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A Vision for Future Observations for Western U.S. Extreme Precipitation and Flooding

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Abstract: Recent and historical events illustrate the vulnerabilities of the U.S. west to extremes in precipitation that result from a range of meteorological phenomena. This vision provides an approach to mitigating impacts of such weather and water extremes that is tailored to the unique meteorological conditions and user needs of the Western U.S. in the 21st Century. It includes observations for tracking, predicting, and managing the occurrence and impacts of major storms and is informed by a range of user-requirements, workshops, scientific advances, and technological demonstrations. The vision recommends innovations and enhancements to existing monitoring networks for rain, snow, snowmelt, flood, and their hydrometeorological precursor conditions, including radars to monitor winds aloft and precipitation, soil moisture sensors, stream gages, and SNOTEL enhancements, as well as entirely new observational tools. Key limitations include monitoring the fuel for heavy precipitation, storms over the eastern Pacific, precipitation distributions, and snow and soil moisture conditions. This article presents motivation and context, and describes key components, an implementation strategy, and expected benefits. This document supports a Resolution of the Western States Water Council for addressing extreme events.

Keywords: *Extreme events, observations, hydrometeorology*

The California Department of Water Resources, Western States Water Council (WSWC), and the Western Governors' Association (WGA) are currently collaborating to develop and, ultimately, implement a plan for a new generation of monitoring, forecasting, and decision support tools that will address ever-present, but growing, needs to better prepare for, and accommodate, extreme precipitation and flooding events across the Western United States. This effort is informed by a range of user-requirements workshops, scientific advances, and technological demonstrations over the last several years. Key elements of a vision for these improvements were prepared (at the WSWC's request) by the authors, and have been presented to the WSWC, which has approved a formal Resolution stating its official "position." The Resolution (the full resolution is available from WSWC and is reproduced in NOAA 2012a,b) states that recent advances in weather forecasting research, such as that of NOAA's Hydrometeorological Testbed program on West Coast atmospheric rivers (Ralph et al. 2005, 2013a), demonstrate the potential for improving extreme event forecasting at operational time scales. Benefits of advanced flood warning can be as much as a third of all residential damages, based largely on the ability to remove valuables from risk areas (Day et al. 1969). Additionally, as forecasts of extreme precipitation and runoff become accurate enough, they could enable forecast-informed reservoir operations that could yield increased water storage using existing flood control structures–offsetting some need for new storage facilities. This, of course, would require careful and comprehensive demonstration prior to implementation. Based on these advances and their potential benefits, the 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 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 for climate extremes.

The purpose here is to describe this vision of next generation observations that could aid in monitoring, prediction, and climate understanding associated with extreme weather events that affect either water supply or flooding in the semi-arid Western U.S. A primary motivation for such an advance is the stark fact that, during a 17-year period studied by Pielke et al. (2002), the Western States of WA, OR, CA, ID, NV, UT, AZ, MT, WY, CO, NM, ND, SD, NE, KS, OK, and TX experienced $24.7 billion in flood damages, an average of $1.5 billion annually. California, Washington, and Oregon alone accounted for $10.6 billion (46 percent) of this regional total (Downton and Pielke (2005) describes the accuracy of these loss data). In this context, there is a growing recognition that more needs to be done to provide: (1) necessary flood protection while ensuring adequate water supply in an environment characterized by extreme events, (2) improved warning lead times with quantified forecast uncertainties out to several days lead time that enable more confident actions by emergency preparedness officials, (3) the best possible observational and forecasting basis for addressing risks from aging flood control infrastructure (e.g., the Howard Hanson Dam crisis (White et al. 2012)) and aging levees in many settings (Florsheim and Dettinger 2007), and (4) better information for management actions to protect endangered species, such as salmon, aided by potential benefits to water supplies. At the extreme, the goal is to avoid, or reduce the impacts of, a "Katrina-of-the-West" scenario in which an extreme event disrupts or overwhelms existing operations or aging infrastructures catastrophically. Studies such as the ARkStorm scenario in California have identified this as a significant risk, with projected damages exceeding $500 billion (Porter et al. 2011). These challenges are only enhanced by the growing recognition of risks associated with the effects of climate change on the water cycle and atmospheric processes, which may include declining overall snowpack, shortening snow seasons with resulting extensions of interior flood seasons earlier into spring, possible expansion of the flood season on west coast to earlier in the fall or later into spring, increasing flood risk with warmer, and possibly more intense, storms, and increasing intensity, duration, or extent of drought.

The envisioned improvements would help reduce potential impacts of climate change by providing better information for developing adaptation strategies such as forecast-informed reservoir operations that can enable greater water supply while maintaining maximum flood control using existing structures

(Figure 1). Thus, responses to extreme events increasingly need to be weighed against the potential impacts of those responses on later water supplies, on fragile ecosystems and ecosystem services, on local to regional economies, and on positioning for accommodating subsequent floods and extremes and ultimately long-term climate changes.

At its core, the ability to meet many of these demands is restricted by two technical limitations: the short lead times over which current forecasts are accurate enough to support hard decision-making, and the fact that at least one key aspect of the extreme events in question–the transport of the water vapor that fuels the extremes–is woefully under-monitored. It used to be adequate to provide a few hours of lead time. Today, however, community leaders not only have to be prepared from a safety standpoint, but they need to be able to minimize the costs of taking preparedness actions (e.g. by shifting work schedules so that preparatory work can be done on regular time versus overtime). Increasingly, community leaders need lead times out to 7, 10, even 14 days. One crucial step necessary to provide these needed lead-time improvements is a better ability to track and predict the basic fuel of the extreme events being forecasted (i.e. the intense episodes of water-vapor transport into and through the region, whether by winter storm, upslope storms or summer monsoon). The good news is that new technologies, not available as recently as 5 to 10 years ago, are now available to improve our tracking and forecasts of these transports. Appropriate uses of these new technologies need to be conceptualized and integrated with existing observational networks to improve the value of the latter and to get the most informational improvements from the former. This paper represents our vision of new technologies to address the many and varied challenges listed above.

This requires innovative solutions that, in turn, will require a strong enterprise of monitoring, observation, modeling, science, and demonstrations. Solutions will depend upon better understanding, tracking, and prediction of the causes of extreme events, and how they might change in the future. Solutions will also depend on innovative engineering efforts to develop capabilities that can cost-effectively fill gaps in observations, forecasts, and related services that support vibrant economies, healthy ecosystems, and reliable water and living resources.

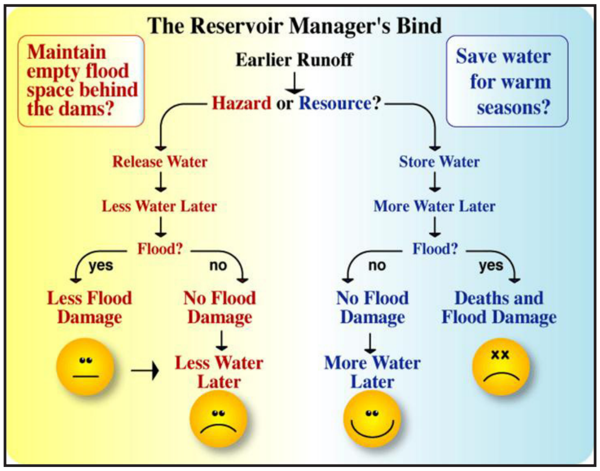

Figure 1. Schematic illustration of possible outcomes associated with early spring runoff depending upon whether the decision is made to release water to preserve flood control space for use in a potential late season flooding storm or to store water in expectation of summertime water-supply demands.

Extreme precipitation and flooding in Colorado's Front Range and in New Mexico in September 2013, catastrophic flooding in Spring 2011 on the upper Missouri River, major damage to a key flood control dam above Seattle in January 2009, the tragic loss of at least 36 lives in a major landslide in Washington State in March 2014 (immediately following a record-breaking drought in the region), and historic flooding events in California (e.g., 1969, 1986, 1997, 2005) illustrate the vulnerabilities of the west to extremes in precipitation. They also point to the urgency to explore and implement 21st Century capabilities.

The Context

Lessons learned from recent projects and requirements assessments

The main drivers for a future observing network are needs related to real-time monitoring, predictions (from minutes to days for flooding, and to seasons for water supply), research, and climate trend analysis. The network vision described here is informed by a broad set of recent user needs and requirements, documents, and demonstration studies (Table 1).

This paper takes advantage of a series of significant recent advances in observing system technology, research findings, experience gained by testing prototype observing systems in NOAA's

Table 1. Key reports, papers, and other sources used to inform the development of this Vision.

Source	Description and References
NRC reports	Flooding in Complex Terrain; Network of Networks; GPM Satellite system
Needs assessments	Reclamation and USACE (2011), USBR Science & Technology Program (2011), Climate change and water resources management- federal perspective (Brekke et al. 2009), USWRP Workshop (Ralph et al. 2005)
IWRSS	USACE, USGS, NOAA formal agreement and coordination; National Water Center
NOAA/HMT	10-year effort on extreme precipitation causes and predictions (Ralph et al. 2005; 2013a)
Atmospheric river research	Understanding of the joint roles of atmospheric rivers in extreme events and water supplies in the west (Dettinger et al. 2011)
ARkStorm	USGS-led emergency preparedness exercise in California focused on atmospheric rivers
NOAA/RISA	Regional Integrated Science and Assessment (RISA) studies on climate change
State Climatologists	Regional expertise and deep experience in states' needs for climate information
Unmanned Aircraft	NOAA UAS Program observing system gap analysis for atmospheric rivers over Pacific
NOAA Radars	Cross-NOAA Radar planning team reports
NOAA Science Plans	NOAA held interagency workshops on water cycle and climate science that produced detailed recommendations for future science directions nationally (NOAA 2012a, 2012b)

HMT (Ralph et al. 2003; White et al. 2012, 2013), the National Integrated Drought Information System (NIDIS), and the North American Monsoon Experiment (NAME; Higgins et al. 2006), as well as advances in numerical weather prediction, hydrologic forecasting, and real-time communications. Interagency needs assessments have also been produced that relate to these issues, including a report focused on extreme precipitation forecasting (Ralph et al. 2005), and more recently, a major report on dealing with issues related to quantifying extreme event probabilities (Workshop on Nonstationarity, Hydrologic Frequency Analysis, and Water Management; Olsen et al. 2010, http://www.cwi.colostate.edu/publications/is/109.pdf).

One broad conclusion of observing system research has been that monitoring of the atmospheric column, and not just the surface meteorology, and monitoring the atmosphere over the Pacific (where key weather features take shape before moving ashore) are vital to understanding and predicting precipitation intensity and form (rain/snow) in the western states (e.g., Ralph et al. 2013b).

Another vital requirement is that data from key elements of this network, especially those that provide observations aloft or offshore, need to be assimilated into numerical weather prediction models to reap maximum rewards. Existing models either already are able to assimilate key observations (e.g., wind profiler, GPS-met, and dropsonde data), or methods to assimilate other data can be developed. An example of a key recent finding (Doyle et al. 2014) is that a relatively small filament of water vapor in an atmospheric river over the Eastern Atlantic was critical to the development of strong European storms, and thus would be key to monitor offshore. Many direct uses of these same data exist even without this data assimilation, but maximum benefits will accrue from the combination of both the direct uses and model assimilation, as highlighted by forecast process evaluations (e.g., Morss and Ralph 2007) and emergency response experiences in the region (e.g., Ralph et al. 2003; White et al. 2012). A new tool, developed to monitor and predict the timing and intensity of landfalling atmospheric rivers (ARs) combines observations from an atmospheric river observatory (ARO; White et al. 2013) and a high-resolution numerical model (Neiman et al. 2009). These several findings are at the root of the vision presented here.

This vision was developed by a team of experts from federal, state, and local agencies, the academic community in hydrometeorology, hydrology, and climate, and representatives of some of the western water-related systems that require information on extreme precipitation, flooding, and water supply. Lessons learned from the recent flood control crisis in Washington State, where the flood protection from Howard Hanson Dam above Seattle was seriously compromised by seepage that developed after a record AR storm in January 2009, are incorporated (White et al. 2012). Similarly, experience from an emergency preparedness scenario named ARkStorm (Dettinger et al. 2012) that explored the potential impacts of a devastating series of atmospheric rivers hitting California, also informed this report. The ARkStorm exercise concluded that over $500 billion in economic impacts could occur from a single major storm sequence in California through damages, business disruption, and other dimensions, and that significant loss of life could occur (Porter et al. 2011). Historical flood damages provide much the same perspective.

This vision was developed within, and recognizing, the context of the following several recent and current efforts to enhance observing capacities and networks related to extreme precipitation events in the West.

Enhanced Flood Response and Emergency Preparedness (EFREP; led by California Department of Water Resources, NOAA and Scripps Institution of Oceanography; White et al. 2013, Ralph et al. 2013a): Development and deployment of statewide monitoring, modeling, and decision-support programs drawing from, and making operational, key findings from HMT-West, for better detection, monitoring, and prediction of ARs and their impacts. Key components are a "picket fence" of four coastal atmospheric river observatories, a statewide soil-moisture network, snow-level radars, and land-based monitoring of vertically integrated water vapor (IWV), with associated decision support capabilities. Out of a total of four "tiers" (i.e., levels of complexity, investment and protection), the ongoing implementation covers key elements of tiers 1 and 2 for California (93 field sites in all), and will be complete in 2015. A brochure from California Department of Water Resources is available online at: http://www.esrl.noaa.gov/psd/atmrivers/projects/pdf/Advanced%20Monitoring%20Network%20FloodER%20Prgrm.pdf. The lessons there apply directly to Washington and Oregon. The top two tiers, 3 and 4, are broader in scope and cost, with benefits stretching across much of the Western U.S., and are included in this white paper. Tier 3 focuses on vulnerable subregions or watersheds, while Tier 4 is offshore.

Deployment of a NEXRAD on the Washington Coast (led by NOAA/NWS): The Next-Generation Radar (NEXRAD) network consists of over 150 radars across the U.S. and territories. Recently a major gap in NEXRAD radar coverage off of the Washington coast has been identified and filled through installation of a NEXRAD radar on the Washington coast that became operational in 2011.

Addition of dual-polarimetric capability to NEXRAD (led by NOAA): Starting in 2011, NEXRAD radars have been upgraded to include dual polarization capability. Dual polarization offers several advantages compared to current single-polarization radar systems, providing additional information about the size, shape, and orientation of precipitation particles. This information can be used to more accurately identify the type of precipitation (e.g., hail vs. rain), correct for signal loss (attenuation) in heavy precipitation, and more easily identify and remove non-meteorological radar echoes. Dual polarization phase measurements allow for rainfall estimation that is much less affected by problems related to absolute calibration of the radar system, to signal attenuation effects, and to partial beam blocking.

Enhancements of the SNOTEL high altitude network (led by NRCS): This includes the addition of soil moisture at a number of SNOTEL sites, as well as selected other instrument upgrades.

Enhancement of the Climate Reference Network (USCRN) to include soil and humidity measurements (led by NOAA): Supported by the National Integrated Drought Information System (NIDIS), by September 2011, all 114 CRN locations had soil probes and associated data loggers and relative humidity instruments installed.

Deployment of Regional Climate Reference Network Pilot Network (USRCRN; led by NOAA): The USRCRN vision consists of about 430 new stations nationally that meet siting and instrumentation standards of CRN. (These sites do not include soil moisture or relative humidity sensors.) A pilot project was installed between

2009 to 2011 involving several dozen sites in the southwestern states in support of NIDIS. Expansion beyond the Southwest has been suspended. See http:www.ncdc.noaa.gov/crn/usrcrn/.

The Winter Storm Reconnaissance (WSR) Program (led by NOAA/NWS): Using NOAA's G-IV and military C-130s, for several years (ending in 2013) an annual monitoring effort was conducted for several weeks over the Pacific Ocean to improve forecasts across the US. However, analyses of the 2011 WSR observations showed minimal impact on forecasts across the U.S. (Hamill et al. 2013). This result contributed to the cancellation of the program in 2014, but also pointed out the potential that alternative sampling and assimilation strategies could have greater impact.

CalWater atmospheric river research flights with the NOAA G-IV aircraft (led by NOAA and Scripps): Following the cancellation of WSR 2014, and in response to planning for a major scientific field campaign off the West Coast in 2015 and potentially additional years ("CalWater" http://www.esrl.noaa.gov/psd/calwater/), the NOAA G-IV was deployed in February 2014 over the northeast Pacific Ocean to observe atmospheric rivers. New flight strategies were invented and demonstrated to measure atmospheric rivers, including their strength, position and presence of mesoscale frontal waves key to landfall predictions (Ralph et al. 2011). Twelve flights were completed, using 190 dropsondes over 3 weeks. It is envisioned that this demonstration could be expanded in future winters to include forecast improvement goals and validation strategies. Unlike the WSR, these flights would focus on atmospheric rivers, and their impacts on precipitation on the U.S. West Coast. The recent results of Doyle et al. (2014) showing model sensitivity to details within an atmospheric rivers suggest a promising avenue of study.

Testing of Unmanned Aircraft Systems (UAS) for offshore weather data collection: (led by NOAA, in close partnership with NASA). The "Winter Storms and Pacific Atmospheric Rivers" (WISPAR) experiment was conducted in early 2011 over the eastern Pacific Ocean. The ability of the unmanned NASA Global Hawk aircraft to carry a NOAA dropsonde system that directly measured atmospheric profiles in atmospheric rivers over the ocean was demonstrated. Flights were up to 25 hours long, and were coordinated with NOAA's G-IV reconnaissance aircraft, which also sampled an AR near Hawaii. The CalWater experiment has proposed using this aircraft to measure ARs over three to four winter seasons.

Water Management Context

Monitoring and observing systems covering all phases of the hydrologic cycle are fundamental to water management. The monitoring infrastructure historically used to support water management has been facing an array of challenges: inadequate federal funding to maintain and modernize basic networks such as USGS streamgages, USDA SNOTEL sites, or NWS cooperative observer weather stations; increased demands for better spatial coverage of observations; and needed upgrades to incorporate improvements in technologies. Emerging challenges such as climate change adaptation place additional demands on observational networks, requiring targeted monitoring to improve process understanding as well as to track expected impacts.

Water management in the West is particularly focused on managing for extremes –floods and droughts. The California Department of Water Resource's experience with the EFREP project led the California Department of Water Resources to recommend to the Western States Water Council that it support expansion of the observing system being developed for California into other states. The observing system vision provides a framework for modernizing existing networks as well as for improving understanding, monitoring, and forecasting of the extreme events that dominate operational water management. Preliminary research associated with scoping the observing system and improving understanding of extreme precipitation has also revealed some unanticipated findings. For example, since atmospheric rivers were determined to play such a dominant role in West Coast total annual precipitation, improving the ability to identify sub-seasonal to seasonal conditions favorable for atmospheric rivers could possibly inform drought prediction at these timescales. Serendipitous discoveries such as this illustrate the value of focused research to improve observations.

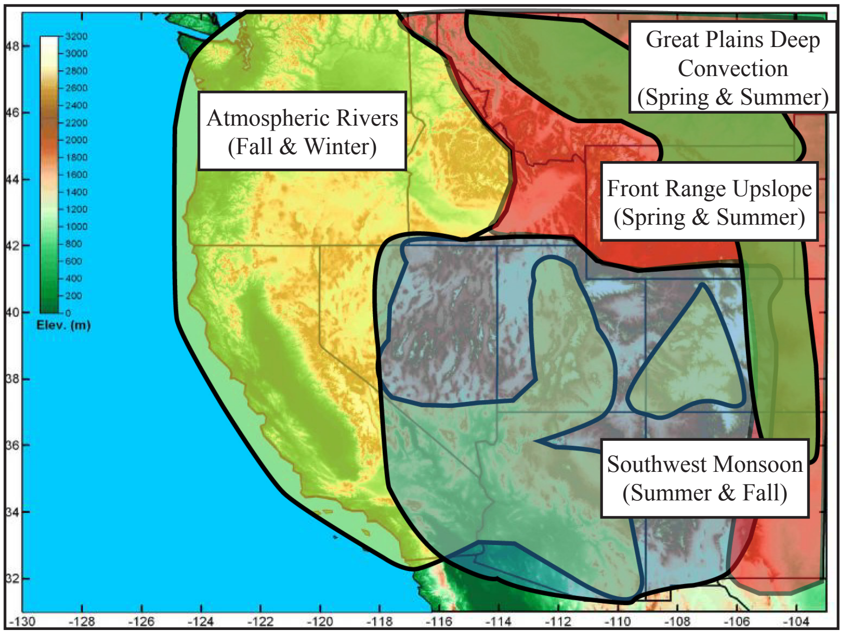

Figure 2. Schematic illustration of regional variations in the primary weather phenomena that lead to extreme precipitation and flooding and contribute to water supply in the Western U.S. This has been developed with input from experts on these phenomena who contributed directly to this document.

Meterological Context

Extreme precipitation is the primary cause of flooding and landslides in the region, and when these events occur in winter they can substantially increase snowpack and thus water supply. Another major cause of extreme runoff and flooding in some regions is snow melt in the spring and summer, which can be triggered by unusually warm and sunny conditions and warm, heavy rainfall.

The meteorological phenomena responsible for extreme precipitation varies across the region, as illustrated in Figure 2. Four primary precipitation-causing phenomena are highlighted here:

- Atmospheric rivers (cool-season storms that come ashore from the Pacific)
- Southwest monsoon (involving summer thunderstorms and remnant tropical storms)
- Great Plains convective storms, i.e., thunderstorms (in spring and summer)
- Upslope storms along the "front range" of the Rocky Mountains (spring and summer)

Although there is some overlap in the seasonality of these phenomena, they are relatively distinct, with hydrometeorologically significant ARs occurring primarily from October through March, spring upslope storms occurring from April to June (can also occur in late summer), the southwest monsoon being almost exclusively in July-October, and Great Plains deep convection from April to August.

The availability of COOP daily precipitation data from thousands of sites in the region, going back 30 years or more, helps to clarify the geographic domains for each of these phenomena. For each COOP site, the 10 historical days with the largest daily precipitation totals were identified (i.e., the top 10 out of roughly 10,000 dates or more days in a site's period of record). The season that had the largest number of these "top-10" extreme precipitation events at each COOP site was then plotted on a map (Figure 3a). While the seasonal and geographic boundaries can blur or overlap to a degree (as in Colorado), the overall patterns are clear enough to illustrate the regionally and seasonally varying causes of extreme precipitation across the West. Peak-streamflow dates (Figure 3b) help to corroborate these patterns. Recent studies of inland penetration of ARs (Rutz and Steenburg 2012; Neiman et al. 2013a; Rutz et al. 2014) has confirmed that such events can have impacts far inland (Figure 3a).

Challenges Associated with the Regional Geography

The geography of the west severely complicates both the monitoring and prediction of these extreme events, including weather and climate time scales, for several reasons. Many storms originate over the Pacific Ocean where there are major limitations in weather observations. For example, severely

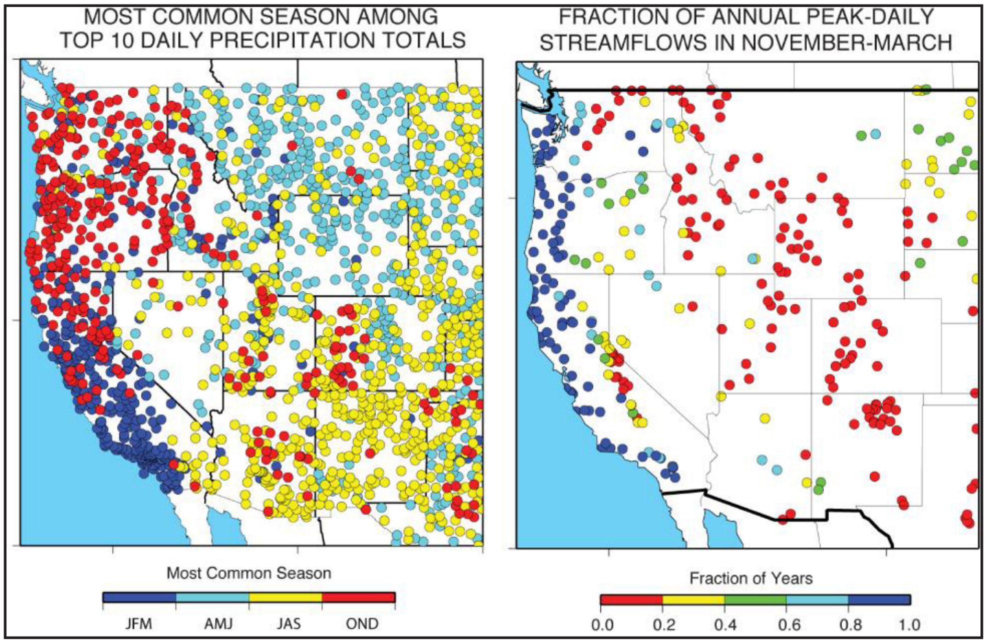

Figure 3. (a) Seasonality of extreme precipitation events across the Western U.S. based on daily precipitation totals from thousands of COOP observations (dots) covering at least 30 years each. The color of each site corresponds to the season of the year when more of the top-10 daily precipitation events occurred than any other season. (b) Seasonality of annual peak daily stream flows highlighting the geographic distributions of AR-, snowmelt, and monsoon dominated regions.

limited measurements of vertical profiles of winds, temperature and moisture in ARs and the larger-scale weather systems within which they are embedded. These limitations contribute to errors in the predicted position of land-fall of ARs of roughly 500 km at 5-days lead time (Wick et al. 2013). The presence of large, complex mountains creates large differences in weather conditions over short distances, making monitoring and forecasting much more challenging. Large areas of the mountainous west are uniquely vulnerable to future increases in flooding during extreme events because over half of the largest (historical) daily precipitation totals occurred when daily mean temperatures were between -3 and 0ºC, meaning that a warming of 3ºC would greatly exacerbate flooding (Bales et al. 2006). Much of the weather-observing infrastructure in place today is simply too sparse, outdated (e.g., most vertical profiling today depends on infrequent in-situ balloon measurements when higher observation frequencies are needed), or is not deployed in an optimal manner for western U.S. applications. For example, quantitative precipitation estimates (QPE) by NEXRAD scanning radars are hamstrung by their siting and scanning strategies, which often miss shallow rain or misinterpret virga aloft as rainfall at the surface, or use inappropriate drop-size distributions (Matrosov et al. 2014).

Selected Requirements

Based on the many user needs and requirements analyses noted earlier, as well as the broad experience of the coauthors of this paper, a list of key requirements is provided in Table 2. From a climate perspective, many of these requirements correspond with the information needs outlined in the Bureau of Reclamation's Science and Technology Program's climate change and variability priority area, specifically addressing the following needs (USBR 2011, section 5.A.2) on time scales of days to years:

- Improved use of existing-quality weather, climate, and hydrologic predictions in the development of operations outlooks (e.g., improved use of forecast uncertainty through novel methods or tool development);
- Development of superior-quality weather and climate and predictions relative to current information products from Reclamation's forecast providers;

Table 2. Key information requirements to support decision making related to extreme events in the water cycle.

Accurate Quantitative Precipitation Estimates (QPE) in complex terrain
Accurate Quantitative Precipitation Forecasts (QPF) for extreme events
Accurate hydrometeorological forcings for the next generation flood-forecasting and streamflow models, including soil moisture conditions, snow pack, existing stream flow, base flow, precipitation inputs, temperature, evapotranspiration, etc.
Atmospheric river landfall position, strength, orientation, timing and duration
Nowcasts and short-term QPF in urban areas for water, stormwater and sewage management
6-h forecasts of the end of heavy rain over key watersheds for reservoir operations
1-5 day guidance/forecasts of the location and intensity of extreme events to support future forecast-informed reservoir operations to optimize flood control and water supply
Better situational awareness to allow enough lead time with quantified forecast uncertainty to enable preemptive actions by emergency preparedness officials out to 10 days where feasible
Seasonal guidance of the potential for both flood risk and water supply that can enable decision makers to select optimal policy options
Accurate QPE and QPF for fire risk management and fire fighting
Short term (minutes to hours) forecasts of rain rates that initiate debris flows over burn scars and other lanslides
Increase in the use of GIS to pinpoint areas of concern to help local forecasters track events

- Enhanced communication of un-certainties and risks associated with weather and climate predictions in the development of Reclamation's operations outlook.

These requirements also reflect some of the goals and recommendations identified in NOAA's Water Cycle Science Challenge Interagency Workshop Report (NOAA 2012a):

- Increase hydrologic forecasting skill for low-to-high stream flow conditions to be as good as the skill afforded by weather and climate prediction.
- Improve representations, understanding and forecasting of hydrometeorological forcings to rival those of other non-water-cycle variables in the weather-climate system.
- Identify and diagnose physical processes key to extreme events (storms and floods) and document their roles in forecast errors.
- Explicitly characterize key uncertainties in climate and hydrologic models.

The Vision

Overview

This section outlines a strategy that would lead to a fully functional modern monitoring system optimized for the West (plausibly over a roughly six-year period). It would largely utilize existing organizations with the suitable expertise, infrastructure, and missions to perform the implementation, and then to carry on long-term operation, maintenance, and ongoing improvements. While many details remain to be worked out, in principle, capabilities (i.e., knowledge, skills, tools) currently exist to execute this strategy if adequate funding becomes available. The vision is an expert opinion on what can be done to address these major societal challenges based on existing and emerging technologies and techniques.

The observational tools and related efforts are based on several key inputs: 1) a set of requirements (often overlapping or complementary to one another) associated with detecting the phenomena that cause extreme precipitation as well as predicting them hours to days beforehand and monitoring signatures of climate change; 2) progress in atmospheric and hydrologic numerical modeling, and need for high resolution observations and predictions of key hydrometeorological conditions that drive them; 3) several years of testing and prototyping of new tools and methods in HMT and other experimental settings and campaigns, such as CalWater and the Yosemite High-Altitude Hydroclimate Network, that have provided many lessons about what works, does not work, and how

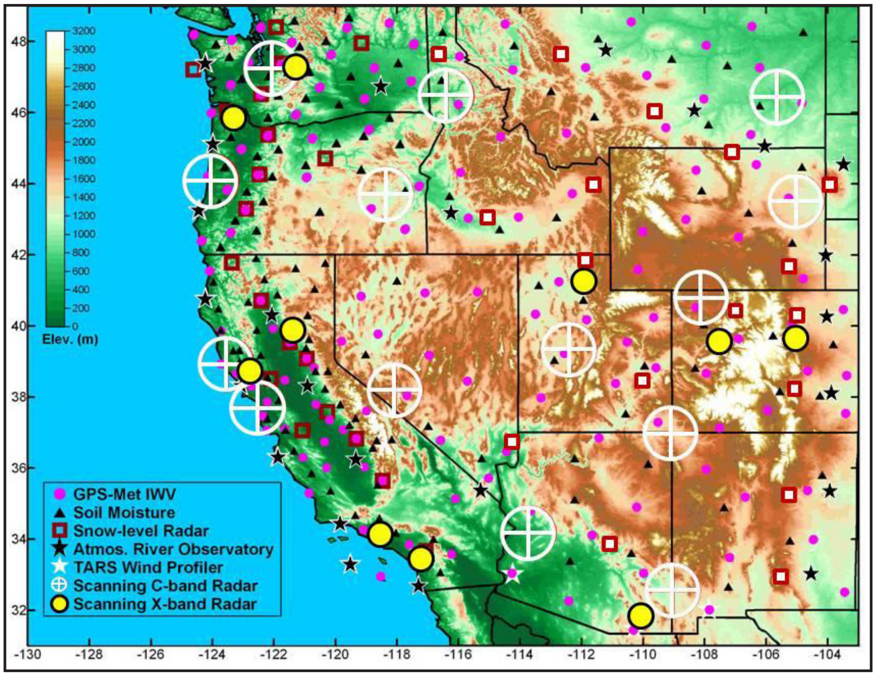

Figure 4. Schematic network of new sensors (land-based) to improve monitoring, prediction, and climate trend detection for hydrometeorological conditions that create extreme precipitation and flooding.

much effort is involved; and 4) the emergence of new observational technologies, information systems, real-time and reliable communication from remote sites, and better understanding of the storms themselves.

The vision consists of:

- A broad land-based network (Figure 4) customized to monitor conditions in the extreme precipitation regimes identified in Figure 2, with observations focused on water vapor content and its transport, QPE, snow level, soil moisture, and dust and rain-on-snow effects. A key strategy is monitoring conditions aloft, below roughly 3 km altitude. This is the layer most difficult to observe using satellite or scanning radars, and yet is where some of the most important meteorological conditions, in terms of extreme precipitation, reside. It is where most of the water vapor and clouds are concentrated, where airflows interact with terrain, and where the atmospheric "boundary layer" conditions set the stage for heavy precipitation.
- Enhancements to the mostly already existing observing network in the mountains (Figure 5), focused on snowmelt preconditioning, including snow density and albedo observations.
- Offshore monitoring, with an emphasis on AR conditions (including frontal waves influencing AR durations and intensities at landfall) and assimilation of data into weather models from the critical upwind region over the eastern Pacific from which most western storms approach. States and communities need time to prepare, to minimize the impact of preparations and recovery from major storms in any ways they can. Offshore monitoring can provide lead time before storms and flooding. This need not be a perfect forecast but a heads up that a big storm is coming with key characteristics of the storm (e.g., cold, wet, windy, once in 10 year event, or a normal winter storm).

The land-based network (Figures 4 and 5) described here would ideally include (see details online):

- 100 new low-mid altitude soil moisture observing sites
- 125 existing high-altitude sites with new snow-related data
- 100 new GPS-met observing sites
- 25 snow-level radars
- 25 wind profiling/ARO sites
- 14 C-band scanning radars
- 10 X-band scanning radars or mini CASA networks

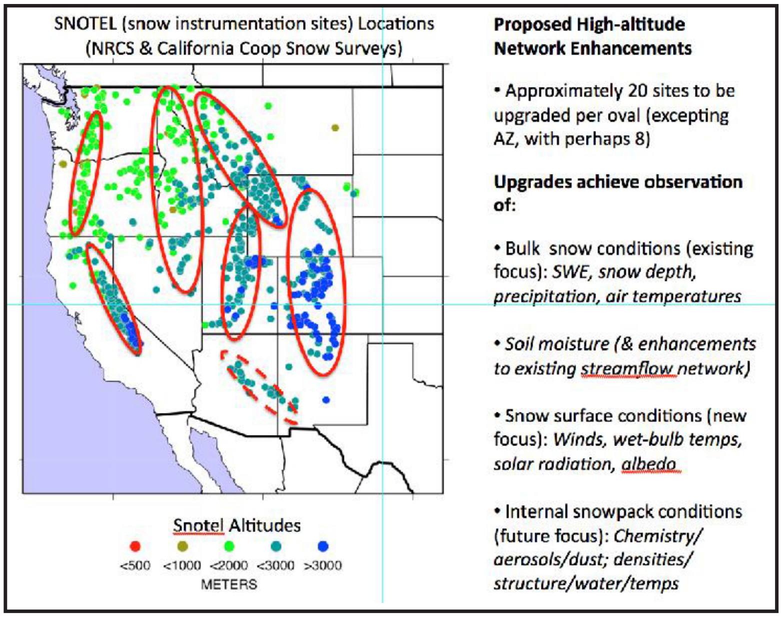

Figure 5. Existing SNOTEL sites color coded to their altitude range. Red ovals highlight regions where a subset of the existing SNOTEL sites would have additional sensors emplaced to support better spring snow melt monitoring and prediction, or where new sites would be needed to broaden the altitude range of coverage.

Overarching Gap: Monitoring Water Vapor Transport – The Fuel for Precipitation

An overarching gap in observations associated with extreme precipitation events is monitoring of water vapor transport (i.e., the "fuel" for the precipitation). Existing observations typically do not measure winds and water vapor aloft except in a handful of locations twice per day using balloon soundings, and yet these are the key variables that determine the water vapor transports that fuels precipitation. A major component of the observing system that is proposed here is based on filling this gap, and designed in many settings on the specific characteristics of ARs that are most important to severe storms and that have now been well documented, including their width, depth, snow level, water vapor transport and orientation. It has recently been shown that 75 percent of the variance in storm-total rainfall at the coast in ARs is explained by variance in storm-total upslope water vapor transport, and that more than 60 percent of the variance in storm-total streamflow was explained by this flux (Ralph et al. 2013b). In addition, it has been shown that the direction of the low-altitude wind in ARs has a major controlling effect on exactly which watersheds will receive the greatest rainfall in a given event (Ralph et al. 2003; Neiman et al. 2011). The orientation of the winds in the AR creates rain shadows that can shelter some regions from the heaviest rainfall. In the case, where the "dividing streamline" crossed the Santa Cruz Mountains, Ralph et al. (2003) showed that it separated flood-producing rain to its west from weak rain to its east that did not create flooding. Recently, studies of the inland penetration of ARs to the Sierras and the intermountain west have highlighted the role of ARs in focusing water vapor transport into these regions (Rutz and Steenburgh 2012; Rutz et al. 2014) and the role of the Sierra Barrier Jet in modulating this (Hughes et al. 2012; Neiman et al. 2013b).

Based on a decade of development at NOAA and in HMT, a method has been invented that deploys a wind profiling radar, GPS met receiver, snow-level radar, and surface data to monitor AR conditions aloft on an hourly basis. This is called an atmospheric river observatory (ARO; White et al. 2013). Because an average AR is about 400 km wide, the optimal horizontal spacing of AROs is 200 km. Four atmospheric river observatories (AROs) are now being deployed along the California coast as part of its EFREP program and the technique was part of NOAA's rapid response to the Howard Hanson Dam crisis (White et al. 2012). Three additional sites along the Oregon and Washington coasts are slated for future deployment supporting multiple applications including wind energy. Ideally, ARO data are shown in combination with output from a high-resolution numerical weather prediction model tailored to the AR phenomenon.

The present vision involves completing a west coast array of AROs to observe water vapor transport from over the Pacific Ocean in ARs, along with a few more AROs farther inland to monitor water vapor transports through preferred pathways into the intermountain west. Similar instrumental arrays (called TARS) already exist along the border with Mexico, to support drug interdiction efforts by providing wind profile information aloft for operation of tethered balloons carrying surveillance radars to detect low-flying aircraft. The present plan would develop tools to take advantage of this border array to help monitor water vapor influx into the Southwest from the South, especially as part of the summer monsoon, which derives its moisture through transport from either Mexico or the Gulf of Mexico. The plan also applies this technology along a line roughly 100 km east of the Front Range of the Rockies to monitor water vapor influxes from the Great Plains towards the Rockies in upslope storms (such as the record flooding of September 2013 along the Colorado Front Range), and would be coupled with snow-level radars in the foothills to monitor, in real time, the fraction of vulnerable watersheds that would be exposed to rain versus snow. This fraction, a critical factor determining the mix of flooding versus snowpack water storage from any given storm, could be a key issue in spring 2014 from Montana and Wyoming to Colorado, where snowpack is greater than 150 percent and people are bracing for spring floods. Because water vapor transport from north to south across the Canadian border tends to be very weak (due to the prevalence of dry cold continental air there), no such array is proposed for that area.

Phenomenological and Regional Requirements and Relevant Observations

This section summarizes specific observational enhancements addressing gaps related to the phenomena primarily responsible for extreme precipitation and streamflow.

Broad Area Coverage Components: (addressing all four meteorological phenomena that cause extreme precipitation, plus spring and summer rapid snowmelt). These represent low-cost sensors that would benefit most of the Western U.S: soil moisture, GPS met for IWV, "bulk" snow measurements (depth, SWE, precipitation), air-snow interface (snow albedo, wind, dew point temperature, solar radiation), snowpack internal conditions (e.g., chemistry of dust, snow densities), and additional stream gages.

Atmospheric River-focused Components. Another element of the network emphasizes horizontal water vapor transport in ARs, along with snow level monitoring and enhanced QPE through gap-filling scanning radars over major urban areas. The design also requires offshore monitoring to extend the range of predictions out to several days. Sensors include atmospheric river observatories (ARO) in the AR-impacted regions, snow level radars, scanning polarimetric radars over major cities (e.g., Seattle, Bay Area, Vegas), and offshore monitoring, including frontal waves that affect ARs (coastal scanning radars C-band, aircraft, buoy-mounted wind profilers, all taking advantage of satellites).

Monsoon-Focused Components. As indicated in Figure 2, the southwestern U.S., including Arizona, Nevada, Utah, Colorado, and New Mexico, are impacted by the precipitation associated with the North American Monsoon (NAM). In particular, parts of southern Arizona and New Mexico receive over 50 percent of their annual precipitation during the NAM season (Douglas et al. 1993; Adams and Comrie 1997). The key gaps for monsoon monitoring include both water vapor transport from Mexico or the Gulf of Mexico, plus scanning radars to fill very large gaps in current radar coverage. Sensors include ARO-like installations, but focused on Monsoon-related water vapor transport and taking advantage of the existing TARS profiler network, and gap-filling scanning radars with polarimetric capability over major urban areas.

Great Plains Convection Components. The Great Plains have one of the best existing radar networks for monitoring broad area storms (although gaps for monitoring tornadoes and severe thunderstorms remain). The present vision emphasizes water vapor distribution and transport, as well as soil moisture and recommends gap filling polarimetric radars in flood-prone, front-range watersheds and an enhanced lightning network.

Front Range Upslope Storms. Upslope storms primarily occur along the east slopes of the Rocky Mountains, extending from Montana to New

Mexico (Figure 2). These storms usually consist of a 200 to 300 km wide area of easterly or northeasterly winds north of a cold front and surface low pressure system. The passage of the cold front is often complicated by local terrain, and uncertainties regarding the specific location of the low pressure center development typically confounds forecasts. The monitoring system thus emphasizes monitoring these features and the conditions that modulate them, with a network of 449 MHz wind profilers 100 km east of the foothills to monitor cold fronts and upslope winds, plus another array of 915 MHz wind profilers 10 km east of the base of the foothills to monitor both barrier jet winds and snow level (449 HMz profilers are more expensive, but can see much higher into the atmosphere than 915 MHz systems), and snow level radars at the base of the foothills as an alternative to the wind profilers.

Snow Melt. As shown in Figure 3b, spring melt creates most of the highest flows on many rivers, especially in the intermountain region. Thus special emphasis is given here to snowmelt conditions. Most of the proposed actions for this purpose require new sensors at high altitudes, but could also include sensors at altitudes where cold storms deposit snow that can contribute to flooding in somewhat rare events. The most effective approach would leverage the existing SNOTEL network, which already targets regions of significant snowpack, and has infrastructure that could facilitate deployment of new tools. Some of this is already happening within the NRCS, and with California's EFREP, in terms of adding soil moisture measurements to some sites. Figure 5 highlights the locations where system enhancements are recommended, and lists the key sensors that would be used. Future remote sensing capabilities, such as JPL's Airborne Snow Observatory (ASO) provide additional opportunities to monitor snow water equivalent and albedo (Painter et al. 2013).

Some Excluded Elements

While additional NEXRAD systems have potential uses here the NEXRAD network is optimized more for Great Plains convection and detection of tornadoes and hail. For example, the NEXRADs do not scan at elevation angles below 0.5 degrees above the horizon. In the west, where radars are commonly positioned in areas of high terrain to reduce blockage, the ability of the radar to observe at or below the horizon is critical for accurate QPE. Moreover, the NEXRAD network is already far more dense in the Great Plains than over the mountainous part of the west and individual new NEXRAD radars are prohibitively expensive relative to the scope of this vision.

Also, although new satellite techniques (i.e., new sensors or next generation satellites) hold potential to support the objectives of this white paper, their costs are beyond the scope of what is being considered here for regional applications. Nonetheless, the proposed network will integrate with existing and future radar and satellite observations, e.g., by using existing satellite sensors and NEXRAD data in new ways. For example, a) passive microwave and GPS occultation satellite observations are crucial over the ocean for AR monitoring; however, the passive microwave method does not work over land. A land-based, GPS-met land-based network is proposed here specifically to help fill this gap. Also, no satellite methods currently monitor AR winds and water vapor transports aloft over the oceans or land, so airborne reconnaissance is proposed here to fill this gap. Finally, some key satellite footprints or spatial resolutions are simply too coarse to resolve conditions associated with the especially complex terrain of the west.

Additional Actions Related to Achieving the Objectives of this Vision. Performance measurements should be developed that focus specifically on extreme precipitation events, and others that represent snow-level and soil moisture forecast performance. Create a scale for assessing the strength of ARs offshore (e.g., compare water vapor transport in an AR to the average flow of the Mississippi River; as in "this AR transports in one day an amount of water as vapor similar to what 7 to 15 Mississippi Rivers transport in one day as liquid). Create a simple scale for communicating and comparing magnitudes of extreme precipitation and stream flow over land (e.g., a 3-day precipitation scaling; Ralph and Dettinger 2012). Develop predictive modeling and decision support tools and systems to optimize use of the data. Use new GIS-based tools for information management, display and dissemination. Ensure that data from key elements of this network, especially those that provide observations aloft or offshore, are assimilated into operational weather prediction models. Note that models either are already able to assimilate many of the observations (e.g., wind profiler, GPS-met and dropsondes data) proposed here when and if they are made, and that methods to assimilate other data types could be developed. Sustaining the western observing network requires a stronger collaboration across agencies.

Transition to Operations

This new observational network would be established in the midst of significant new capabilities in the nation's water resources science and services, which would facilitate the operational transition and increase the operational impacts of these new information streams. This section discusses this operational framework as well as related existing infrastructure and alternative strategies.

The Integrated Water Resources Science and Services (IWRSS). IWRSS is a new multi-agency framework to meet the nation's growing water resource challenges. In May 2011, the National Oceanic and Atmospheric Administration, the US Army Corps of Engineers, and the US Geological Survey signed a memorandum of understanding establishing IWRSS. Through IWRSS, these agencies will engage in collaborative science and develop services and tools to support integrated and adaptive water resources management. IWRSS consortium members will operate within a common operating picture, employing shared modeling and information services frameworks, allowing their individual decision support systems to work in concert towards meeting the water challenges faced by our Nation. IWRSS considers a broad range of time scales – from historical "analyses of record" through forecasts and projections spanning weather and climate. A key element of the IWRSS strategy is a series of regional watershed demonstrations (or pilots), including one recently identified in the region, i.e., California's Russian River. More information on IWRSS is available at: http://www.nohrsc.noaa.gov/~cline/IWRSS/IWRSS_ROADMAP_v1.0.pdf.

The National Water Center (NWC). NWC is housed in a new NOAA facility constructed in Tuscaloosa, Alabama and will serve as a focal point for IWRSS developments and NOAA's water resource information services. The NWC will provide capabilities to integrate the new observations discussed herein, through assimilation into the IWRSS forcing data engine and operational modeling framework, and by integrating them into a data model that supports both NWS operations, as well as those of the IWRSS consortium. The NWC then becomes a vehicle for widespread dissemination and application to operational centers and stakeholders and customers of water resource information.

NCEP/WFOs. The IWRSS/NWC will complement and enhance the NWS's long-established framework for disseminating weather and water information, forecasts and warnings. The NOAA National Centers for Environmental Prediction (NCEP) provide 24x7x365 large scale modeling forecasts and guidance. This information supports a network of 122 Weather Forecast Offices (WFOs) and 13 River Forecast Centers (RFCs), that serve as focal points of local expertise and knowledge, as well as for engagement with local communities and stakeholders. These data will feed into WFOs, supporting their role in issuance of local watches and warnings.

NCEP leads NOAA's assimilation of observations into operational numerical models, including wind profiler and dropsondes data from aircraft. NOAA's Global Systems Division innovates on assimilating observations from many sources in high resolution models. The existing capabilities in these arenas will be utilized, including use of current assimilation methods and development of new ones.

Additional operational strategies. Outside of the relatively traditional approaches outlined above, many observing networks have been developed, deployed and operated under a diverse array of strategies that differ from the large federal approach, and they had large impact on a diverse array of information users using alternative strategies. These include State Departments of Transportation, individual water system operators, agricultural services and many others. Transitioning of new observations, such as those identified in this vision, into "operations" could very well take place in this alternative manner. The emergence of Testbeds linking weather research to forecasting operations over the last 10 to 15 years has illustrated many possibilities in this regard (Ralph et al. 2013a). Regional Centers, local agencies, state agencies, universities and other groups represent a versatile pool of knowhow that can support the transfer of information from this network, or sub-elements of it, into targeted applications, and can develop new methods in a highly adaptable manner.

Comments on Implementation

Laying out a specific set of strategies for implementation is beyond the scope of this report; however, some comments on broad strategies are feasible. The costs to operate, maintain and optimize the network can be reduced considerably by deploying automated monitoring systems and methods for monitoring performance, diagnosing faults, emphasizing reliability during critical meteorological conditions, training local "hosts" who can perform less technical tasks (e.g., restarting a computer), depending upon existing sensor network communications and quality control tools (such as MADIS - http://madis.noaa.gov/ and MESOWEST - http://mesowest.utah.edu/index.html), maintaining a small, technical and engineering staff that can be on call to perform repairs, and using methods developed partly in HMT for maintaining regional networks in a cost-effective manner. The envisioned network is also structured to also take advantage of existing, underutilized networks, such as the TARS profiler network along the southern border with Mexico, pre-existing GPS sensors currently deployed for seismic monitoring, and extensive existing SNOTEL and streamgage networks, and provides resources to ensure key stream gauges are supported long-term. Experiences gained in various projects, e.g., California's EFREP network (White et al. 2013) and NOAA's aircraft reconnaissance experience, provide a basis for a rough order of magnitude cost estimate in the range of $200 million, spread over several years, followed by an O&M "tail" of roughly $30 million per year.

Anticipated Outcomes

Based on past experience with major new observational infrastructure (e.g., NEXRAD, satellites, EFREP, and HMT-West), the time frame for implementation is roughly 5 to 10 years. During this time the methods and tools to use the new data would also be enhanced, and benefits would begin to accrue. This is not a "quick fix." It is a thorough, scientifically based, interagency-requirements-driven strategy to modernize the region's observational infrastructure for dealing with the extremes of too much, or too little water. This 21st century observing system for the West will meet many of the 21st Century needs for solid, real-time information based on up-to-date science, to support decisions affecting millions of people, innumerable businesses and the environment of the west.

Benefits will include:

- Mitigating risks of greater than $100 billion Katrina-like disasters on the U.S. West coast (see NRC reports from before Katrina and ARkStorm activities since then);
- Reducing flood risks and damages through development of modern decision support tools that allow for pre-storm releases from flood control reservoirs that are refilled by the storm, thereby also enhancing water supply for the summer;
- Enabling forecast-informed reservoir operations for combined benefits of improved flood control and enhanced water supplies, possibly offsetting some requirements for new reservoir space being considered in the west, resulting in billions of dollars in savings;
- Improving drought monitoring and associated benefits in support of NIDIS;
- Improving capacity for early detection of climate change impacts on water supply and flooding in the west to inform adaptation and mitigation strategies optimized for regional impacts and needs;
- Tighter collaborations across federal, state, and local agencies to assure effective implementation into existing water information and management systems;
- Strengthening of science and technology job sectors in the region.

From a policy perspective, it is perhaps most notable that improved water-year-type forecasts in California alone have estimated values that could exceed $100 million in a single year (Simpson et al. 2004). In terms of flood risks, enhanced preparedness for flooding events that mitigates loss of life and property for flooding–the phenomena that is responsible for the greatest impacts as defined through Presidential disaster declarations (e.g., average flood losses in the region are $1.5 billion per year)–is a primary strategy for controlling and reducing those risks. With improved monitoring, forecasts and longer lead times, community leaders will be better able to prepare for extreme events, not only from a safety standpoint, but to minimize the costs of taking preparedness actions (e.g., by shifting work schedules so that preparatory work can be done on regular time versus overtime).

This vision describes an approach to dealing with extreme events in a way that is tailored to the unique meteorological conditions and user needs of the Western U.S.

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