhere all the time is not something that NOAA can do…a challenge for NOAA is defining what the limits of what it is willing and able to do. The community really needs this and it would serve in many ways as a gold standard for us all.

Appendix 4

Synopsis of Key Earlier Requirement Surveys Related to Water Cycle Science: Purpose, Context and Examples

Water resources managers face many challenges given our limited understanding and capabilities in predicting conditions associated with either too much or too little water. Challenges include managing reservoir systems through flood events, aiming to minimize loss of life and property damage, but being limited by imperfect foresight of short-term hydrologic conditions at high spatial resolution. Challenges also include managing through slowly developing and persistent regional drought conditions, aiming to inform the decision on how much supply to reserve as protection against sustained drought versus allocating additional supply to ease stress on immediate water demands, and doing so with limited information about the drivers of the current drought or the prospects for its persistence.

Recognizing the need to invest in research and capacity building to address water cycle science and prediction challenges, water resource managers have issued several requirements surveys describing water users' perceptions on various levels of need, including data, methods, tools, and agency capacity. Many of these surveys have been developed in response to concern about implications of a changing hydroclimate for water resources (**Milly et al. 2008, USGCRP 2009**) and concerns about how water managers might adequately consider such changes in planning and management (**Brekke et al 2009**). A common theme among these requirements surveys, whether they're focusing on using of being better prepared for longer-term hydroclimate change or shorter-term weather and climate variations, is to promote research and capacity building that leads to:

- better-quality predictions
- better use of existing-quality predictions while we wait for better-quality to arrive, and
- better communication of risk and uncertainty during decision-support processes.

When reviewing requirements surveys, it is important to understand the context in which they're formulated. Requirements surveys differ in terms of their purpose (research vs. capacity building?), target audience (appropriators vs. program managers?) and depth of discussion (higher-level vs. technically detailed). On capacity building, the surveys may be designed to invite various types of public or private sector investment, including data collection, staff development, and education.

- Requirements surveys tend to be good barometers of research and development relevance, but not necessarily research feasibility. A survey's utility as a relevance indicator typically stems from how they are formulated to report pressing or emerging issues among those participants from the water management community. However, participants may be disengaged from the research process and thus may not have understanding on necessary strategies required to address needs. Hence there is potential – perhaps even likelihood - for the surveys to emphasize highly relevant needs that unfortunately pair with low research feasibility and low-likelihood of developing research outcomes to address needs in a timely fashion. Thus, it is important to review requirements surveys with thought toward what's feasible.

The following are example requirements surveys that have been completed in recent years, all of which offer insight on user needs related to water cycle science and prediction research.

- "Addressing climate Change in Long-Term Water Resources Planning and Management" (**Reclamation-USACE 2011**)[1]: This interagency report was developed by the federal Climate Change and Water Working Group (CCAWWG) and reflects of the views of the Bureau of Reclamation, U.S. Army Corps of Engineers, U.S. Environmental Protection Agency,

1 http://www.usbr.gov/climate/userneeds/

Federal Emergency Management Administration, and other federal and non-federal water management organizations on knowledge, method and data needs to support long-term water resources planning. Needs are outlined according to the various types of analyses necessary to assess climate change implications for water resourcesmanagement (e.g., obtaining climate projection information; making decisions on how to relate such information to planning assumptions; choosing methods for assessing impacts on hydrologic, ecological and other natural systems, or impacts of socioeconomic systems and institutions that frame and influence water management values; understanding how to assess, characterize and communicate results and uncertainties to decision-makers for effective decision-support). The document offers technical discussion in terms of desired capabilities, current capabilities, and gaps, and is aimed at informing programming of science-management research collaborations to address needs. To that end, a companion research strategy document is in development, led by CCAWWG science lead agencies (NOAA and USGS). These paired assessments serve as the first of two paired assessments outlining user needs and research response, this first effort focusing on long-term hydroclimate prediction and associated planning, and a second effort (in development, due in 2012) focusing on better use of weather forecasts and short-term climate predictions in water resources management.

- "Water Needs and Strategies for a Sustainable Future" (**WSWC 2006**)[2]: This report offers states' perspectives and high-level discussion on needs related to several water management aspects, inviting both research and capacity-building activities. The report emphasizes the need for enhanced hydrologic data collection to track changing hydroclimate conditions, and improved capabilities in the areas of hydrologic prediction, modeling and impact assessment. An associated "Next Steps" report was subsequently issued (**WSWC 2008**)2, offering more technical discussion of needs, including those related to managing through droughts and other shorter-term weather variations, and developing locally-relevant (downscaled) long-range projections of climate and hydrology necessary to support climate change vulnerability and adaptation assessments in the western U.S.
- "Options for Improving Climate Modeling to Assist Water Utility Planning for Climate Change" (**WUCA 2009**)[3]: This report discusses water utilities' perspectives on information that they would like to obtain from global and regional climate projections and relate to their planning activities (e.g., variables and scales). The report then reviews the state of science on developing global to regional climate projections, and prospects for improving this science. "Decision Support Planning methods: Incorporating Climate Change Uncertainties into Water Planning" (**WUCA 2010**)[3] serves as a companion to **WUCA 2009**, providing a review of methods for making decisions under climate change uncertainty (e.g., Robust Decision Making, Decision Analysis, Real Options). The report highlights case study applications of these methods and discusses research needs in relation to implement these methods (e.g., probabilistic information on data and modeling uncertainties).
- "The Future of Research on Climate Change Impacts on Water – A Workshop Focusing on Adaptation Strategies and Information Needs" – Subject Area: Water Resources and Environmental Sustainability (**WRF 2011**)[4]: This assessment focuses on needs and potential research directions in five areas, including Flooding and Wet Weather, Water Supply and Drought, and Water/Energy Nexus.
- "Chapter 7 - Major Scientific and Technological Advances Needed to Promote Effective Adaptation to Climate Change" in *Adapting to the Impacts of Climate Change* (**Jacobs et al. 2010**)[5]: This chapter presents a high-level overview of needs related to adaptation, including the need for better hydrologic prediction to serve various planning and management situations in the water sector.

2 http://www.westgov.org/wswc/publicat.html
3 http://www.wucaonline.org/html/actions_publications.html
4 http://www.waterrf.org/projectsreports/publicreportlibrary/4340.pdf
5 http://www.nap.edu/openbook.php?record_id=12783&page=203

Appendix 5

MOU between NOAA, USGS and USACE on IWRSS

MEMORANDUM OF UNDERSTANDING
BETWEEN THE
U.S. ARMY CORPS OF ENGINEERS
OF THE
U.S. DEPARTMENT OF THE ARMY
THE
U.S. GEOLOGICAL SURVEY
OF THE
U.S. DEPARTMENT OF THE INTERIOR
AND THE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
OF THE
U.S. DEPARTMENT OF COMMERCE

Collaborative Science, Services and Tools to Support Integrated and Adaptive Water Resources Management

Article I. Background

Federal agencies are engaged actively in water resources services, planning, development, operations, management and information gathering, analysis and communications. The U.S. Army Corps of Engineers (hereinafter referred to as USACE) of the U.S. Department of the Army, the U.S. Geological Survey of the U.S. Department of the Interior (hereinafter referred to as USGS), and the National Oceanic and Atmospheric Administration of the U.S. Department of Commerce (hereinafter referred to as NOAA), together referred to as the Parties, have related and complimentary responsibilities in a number of program areas. It is in the national interest that such Federal programs be closely coordinated and mutually supportive to efficiently and effectively meet the growing demand for water resources information and services.

The mission of the USACE is to provide vital public engineering services in peace and war to strengthen our Nation's security, energize the economy, and reduce risks from disasters. These engineering services include water resource planning, development and management activities involving flood risk management, navigation, ecosystem restoration, emergency preparedness and response, multi-purpose water resources, infrastructure, and environmental stewardship.

The mission of the USGS is to provide the Nation with reliable, impartial information to describe and understand the Earth. This information is used to minimize loss of life and property from natural disasters; manage water, biological, energy, and mineral resources; enhance and protect the quality of life; and contribute to wise economic and physical development.

The mission of NOAA is to understand and predict changes in the Earth's environment and conserve and manage coastal and marine resources to meet our Nation's economic, social, and environmental needs. Critical elements of this mission include monitoring and analyzing our water resources and issuing predictions and warnings for all hydroclimatic conditions from floods to droughts.

With complementary mission elements centered on water resources, the Parties agree with the widely held view that water resources are one of the most significant challenges facing societies and governments in the 21st century. Managers and decision makers in all sectors of water resources require new and more integrated information and services to adapt to uncertainty, climate and land-use changes, and increasing demand on limited resources. To meet this challenge, an innovative partnership of Federal agencies with complementary operational missions in water science, observation, prediction and management has been developed. This collaborative partnership currently consists of the Parties; however, it will grow to include other agencies. The partnership will address the goals of the Integrated Water Resources Science and Services (IWRSS) initiative and the objective of the Building Strong Collaborative Relationship for a Sustainable Water Resources Future initiative to build a Federal Support Toolbox for Integrated Water Resources Management.

Article II. <u>Purpose</u>

The purpose of this Memorandum of Understanding (MOU) is to document the commitment of the Parties and formalize this interagency partnership to, better align agency programs within current authorities, enhance communications and the exchange and availability of information, and to establish opportunities for joint projects, programs, facilities, and other collaborative science, services and tools to support integrative and adaptive water resources management. This MOU is designed to facilitate the Parties' scientists, engineers, and managers to work together, achieve mutual goals and leverage resources for sharing information and planning, developing, and implementing science and services in support of integrative and adaptive water resources management. It is also intended to serve as the foundation and mechanism for other Federal agencies and partners to join this collaborative partnership in the future to further address our Nation's water resources information and knowledge capacity needs.

Article III. <u>Scope</u>

This MOU serves as an umbrella agreement that sets forth the general terms and conditions under which the Parties will coordinate and cooperate in activities to improve water resource science and services. Cooperative activities in these fields may include, but are not limited to, project plan development, exchange of technical information, tools and services, joint studies, research and development activities of mutual interest, joint educational and communications activities to advance the understanding of water resources science and services, and exchange visits and work details of individuals sponsored by all Parties who are engaged in water resources projects of mutual interest.

Article IV. <u>Responsibilities</u>

The Principals for this MOU are the Assistant Secretary of the Army (Civil Works), the Director, USGS, and the Department of Commerce Under Secretary for Oceans and Atmosphere (NOAA).

The Parties agree to provide membership and participate in a governance structure for the MOU that includes:

The Parties agree to refer requests from third parties to become parties to this MOU to the Executive Oversight Committee.

Article XI. Approval

U.S. Army		U. S. Geological Survey U. S. Department of the Interior		National Oceanic and Atmospheric Administration U.S. Department of Commerce	
Signature		Signature	Marcia McNutt	Signature	
Name	Jo-Ellen Darcy	Name	Marcia McNutt	Name	Jane Lubchenco
Title	Assistant Secretary of the Army (Civil Works)	Title	Director, U.S. Geological Survey	Title	Under Secretary for Oceans and Atmosphere
Date	May 11, 2011	Date	5/11/2011	Date	May, 11, 2011

Appendix 6

MOU Between NOAA and WGA on Extreme Events

Memorandum of Understanding
Between the Western Governors' Association
and the National Oceanic and Atmospheric Administration

WESTERN GOVERNORS ASSOCIATION

Collaboration on Information Service Needs and State Capacity Building for Effective State Adaptation to Climate Variability and Change

June 30, 2011
Coeur d'Alene, Idaho

Background and Purpose

The National Oceanic and Atmospheric Administration (NOAA) and the members of the Western Governors' Association (WGA) (together, "the Parties") share a common goal to develop and use sound data and information related to climate variability and change to effectively manage natural resources and human infrastructure.

NOAA's mission is to provide the science, service, and stewardship needed to build healthy ecosystems, communities, and economies resilient in the face of climate variability and change. NOAA is working to organize its capabilities to best contribute to a coordinated federal approach to climate services, supporting effective preparation as climate varies and changes. NOAA also aims to partner with states, territories, tribes and local communities to develop strategies to communicate research results on climate impacts and improve the effectiveness of science to inform decision-making.

The WGA represents the Governors of 19 Western states and three U.S. Flag Pacific Islands. The Governors recognize the significant impacts of climate on our environment, infrastructure, economies and communities, and they are committed to developing better information and new management strategies to build a resilient West. In 2009, the Western Governors adopted policy resolution 09-2: *Supporting the Integration of Climate Adaptation Science in the West.* In 2010, the WGA Climate Adaptation Work Group released a report, *Climate Adaptation Priorities for Western States: A Scoping Report* (the Scoping Report). This report details the economic, social and environmental impacts anticipated from climate change and urges collaboration among all levels of government and between the scientific and management communities.

The purpose of this Memorandum of Understanding (MOU) is to improve the development, coordination and dissemination of climate information to support the adaptation priorities and resource management decisions of WGA members. This would include strengthening existing ties between science and decision-making regarding climate variability and change.

Objectives and Actions

1) The Parties will undertake an initial set of projects of immediate interest that will focus on options for incorporating information on climate extremes, variability and future trends at the appropriate scale in the following two areas:

a) Disaster risk reduction focusing on the impact of extreme events (e.g., droughts, floods, fires, hurricanes and tropical cyclones) on economies, communities, and ecosystems; and,

b) Improved science and climate information to support management of coastal, estuarine and marine resources important to achieving resilient communities and ecosystems.

The Parties will work together to understand and prioritize the climate information needed to address near term management challenges. This could include developing and delivering early warning or rapid response information to address these needs.

2) The Parties will assist one another in coordinating with other federal efforts that are also addressing climate information needs, services and adaptation strategies. These could include relevant Council on Environmental Quality (CEQ) task forces, U.S. Global Change Research Program (USGCRP) interagency coordination efforts, and various agency-specific efforts to link to the sectors of interest to the Western states and Pacific Island territories.

3) The Parties will also work with states and other agencies collectively or subregionally (e.g., West Coast states, Intermountain West states) to identify other key vulnerabilities or sectors that are affected by climate, such as forestry, agriculture, wildlife, biodiversity, and air quality. The Parties will consider how to meet information needs at the appropriate scales, and they will identify options to increase capacity to conduct planning and implement strategies to address these issues.

Implementation

The objectives and actions described above are consistent with the Scoping Report and NOAA's mission. The Parties will identify the appropriate staff from the states, territories and NOAA to execute the activities described above. The Parties will actively recruit other federal and non-federal partners to contribute to this effort, particularly with respect to identifying other key sectors that are being, or are projected to be, affected by climate change and the information and resources needed to prepare for climate variability and change.

When appropriate, specific projects or activities undertaken by the Parties under this MOU will be carried out pursuant to Implementing Agreements. Such Agreements will specify the responsibilities of the Parties, the expected resource commitments, legal authority citations, a description of any financial arrangements, programmatic points of contact, and other relevant information Other public and private partners may be included by the Parties in such Agreements, as appropriate.

Settlement of Disputes

Any dispute concerning interpretation or implementation of the MOU will be resolved through discussion by the Parties.

Effective Date, Duration, Amendment and Termination

This MOU will be effective on the last date appearing below and will remain in effect for three (3) years from that date.

This MOU may be amended by mutual consent of the Parties. The Parties may terminate this MOU upon mutual consent or by one Party providing the other Party ninety (90) days prior notice.

Agreed to this 30 day of June 2011,

C.L. "Butch" Otter
Governor of Idaho
WGA Chairman

Christine Gregoire
Governor of Washington
WGA Vice-Chair

Dr. Jane Lubchenco
Administrator
National Oceanic and Atmospheric Administration

NOAA-WGA MOU Page 3 of 3 *June 30, 2011*

Appendix 7

Resolution from the Western States Water Council to the Western Governors Association

RESOLUTION
of the
WESTERN STATES WATER COUNCIL
supporting
FEDERAL RESEARCH AND DEVELOPMENT OF UPDATED HYDROCLIMATE GUIDANCE FOR EXTREME METEOROLOGICAL EVENTS

Bend, Oregon
July 29, 2011

WHEREAS, Western states have recently been experiencing near-record flooding, droughts, or wildfires that threaten public safety, tax aging water infrastructure, and/or have significant economic consequences; and

WHEREAS, before the first half of 2011 was over, the year had already set records for extreme weather events, with the nation having experienced eight $1 billion-plus disasters, according to the National Oceanic and Atmospheric Administration (NOAA); and

WHEREAS, extreme weather events have grown more frequent in the U.S. since 1980, according to NOAA, and are believed to be caused by a changing climate; and

WHEREAS, the top twelve warmest years on record globally all have occurred since 1997, and climate change is expected to result in future increases in the frequency, extent, and/or severity of floods, coastal inundation, and droughts.

WHEREAS, some of NOAA's probable maximum precipitation estimates used by water agencies for dam safety 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 neither of these guidance documents address hydroclimate non-stationarity; and

WHEREAS, flood frequency analyses are used by public agencies at all levels of government to design and manage 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, a federal agency committee composed of the U.S. Army Corps of Engineers, U.S. Bureau of Reclamation, NOAA, U.S. Geological Survey, and U.S. Environmental Protection Agency held a 2010 national science workshop on non-stationarity, hydrologic frequency analysis, and water management, to identify information gaps and the state of the science for handling hydroclimate uncertainty; and

Position No. 332

WHEREAS, the Council co-sponsored a 2011 workshop on hydroclimate non-stationarity and extreme events, to identify actions that could be taken at planning to operational time scales to improve readiness for extreme events; and

WHEREAS, the federal and the Council workshops identified multiple approaches that could be employed at the planning time scale, including ensembles of global circulation models, paleoclimate analyses, and alternative techniques for flood frequency analysis; 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, the 2006 Western Governors' Association (WGA) report on *Water Needs and Strategies for a Sustainable Future* and the follow-up 2008 WGA *Next Steps* report identify addressing climate change impacts as a priority for moving forward, and make specific recommendations for actions that the federal government and the states should take to support adaptation, including detailing research and planning needs.

WHEREAS, WGA and NOAA signed a memorandum of understanding on June 30, 2011, regarding state adaptation to climate variability and change that focuses on climate extremes, variability and future trends as they relate to disaster risk reduction and improved science for coastal and marine resource management; and

WHEREAS, the Draft Vision and Strategic Framework for a Climate Service in NOAA includes changes in extremes of weather and climate as one of the four key societal challenges that will initially be a focus of the climate service.

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; and

BE IT FURTHER RESOLVED, that the Western States Water Council supports development of an improved observing system for Western extreme precipitation events, to aid in monitoring, prediction, and climate trend analysis associated with extreme weather events; and

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, paleoflood analysis, design of monitoring and change detection networks, and probabilistic outlooks of climate extremes.

BE IT FURTHER RESOLVED, that the Western States Water Council will work with NOAA in supporting efforts on climate extremes, variability, and future trends as called for in the WGA-NOAA memorandum of understanding.

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Appendix 8
Acronyms

AOR	Analysis of Record
AMO	Atlantic Multidecadal Oscillation
BC	Boundary Condition
CASA	Construcciones Aeronauticas SA
CBRFC	Colorado Basin River Forecast Center
CEQ	Council on Environmental Quality
CUAHSI	Consortium of Universities for Advancement of Hydrologic
COLA	Center for Ocean-Land-Atmosphere studies
CPO	Climate Program Office
DMIP	Distributed Model Intercomparison Project
EFREP	Enhanced Flood Response and Emergency Preparedness
EnKF	Ensemble Kalman Filter
ENSO	El Niño Southern Oscillation
ESM	Earth System Models
ESRL	Earth System Research Laboratory
GFDL	Geophysical Fluid Dynamics Laboratory
GFS	Global Forecast System
GPRA	Government Performance Results Act
HMT	Hydrometeorology Testbed
HP	Hourly Precipitation
HPC	High Performance Computing
IPCC	International Panel on Climate Change
IWRSS	Integrated Water Resources Science and Services
MJO	Madden-Julian Oscillation
MOU	Memorandum of Understanding
NAM	North American Mesoscale Model
NAO	North Atlantic Oscillation
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCDC	National Climatic Data Center
NCEP	National Centers for Environmental Prediction
NCEP EMC	National Centers for Environmental Prediction Environmental Modeling Center
NEMS	National Environmental Modeling System
NESDIS	National Environmental Satellite Data and Information Service
NESDIS STAR	National Environmental Satellite Data and Information Service Center for Satellite Applications and Research
NIDIS	National Integrated Drought Information System
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NOAA RC	National Oceanic and Atmospheric Administration Research Council
NWC	National Weather Center
NWP	Numerical Weather Prediction
NWS	National Weather Service
NWS CHIPS	National Weather Service
NWSRFS	National Weather Service River Forecast System
OAR	Oceanic and Atmospheric Research
OFS	Operational Forecast System
OHD	Office of Hydrological Development
PDO	Pacific Decadal Oscillation
PDSI	Palmer Drought Severity Index
PET	Potential Evapotranspiration
PNA	Pacific North America Pattern
PSD	Physical Sciences Division
PUC	Predictions Under Change
QPE	Quantitative Precipitation Estimation
QPF	Quantitative Precipitation Forecasting
RFC	River Forecast Center
RISA	Regional Integrated Sciences and Assessments
ROMS	Regional Ocean Modeling System
SM	Soil Moisture
STAR	Center for Satellite Applications and Research
USBR	US Bureau of Reclamation
USACE	US Army Corps of Engineers
USACE ERDC	Army Corps of Engineers -Engineer Research and Development Center
USGCRP	US Global Change Research Program
USGS	US Geological Survey
WGA	Western Governors Association
WRF	Weather Research and Forecasting
WSFO	Weather Service Forecast Office
WSWC	Western States Water Council
WUCA	Water Utility Climate Alliance