ASO in Colorado:
supporting resilient water management through research support & emerging partnerships

Jeffrey S. Deems
Airborne Snow Observatory
Western Water Assessment
National Snow and Ice Data Center
University of Colorado

NASA AIRBORNE SNOW OBSERVATORY
Measuring Spatial Distribution of Snow Water Equivalent and Snow Albedo
Motivation: forecast & management challenges
ASO overview & highlights
ASO projects & partnerships in Colorado
  • Uncompahgre
  • Rio Grande
  • Upper Gunnison
  • Blue River
  • NASA SnowEx
Future outlook...
CO Collaborators & Partners

NASA/JPL Airborne Snow Observatory
CWCB – Joe Busto
RGRB Division 3
  Craig Cotten
UGBWCD – Frank Kugel
NCAR
  Dave Gochis
  Logan Karsten
DOE/LBNL
East River Watershed Function
Scientific Focus Area
  Ken Williams
  Rosemary Carroll
Denver Water – Nathan Elder

Upper Gunnison River
WATER CONSERVANCY DISTRICT

University of Colorado Boulder
NCAR
WESTERN WATER ASSESSMENT
A NOAA RISA TEAM
Some motivation…

Rio Grande @ Del Norte
June Forecast & measured Apr-Sept Volumes

- Over-forecast means risk of late season compact shortage
- Under-forecast means junior users are curtailed

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>WY 2005</td>
<td>795,000</td>
<td>683,000</td>
<td>+112,000 (16%)</td>
</tr>
<tr>
<td>WY 2006</td>
<td>350,000</td>
<td>412,000</td>
<td>-62,000 (15%)</td>
</tr>
<tr>
<td>WY 2007</td>
<td>450,000</td>
<td>593,000</td>
<td>-143,000 (24%)</td>
</tr>
<tr>
<td>WY 2008</td>
<td>655,000</td>
<td>623,000</td>
<td>+32,000 (5%)</td>
</tr>
<tr>
<td>WY 2009</td>
<td>490,000</td>
<td>513,000</td>
<td>-23,000 (5%)</td>
</tr>
<tr>
<td>WY 2010</td>
<td>485,000</td>
<td>455,000</td>
<td>+30,000 (6%)</td>
</tr>
<tr>
<td>WY 2011</td>
<td>435,000</td>
<td>415,000</td>
<td>+20,000 (5%)</td>
</tr>
<tr>
<td>WY 2012</td>
<td>352,000</td>
<td>328,000</td>
<td>+24,000 (7%)</td>
</tr>
<tr>
<td>WY 2013</td>
<td>230,000</td>
<td>344,000</td>
<td>-114,000 (50%)</td>
</tr>
<tr>
<td>WY 2014</td>
<td>420,000</td>
<td>519,000</td>
<td>-99,000 (24%)</td>
</tr>
<tr>
<td>WY 2015</td>
<td>385,000</td>
<td>555,700</td>
<td>-170,700 (31%)</td>
</tr>
<tr>
<td>WY 2016</td>
<td>475,000</td>
<td>566,000</td>
<td>-91,000 (16%)</td>
</tr>
<tr>
<td>WY 2017</td>
<td>535,000</td>
<td>574,000</td>
<td>-39,000 (7%)</td>
</tr>
</tbody>
</table>

Data courtesy Craig Cotten, CO DWR Division Engineer, Division 3
Operational forecasts are vulnerable to unusual conditions...

...and conditions are changing

Statistical streamflow forecast (e.g. USDA NRCS)
- Regression relates spring SWE to spring/summer flows

Temperature index runoff forecast (e.g. NOAA CBRFC)
- Calibrated air temperature/snowmelt relationship

Snow water resources & forecasts are affected by:
- Warming temperatures
- Snow season duration
- Rain/snow fraction
- Mid-winter melt
- Rain-on-snow
- Forest change
- Dust on snow

* Period-of-record-based methods assume calibrations apply to current conditions

* Stationarity is dead!
How do we add resilience to forecast models?

- Decrease reliance on historic record
- Improve model realism
- Increase availability/use of spatial data
  - Satellite
  - Airborne
  - Mesoscale weather model output

Snow accumulation patterns drive melt volume & timing
- distribution of SWE determines melt & runoff patterns

Solar radiation controls snowmelt
- net solar driven by snow albedo

* These factors can be monitored operationally with remote sensing
Pathfinder: The JPL Airborne Snow Observatory

Snow Water Equivalent
- Riegl Q1560 Lidar
- Up to 800 kHz Pulse Rate
- 2 lasers with fore/aft pointing

Snow Albedo
- CASI-1500 Spectrometer
- 0.35-1.05 μm
- 2m spatial resolution from 4000m

- Map surface elevations: snow-free & snow-on
- Difference gives snow depth
- SWE variation primarily due to depth
- SWE from assimilation of modeled density
- Constrained by observations
- Spectrometer maps albedo
Snow depth & SWE from lidar

• Majority of SWE spatial variability due to snow depth
• Depth can be measured by differential elevation mapping
  • collect snow-free & snow-covered data sets
  • classify & remove vegetation points
  • subtract snow-free from snow-covered
• Apply obs/modeled density
  • SWE = depth * density

Lidar-derived snow depth, Colorado (Deems et al., 2013)
Snow albedo from hyperspectral imagery

Reflectance (%) vs Wavelength (μm)

Visible Near IR

- Clean Snow
- Dirty Snow
The NASA Airborne Snow Observatory

basin-wide snow inventory enables responsive water management

Example:
Tuolumne River, CA

- utility to reservoir operations shown over wide range of runoff year types
- ASO SWE is a very strong predictor of total reservoir inflow

Snow Water Equivalent
Tuolumne Basin
Apr 26, 2016

Hetch Hetchy Inflows

2014 Hetch Hetchy Observed & Forecasted

ASO SWE + 0.28 * Accumulated Precipitation to July 1 (TAF)

2013 2014 2015 2016 2017

Courtesy Dr. Chris Graham, Hetch Hetchy Water & Power
California overview

CA work to-date
- Initiated 2013
- Weekly/monthly flights in 6 primary southern basins
- Daily snow model output in Tuolumne, San Joaquin

Future plans
- Continue monitoring in southern & central Sierra
- Add northern Sierra basins
- Regular full-Sierra coverage within 5 years
- Data integration with FERIX & CDEC
- USFS collaboration for forest health inventory

“What you’ve done is created new reservoir space and water supply without any impacts to the current physical or environmental paradigms.”

“Having used this technology, it is hard to imagine a future without it.”

Wes Monier, Chief Hydrologist, Turlock Irrigation District

Dave Rizzardo, Chief of Snow Surveys and Water Supply Forecasting, Department of Water Resources
Colorado activities

**Uncompahgre above Ridgway**
- 1-4 Melt season flights since 2013 (NASA Terrestrial Hydrology)

**Rio Grande & Conejos Rivers**
- 2 melt season flights 2015, 2016 (CWCB)
- 1 flight 2017

**Grand Mesa & Senator Beck Basin**
- Multiple high-resolution flights Feb 2017 (NASA SnowEx Campaign)

**Upper Gunnison River**
- Upper East River 2016 (DOE WFSFA)
- Spring 2018: East R. abv Cement Cr., Upper Taylor, Upper Ohio (CWCB)
Rio Grande Basin Forecasting Project

Coordinated projects to improve quantitative runoff forecasts in the Upper Rio Grande Basin

- Enhanced ground observations
- NSSL mobile weather radar
- ASO mapping: 2014/15
- NCAR WRF-HYDRO data assimilation & forecasting

Monitoring & simulation of snow accumulation & melt

- Filling in the gaps between SNOTEL stations
- Improved snowpack & runoff modeling

ASO SWE improves WRF-Hydro simulations
Conejos River
“Miracle May” 2015

- ASO flights:
  - 6 April
  - 2 June
- SNOTELs recorded almost no new snow in that period
- Snow area decreased dramatically
- SWE decreased ~10%

SWE difference: -6.5 kAf
Upper Gunnison project

- CWCB $$ support
- Collaboration with:
  - UGRWCD
  - DOE WFSFA
  - NCAR WRF-HYDRO forecasting project
- Snow-on flights
  - 1 Spring 2016 (East R.)
  - 2 Spring 2018 (East/Ohio/Taylor)
- Snow-off flight Fall 2018
- Planning 2 snow-on flights in melt season 2019
  - Likely 2 accumulation season flights with NASA SnowEx support
2018 results

1st Survey: March 30 - Apr 1
2nd Survey: May 24 & 25
Snow-free survey: Sept 8

Field validation campaigns
- SWE, depth, density
- Snow chemistry samples

I April Snow Depth
RMSE: 16cm

[Graph showing 1 April Snow Depth with RMSE: 16cm]
## 2016 SWE & forecast volumes

<table>
<thead>
<tr>
<th>East R. @ Almont</th>
<th>1 Apr</th>
<th>1 May</th>
<th>1 Jun</th>
</tr>
</thead>
<tbody>
<tr>
<td>Runoff Forecast (kAf)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CBRFC</td>
<td>128</td>
<td>130</td>
<td>141</td>
</tr>
<tr>
<td>NRCS</td>
<td>139</td>
<td>165</td>
<td>163</td>
</tr>
<tr>
<td>ASO SWE (kAf)</td>
<td>121</td>
<td>(157)</td>
<td></td>
</tr>
<tr>
<td>(*not incl. Brush, Cement creeks)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Accumulated streamflow after this date (kAf)

- 154
- 138
- 96

---

Between snowpack & gage:
- Additional snow or rain
- Flow in channel/groundwater
- Consumptive use
- Snowpack sublimation
- Evaporation & transpiration
- Soil infiltration
- Deep groundwater infiltration
2018 SWE & forecast volumes

<table>
<thead>
<tr>
<th>East R. @ Almont</th>
<th>1 Apr</th>
<th>1 May</th>
<th>1 Jun</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apr-Jul 50% Runoff Forecast (kAf)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CBRFC</td>
<td>108</td>
<td>107</td>
<td>95</td>
</tr>
<tr>
<td>NRCS</td>
<td>93</td>
<td>101</td>
<td>91</td>
</tr>
<tr>
<td>ASO SWE (kAf)</td>
<td>136</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>1 Apr &amp; 24 May</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accumulated streamflow after this date (kAf)</td>
<td>78</td>
<td>67</td>
<td>40</td>
</tr>
</tbody>
</table>

Between snowpack & gage:
- Additional snow or rain
- Flow in channel/groundwater
- Consumptive use
- Snowpack sublimation
- Evaporation & transpiration
- Soil infiltration
- Deep groundwater infiltration
DOE LBNL East River Project

Watershed Function Scientific Focus Area

10-year project led by Lawrence Berkeley National Lab

Grand Challenge Question:

How do mountainous watersheds retain & release water, nutrients, carbon & metals over episodic to decadal timeframes?

Supporting Science Questions address:

- perturbations to individual watershed subsystems
- early snowmelt &/or drought impacts on subsystem connectivity
- fine-scale process representation improvements to prediction of watershed hydrology & biogeochemistry
- impacts of water flow & nutrient transport perturbations on metals release from mining-impacted systems
- opportunities to improve operational forecasting predictions of water quantity & quality in response to watershed perturbations

http://watershed.lbl.gov/
Upcoming 2018 & 2019 ASO Colorado plans

- 2 Gunnison flights
  - Spring 2019:
    - Peak SWE
    - Mid-melt
- NASA SnowEx activity in Gunnison in 2019
  - Winter season ASO flights
  - Other airborne data sets
  - More extensive field measurements
  - Possibly Grand Mesa & Senator Beck Basin as well
- Blue River Basin - proposed
  - Denver Water collaboration
Blue River Basin  
*Denver Water*

- Disturbances & changing conditions highlight need for improved snow monitoring
- 4 SNOTEL sites
  - 10500 - 11400’

Proposed ASO project

- Use existing snow-free lidar dataset initially
- Exploring options for flight(s) in 2019:
  - 2 flights
    (Peak SWE, mid-melt)
  - Bi-weekly peak – melt
SnowEx: a Multi-Sensor Airborne Snow Campaign

Key Questions:

- What is the **global distribution** of SWE, & snow energy balance, in a variety of land covers & canopy types & densities?
- What are the **sensitivity** & **accuracy** of remote sensing techniques to measure SWE across a variety of snow conditions & confounding factors?
- What is the best **combination** (multi-sensors & with models) of sensing methods to measure SWE globally?

Year 1 (2017): Test & develop snow remote sensing techniques & models in forested environments
  - 3 week-long campaigns @ Grand Mesa & Senator Beck

Year 3 (2019): Observe midlatitude mountain snowpacks in time series over accumulation & melt seasons
  - ASO lidar & spectrometer; UAVSAR L-band radar; others
  - Operations/research collaboration
Future opportunities

- Explore water balance
  *especially 2018
- Add to time series in Gunnison
- Integrate existing data with forecast efforts
  - CBRFC (CRCHWG supported)
  - NWM/WRF-Hydro
- Identify other priority basins in CO

Leverage high-precision, spatial snowpack knowledge to improve water resource inventory & management