Potential to Improve Forecasts and Reservoir Operations with a 21st Century Observing Network

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BIOGRAPHICAL SKETCH

Mr. David Reynolds retired from the National Weather Service in 2012. He held the position of Meteorologist-in-Charge of the National Weather Service (NWS) San Francisco Bay Area Forecast Office from June 2002 to December 2012. Prior to assuming this position he was Chief of Operations of the Hydrometeorological Prediction Center (HPC), one of the service centers of the National Centers of Environmental Prediction in Washington DC. His primary interest is in Quantitative Precipitation Forecasting and in climate change impacts in California.

Mr. Reynolds received a B.S. in Atmospheric Science from the University of California, Davis in 1971, and a M.S. in Atmospheric Science from Colorado State University (CSU) in 1973. He was accepted into the Doctoral Program at CSU in 1982 and completed a year of post-graduate studies. Mr. Reynolds was a Research Assistant Professor at CSU from 1973 to 1980, Chief of the Alaska Avalanche and Fire Weather Forecast Center from 1980 to 1981, a team leader with what is now the NOAA Global Systems Division from 1981 to 1983. He was Site Director of the U. S. Bureau of Reclamation's Sierra Cooperative Pilot Project from 1983 until 1988. This cloud seeding research program studied the feasibility of augmenting the snow pack in the central Sierra Nevada. Based on this research, Mr. Reynolds worked for California's Department of Water Resources from 1988 until 1994 to design, implement, and conduct a snow augmentation program for the Feather River above Oroville Reservoir in northern California.

In 2011 Mr. Reynolds was named a Fellow of the American Meteorological Society. He also received in 1997 the National Oceanic and Atmospheric Administration's Administrator Award. He was the recipient of a Department of Commerce group Gold Medal -- the Department's highest honorary award -- for HPD's excellent rainfall forecasts associated with Hurricane Floyd. He also received three NOAA group Bronze Medals associated with his participation in the restructuring of the NWS's quantitative precipitation forecasting process and developing a decision support tool for monitoring Atmospheric Rivers.

ABSTRACT

In 2008, the California Department of Water Resources (CA-DWR) signed a five-year agreement with NOAA's Earth System Research Laboratory (ESRL). The joint project between CA-DWR, ESRL, and the Scripps Institute for Oceanography is part of CA-DWR's Enhanced Flood Response and Emergency Preparedness (EFREP) Program. The underlying goal of the joint project is to improve precipitation monitoring and prediction, especially for extreme events. The statewide deployment of observing systems and suite of highly detailed weather forecast models builds on NOAA's Hydrometeorology Testbed (HMT) project carried out in the North Fork of the American River.

During northern hemisphere winters, the western coast of North America is battered by land-falling storms. The impact of these storms is a paramount concern to California, where water supply and flood protection infrastructure is being challenged by the effects of age, increased standards for urban flood protection, and projected climate change impacts. In addition, there is a built-in conflict between providing flood protection and the other functions of major water storage facilities in California: water supply, water quality, hydropower generation, water temperature and flow for at-risk species, and recreation. In order to improve reservoir management and meet the increasing demands on water, improved forecasts of precipitation,
especially during extreme weather events, will be required. The following observing networks are being installed throughout California to improve short term forecasts of extreme events.

Water vapor fuels precipitation, and GPS technology provides a viable method of measuring the vertically integrated water vapor (IWV). HMT is partnering with UNAVCO, the operators of the Plate Boundary Observatory, where many GPS receivers already exist for geodetic purposes, to provide IWV measurements from 45 locations in or near California. The snow level is important with respect to flooding in mountainous watersheds because it determines the surface area throughout the watershed that is exposed to snow versus rain. ESRL engineers have invented a new compact radar designed to measure the snow level at a much reduced cost compared to other radars used for this purpose. These “snow-level radars” are being installed in ten key watersheds across California.

A major finding from HMT is the role that atmospheric rivers, narrow regions of enhanced water-vapor transport, have in creating heavy precipitation that can lead to flooding. A picket fence of atmospheric river observatories (AROs) is being deployed along the California coast. The AROs provide critical information on water vapor transport aloft and the snow level. Antecedent soil moisture can determine whether a storm produces a flood, so soil moisture sensors with other associated meteorological equipment are being placed at 43 new sites across California.

Taking full advantage of the new measurements requires a complementary effort in data assimilation and weather forecast modeling. Decision support tools also are being developed to integrate the new information provided by the observations and models into flood forecasts and water management decisions. This talk will review the current status of the observation installation and discuss how these observations will improve rainfall and runoff forecasts for improved reservoir operations.
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Outline

• What are the ingredients that produce an extreme rainfall event
• Forecasting extreme rainfall events –
• Observing systems required to produce accurate rainfall forecast
• Assimilating these new observations into numerical models
• How these requirements and gaps have been met by HMT-West in California
  – 21st Century ground-based observing network
Extreme Rain Event

- What are the ingredients?
  - Good source of moisture
  - Warmer the air the deeper the moisture
    - Impacts from warming globe....
  - Something to lift the moisture to produce clouds
  - Mechanism to convert cloud drops to rain

- The longer these conditions/processes coexist and remain over a given location the more rain will fall.
- The wetter the ground the more runoff
- Forecast challenge is to observe, identify, quantify, and then extrapolate in space and time
Predict the Extreme Event

- Need to observe and quantify the moisture content of the atmosphere
- Need to observe the depth of the atmosphere below the freezing level – where the action is
- Need to observe the upper and lower-level winds to determine where air is rising and how fast
- Need to determine the dominate mechanism producing rainfall – liquid only or mixed liquid and ice – a challenge for current numerical models
- Observe any phenomena that will slow or stall these processes over a given location for an extended period
A tiered approach for new obs to help address CA’s water resource issues

**Tier I:** Address well-defined needs with proven technology
Ex: Soil moisture sensors at CIMIS sites, GPS receivers of opportunity, snow-level radars

**Tier II:** Expand on well-defined needs with proven technology
Ex: Wind profilers, Coastal Atmospheric river observatory

**Tier III:** Newer technology
Ex: Gap-filling radars, Buoy-mounted WPs

**IV:** Off-shore recon.

(NOAA, DWR)
Temporal and Spatial Scales of Meteorological Phenomena

Instrument Function

- **Land-based GPS sensor** – measure the fuel (water vapor content) carried by the winds as the storm makes landfall.

- **Wind Profilers** – measure the rate at which the fuel is being supplied to generate heavy rain (fuel rate)

- **Snow level radar (S-band profilers)** – measure the depth of the atmosphere warmer than freezing. Deeper this layer more moisture is available and the higher the elevation snow will fall in the mtns. Higher snow level more runoff will occur.

- **Soil Moisture Sensor** - measure the moisture content of the soil and calibrate that to field capacity to determine runoff potential.
Atmospheric rivers - Our Hurricanes: Two recent examples that produced extreme rainfall and flooding

These color images represent satellite observations of atmospheric water vapor over the oceans.

Warm colors = moist air
Cool colors = dry air

ARs can be detected with these data due to their distinctive spatial pattern.

BUT NO DATA OVER LAND!!

In the top panel, the AR hit central California and produced 18 inches of rain in 24 hours. In the bottom panel, the AR hit the Pacific Northwest and stalled, creating over 25 inches of rain in 3 days.

From Ralph et al. 2011, Mon. Wea. Rev.
Tier 1: GPS receivers of opportunity

- NSF/UNAVCO Plate Boundary Observatory (PBO) network of GPS receivers for primarily geodetic applications

- Installing surface temperature and pressure sensors at existing GPS receiver sites will allow the network to map out the horizontal distribution of vertically integrated water vapor (IWV)

- Energy industry (electricity distribution) benefits because GPS receivers are used by Space Weather Center to monitor geomagnetic storms
As of June 2013: 95% complete
Water vapor observations onshore fills gap in satellite observations

2 Dec 2012

Satellite observations of water vapor offshore

New GPS-Met network

Example and satellite image courtesy of Marty Ralph and Gary Wick (NOAA/ESRL/PSD)
Google Map IWV from GPS Met Stations

Water vapor observations onshore fills gap in satellite observations
LAPS (Local Analysis and Prediction System) IPW Hourly Initialization Using Satellite and GPS Met
### HMT Snow Level Research Results

**Winters 2002-2003:**
West Coast WFO, RFC usage of wind profiler data products


**Forecast Freezing Level - Radar-Derived Freezing Level (Thousands of Feet)**

- Forecast Lower than Observations
- Forecast Higher than Observations

**White et al. 2010**

**NWS RFS**
Snow-17
SAC-SMA

**24-h QPF = 4 in.**

**Forecast Freezing Level - Radar-Derived Freezing Level (Thousands of Feet)**
Tier 1: Snow level radars

- Provides proxy snow-level height during precipitation events
- Utilizes proven FMCW technology to substantially lower cost
- Uses the patented ESRL automated snow-level detection algorithm proven in nationwide field experiments
- Less than 8’ diameter footprint
- Low-power requiring minimal infrastructure
~21 kt motion allows 3 to 10 hrs lead time of front and cessation of heavy rain
Snow level was 8000-9000 ft initially. Sugar Pine Dam received 5 inches of rain in 27 hours.
Folsom Inflow

FOLSOM LAKE (FOL)

Date from 03/15/2011 10:51 through 03/17/2011 10:51 Duration: 2 days

Max of period: (03/16/2011 07:00, 51680.04) Min of period: (03/15/2011 15:00, 13701.34)

CFS

15-Mar, 12:00 16-Mar, 00:00 16-Mar, 12:00 17-Mar, 00:00

RESERVOIR INFLOW - CFS (594)
As of June 2013: 90% complete
- The Russian River was impacted by three separate precipitation events within a five-day period in late Nov. to early Dec. 2012.
- Peaks in Russian River stream flow were observed each time the observed precipitation rate and amount kept the 10 cm soil at field capacity for a period longer than 3 h.
- The 15,000 cfs flow peak that occurred early on 3 Dec. was 0.42 m below flood stage for this location.
As of June 2013: 20% complete
When atmospheric rivers strike coastal mountains (Ralph et al. 2003)

- Details (e.g., wind direction) of the atmospheric river determine which watersheds flood
Atmospheric River Observatories to Fill Largest Single Monitoring Gap
Prototype forecast tool tested at 3 CA couplets during NOAA's HMTs

0030Z 5-Jan-08: Intense western U.S. storm

Couplet
North: Bodega Bay (BBY; 12 m MSL)
Central: Piedras Blancas (PPB; 11 m MSL)
South: Goleta (GLA; 3 m MSL)

Coast (profiler, GPS, rain gauge):
Mountains (rain gauge):
Cazadero (CZD; 475 m MSL)
Three Peaks (TPK; 1021 m MSL)
San Marcos Pass (SMC; 701 m MSL)
AR Propagation: \(\sim12 \text{ m s}^{-1}\).

\(\frac{1}{2}\)-day lead time for SoCal
ESRL's Real-time Upslope Water Vapor Flux Tool Display

2009 NOAA Bronze Medal awarded to OAR/NWS team “for innovative contributions to the development of the Coastal Atmospheric River Monitoring and Early Warning System [i.e., upslope water vapor flux tool].”
Key conditions during 91 ARs observed at the Earth’s surface and aloft north of San Francisco, WY2005-2010

The following attributes characterize the 10 longest-duration ARs, which produced the most extreme rainfall and streamflow:
- AR conditions persisted for > 31 h
- Coastal rainfall averaged 144 mm during AR conditions
- Wind direction between 180° to 240° at about 1 km MSL
- Storm-total Bulk Upslope IWV flux was > 1000 units
- Precursor soil moisture was > 36%
- Heavy rain was in DJF and transition seasons (SON, MAM)
- Extreme runoff was in December, January, February (DJF)

From Ralph et al. 2013 J. Hydrometeor.
91 AR events observed over 6 years

(a) CZD rainfall vs BBY upslope IWV flux; $R^2 = 0.7453$

Storm-total rainfall at CZD (mm)

Storm-total upslope water vapor flux at BBY (cm m/s)
91 AR events observed over 6 years

(a) CZD rainfall vs BBY upslope IWV flux; $R^2 = 0.7453$

AR duration (hours)
- 8-15
- 16-23
- 24-31
- > 31

(b) Austin Creek stream volume vs BBY upslope IWV flux; $R^2 = 0.6162$

Soil moisture (%) before AR event
- < 20
- 20-30
- 30-40
- > 40
With western WA terrain orientation, wind direction plays a key role in determining which watershed will be prone to flooding.
HHD Meteorological Observing Enhancements for 2009-10 Winter

Prime range of low-level wind directions in ARs for Green River flooding

Raingauge Network Enhancements

Westport ARO

Spanaway ARO Couplet

Ravensdale ARO Couplet
(Top) Histogram of how many times a product from one of the ARO deployments was accessed on the internet by a staff member from the Seattle Weather Forecast Office each day.

(Bottom) Histogram of daily precipitation measured at Westport, WA, the location of the coastal ARO.
Weather forecast applications for which ARO data products were quoted in 59 individual Area Forecast Discussions issued by the Seattle Weather Forecast Office.
Quotes from Larry Schick, Meteorologist with the USACE in Seattle

- Re: Jan 2010 AR event in Western WA: “We were right on the edge of taking over Wynoochee Dam today for flood control, but we had high confidence we didn’t need to with the AR Observatory info that the rain would taper off quickly – and it did.”

- Re: Jan 2012 storms in Western WA: “Yesterday, I used the new coastal radar and ARO in tandem to refine the forecast and give our dam regulator engineers critical forecast information… Of course, I was monitoring local WFO Seattle NWS forecasts and NWRFC as well and they were right on, but the ARO does allow a strong confirmation for making these rapidly changing but important dam operational decisions.”
HMT-Legacy Project is deploying a 21st-century observing system to bear on the State of CA's water resource and flood protection issues.
Weather Forecast Models

• **Operational Numerical Models**
  – Global Models – hours to two weeks – resolve phenomena down to 20 – 30 km - provide boundary conditions for:
  – Regional Models- 1 hour to 3 days – resolve phenomena down to 3- 12 km – used most for rainfall forecasts in west

• **Models require 3-D observations of the atmosphere.**
  – Ground based balloon-borne and remote vertical soundings and remote satellite observations over oceans – Global Data Assimilation System
  – LAPS – Local Analysis and Prediction System – uses local observations such as GPS, radar, wind profilers, soil moisture to improve model initial state

• **HMT WRF** – Uses LAPS and run in ensemble mode –
  • Will be used to test impact of these additional observations on precipitation forecasts
  • Observations will be used to validate model physics and tune model for regional phenomena – warm rain process
Benefit of Expanded Observation Networks Recent Past and Near Future

- Allowed us to begin a climate record of land-falling AR magnitude, duration, relationship to flooding, seasonality.
- Allowed us to define the spatial and temporal resolution needed to monitor extreme rainfall events.
- Allowed us to define the critical observations that we need to properly model extreme events - gaps.
- Test beds have provided the scientific credibility needed to bridge the research to operations gap - Sustainability – not just a research project...
- Expand capability to all areas in the west.
HMT-West
Meeting Requirements

• Leveraging existing networks
• Developing new ones
• Transitioning to operations with stakeholder support
• Providing the foundation for improved reservoir operations
Coauthors M. Ralph and A. White win 2013 CA-DWR Climate Science Service Award

"DWR is pleased to acknowledge the exemplary assistance that these scientists have provided to us, and we look forward to a productive long-term working relationship in improving the ability to understand, monitor, and forecast extreme precipitation in California", said DWR Director Mark Cowin. "This cooperative research effort between the National Oceanic and Atmospheric Administration (NOAA) and DWR has provided tremendous information about atmospheric river storms and their role in flood events and contribution to the state's water supply."

Photo credits: DWR
Thank You

- HMT web page
  - http://hmt.noaa.gov

- Atmospheric Rivers Information Page
  - http://www.esrl.noaa.gov/psd/atmrivers/

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