Snow-related Measurements in Operational Streamflow Forecasting at NOAA/CBRFC

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Colorado Basin River Forecast Center
Salt Lake City, UT

Western Water Assessment
Snowpack Monitoring Workshop

Landen, WY

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NWS RFCs

NOAA/National Weather Service River Forecast Centers (RFCs)

Operational streamflow forecasts across the United States

WY is covered by three RFCs:
• CBRFC (Salt Lake City, UT)
  ➢ 35% of RFC forecast points in WY
• MBRFC (Pleasant Hill, MO)
  ➢ 55% of RFC forecast points in WY
• NWRFC (Portland, OR)
  ➢ 10% of RFC forecast points in WY

Forecast types:
• short-term streamflow, out 5-10 days
• seasonal runoff volume
• seasonal peak streamflow (NW and CB only)

www.cbrfc.noaa.gov
www.weather.gov/mbrfc/
www.nwrfc.noaa.gov/rfc/
Colorado Basin River Forecast Center (CBRFC)

Hydrologic regimes:
• snow-dominated to flash flood hydrology
• natural to regulated

500+ streamflow forecast points across 7 states

~1150 modeling units (snow and soil moisture model run on each)

Stakeholders dependent upon snowmelt-driven streamflow forecasts:
• NWS Weather Forecast Offices
• US Bureau of Reclamation
• water conservation districts
• municipalities
• recreational community
• others
Importance of Snow Info

Snow (especially water equivalent) = primary predictor of seasonal runoff volume

Recent years’ snowpack - extremes in both directions
→ mostly dry (🙁)
→ sometimes, wet (generally 😊)
→ variability in “dust on snow”

“Dust on snow” images for 2005 (light dust) and 2009 (heavy dust)

Precip type = primarily snow
• 60-80% of precipitation shows up as SWE

<table>
<thead>
<tr>
<th>SNOTEL site</th>
<th>Precip through April 30, on average (inches)</th>
<th>May 1 SWE, on average (inches)</th>
<th>SWE/precip (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loomis Park (NWS id: LOPW4)</td>
<td>18.8</td>
<td>11.3</td>
<td>60%</td>
</tr>
<tr>
<td>Gros Ventre Summit (NWS id: GRVW4)</td>
<td>14.5</td>
<td>12.3</td>
<td>85%</td>
</tr>
</tbody>
</table>
Importance of Snow Info

Additional datasets and information about snowpack conditions assist CBRFC hydrologists with more informed forecasting decisions.

Expanding CBRFC’s use of snow-related measurements is key.

Past (through 2009):
Surface-based networks (SNOTEL) only, SNOTEL sites w/ < 30 year period of record

Past (through 2010-2012):
Surface-based networks (SNOTEL) only, ** most SNOTEL now w/ 30 yr period of record **

Present and into the future (2013 to present):
Surface-based networks (SNOTEL, CSAS field obs) + Remote sensing (MODIS, VIIRS, ASO) = More complete set of snowpack observations

Note: Remote sensing datasets are NOT intended to replace surface-based observations in CBRFC modeling and forecasting but rather to complement surface-based observations.
Operational CBRFC Modeling

→ each watershed is sliced & diced into multiple areas
→ modeling units = elevation bands or zones
→ snow and soil moisture models are run daily for each “zone”

EXAMPLE: Green River headwaters in WY (NWS ID = WBRW4)

<table>
<thead>
<tr>
<th>Elevation Zone</th>
<th>Mean Elevation (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WBRW4HUF (Upper)</td>
<td>11054</td>
</tr>
<tr>
<td>WBRW4HMF (Middle)</td>
<td>9140</td>
</tr>
<tr>
<td>WBRW4HLF (Lower)</td>
<td>8005</td>
</tr>
</tbody>
</table>
NRCS’s SNOTEL network = primary source of surface-based snowpack information for CBRFC

- 1st-of-month SWE data - statistical modeling for runoff volume forecasts
- SNOTEL precipitation data:
  - Real-time hourly – initially build the simulated snowpack in SNOW17
  - QC’d monthly values – “update” the snowpack simulated by SNOW17

Additional surface based info: field observations from the Center for Snow and Avalanche Studies/Colorado Dust-on-Snow Program

Photo (right): Clean snow over a dust layer, April 2014.

Courtesy Center for Snow and Avalanche Studies, Colorado Dust-on-Snow Program, Silverton, CO

Map: NRCS SNOTEL network for CBRFC AOR
Surface Measurements: SNOTEL SWE

SNOTEL SWE: used on the 1st of the month for water supply forecasting

Quantitative use:
as a predictor in statistical regression models

Qualitative use:
forecaster awareness of general snowpack conditions (above/below average, median, determine analog years, etc.)
Surface Measurements: SNOTEL Precip

SNOTEL Precipitation Uses:

• **real-time precipitation** - build the SNOW17-simulated snowpack in the deterministic CBRFC hydro model (run daily)
  
  ➢ **Note**: SNOW17 builds snowpack w/ precip data, **not SWE data**

• **monthly precipitation** – “update” the SNOW17-simulated snowpack

• **seasonal accumulated precipitation** – statistical models for water supply forecasting
Building the simulated snowpack with real-time SNOTEL precipitation

**SNOTEL Stations Used to Compute MAP Value**

<table>
<thead>
<tr>
<th>Elevation Zone</th>
<th>SNOTEL Stations Used to Compute MAP Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>WBRW4HUF (Upper)</td>
<td>LTWW4 (Little Warm) LOPW4 (Loomis Park)</td>
</tr>
<tr>
<td>WBRW4HMF (Middle)</td>
<td>LTWW4 (Little Warm) LOPW4 (Loomis Park)</td>
</tr>
<tr>
<td>WBRW4HLF (Lower)</td>
<td>KNDW4 (Kendall R.S.) LOPW4 (Loomis Park) GRVW4 (Gros Ventre Summit)</td>
</tr>
</tbody>
</table>

SNOW17 adds MAP as snow to simulated SWE (or types precip as rain)
Surface Measurements:
SNOTEL Precip

Building and updating the SNOW17-simulated snowpack

Daily model runs use real-time, hourly data – jumpy, can add uncertainty to sim. snowpack

So, when QC’d monthly precip obs become available, use those to “update” model SWE.

Example Update Date = Feb 10

accumulated full month MAPs (derived from QC’d monthly SNOTEL precip)

+ accumulated MAPs for any partial months (derived from real time SNOTEL precip)

= “updated” precipitation accumulation (using Feb 10 as an example)

Model is then run forward in time with the new, “updated” estimate of SWE accumulation.
### Remotely-sensed snow data used by CBRFC:

<table>
<thead>
<tr>
<th>Snowpack Characteristic</th>
<th>Instrument</th>
<th>Algorithm</th>
<th>CBRFC Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>fractional snow-covered area</td>
<td>MODIS</td>
<td>MODSCAG (provided by NASA/JPL)</td>
<td>adjust SNOW17 model SWE as snowpack dwindles</td>
</tr>
<tr>
<td>(fSCA)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>dust-on-snow</td>
<td>MODIS</td>
<td>MODDRFS (provided by NASA/JPL)</td>
<td>used to adjust melt rates in SNOW17</td>
</tr>
<tr>
<td></td>
<td></td>
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</table>

- Data are available across all of WY (global datasets) – JPL, CBRFC can share
- Period of record = 2000 to present

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**CBRFC Uses of Remote Sensing**

- RFCs
  - Importance of Snow Info
  - Operational CBRFC Modeling
- CBRFC Uses of Surface Observations
- What’s Next?
- Questions & Comments

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**Legend**
- Blue: MODIS Tile Boundaries
- Red: CBRFC AOR
- Light Blue: North Dakota
- Dark Blue: Montana
- Orange: Wyoming
- Yellow: Colorado

**Map Image**: MODSCAG fSCA April 29, 2015
MODSCAG fSCA (percent) over southwestern Utah (Coal Creek near Cedar City, NWSID = COAU1), May 12, 2013, as viewed by CBRFC forecasters. The COAU1 basin is outlined in black, with the division between CBRFC elevation zones in red.
Currently, MODSCAG fSCA is most useful at end of melt as pseudo-binary indicator of snow presence. Probably need more advanced snow model to fully quantitatively use MODSCAG fSCA at CBRFC (snow model research projects are in progress).
2014 Dust-on-snow Example

Current operational CBRFC forecasting system:
• allows (and usually requires) manual adjustment to model simulation by CBRFC hydrologists

To address snowmelt potentially accelerated by dust-on-snow, consider and combine information from:

1. Historical analysis
2. Field observations
3. Remote sensing
4. CBRFC forecaster experience and knowledge of future weather possibilities

Better informed forecaster $\rightarrow$ improved Q forecasts
Historical Remote Sensing Data:
Dustier than average snowpack → *earlier* snowmelt than what SNOW17 predicts

Very dusty years → typically larger streamflow prediction errors (timing)

Real-time Field Observations:
Provide information about
→ Whether or not dust layers exist within the snowpack
→ How close the dust layers are to the sfc
→ Whether or not the dust layers have emerged

Photo (right): Several inches of clean snow above D4 dust layer, as of the morning of April 4. Courtesy Center for Snow and Avalanche Studies, Colorado Dust-on-Snow Program, Silverton, CO (http://www.codos.org/sbb-4-04-14)

REFERENCE:
Remote Sensing + Field Obs

Consistency between new-to-CBRFC datasets and information → confidence in both datasets

MODDRFS
Dust Radiative Forcing (W m\(^{-2}\))

<table>
<thead>
<tr>
<th>Value</th>
<th>Color</th>
<th>Legend</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;= 0.1</td>
<td>White</td>
<td>Clean</td>
</tr>
<tr>
<td>&gt;= 50</td>
<td>White</td>
<td></td>
</tr>
<tr>
<td>&gt;= 100</td>
<td>White</td>
<td></td>
</tr>
<tr>
<td>&gt;= 150</td>
<td>White</td>
<td></td>
</tr>
<tr>
<td>&gt;= 200</td>
<td>White</td>
<td></td>
</tr>
<tr>
<td>&gt;= 250</td>
<td>White</td>
<td></td>
</tr>
<tr>
<td>&gt;= 300</td>
<td>White</td>
<td></td>
</tr>
<tr>
<td>&gt;= 350</td>
<td>White</td>
<td></td>
</tr>
<tr>
<td>N/A - Unrealistic value</td>
<td>Red</td>
<td></td>
</tr>
<tr>
<td>Clouds (2000)</td>
<td>Red</td>
<td></td>
</tr>
<tr>
<td>Edge of snow pixel (2300)</td>
<td>Red</td>
<td></td>
</tr>
<tr>
<td>Net processed by JPL (2350)</td>
<td>Red</td>
<td></td>
</tr>
<tr>
<td>Clouds (2500)</td>
<td>Red</td>
<td></td>
</tr>
</tbody>
</table>

Durango, Colorado

April 8, 2014  April 10, 2014  April 11, 2014

Photos: D4 emerging in the upper Animas watershed proper (along Hwy 550 south of Red Mountain Pass). Courtesy Center for Snow and Avalanche Studies, Colorado Dust-on-Snow Program, Silverton, CO
CBRFC Uses of Remote Sensing

Before
“cranking up the melt” – sim Q is too low

After
“cranking up the melt” – sim Q matches much better

Credit: plots courtesy B. Bernard (CBRFC)

RFCs
Importance of Snow Info
Operational CBRFC Modeling
CBRFC Uses of Surface Observations
What’s Next?
Questions & Comments
How did we do in this April 2014 case?

**Before** informed manual adjustment (dotted): fcsts too low

**After** informed manual adjustment (dashed): fcsts closer to observed streamflow

Perfect? No.

Though, still an improvement!

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**CBRFC Uses of Remote Sensing**

- RFCs
- Importance of Snow Info
- Operational CBRFC Modeling
- CBRFC Uses of Surface Observations
- What’s Next?
- Questions & Comments
MODDRFS-informed manual adjustments to snowmelt rate by CBRFC forecasters are:

1. helpful (see previous example)
2. but subjective and time-consuming

➢ Need a more efficient, objective method of incorporating MODDRFS “dust-on-snow” data into CBRFC forecasting

➢ MODDRFS ➔ use it to tweak temperatures that are input to snow model (SNOW17, which is a temperature-index snow model)
Where to start experiments w/ DRFS-informed SNOW17 MAT-adjustment method?

Mean 2000-2010 melt period dust forcing, where colors denote the 
- **Central Basin** region, 
- **Eastern Basin** region, and 
- **Northern Basin** region (Bryant-Burgess, 2014)

**Nutshell:** Larger circles indicate more dust, on average

- **Initial focus area = southwestern Colorado (most impacted by dust events)**
  - UT and WY are less-impacted by dust events (differences in weather events, dust sources, dust deposition event characteristics...)

Map credit: Colorado River Commission of NV, available via http://crc.nv.gov/images/colorado_river_basin.gif)
DRFS-informed MAT Adjustments

**Methodology, in a nutshell**: **→ If you want details, just ask!**

- Original, unadjusted MATs + DRFS values (remote sensing of dust-on-snow) + Land Cover Info (coniferous veg.) = DRFS-informed, adjust MATs that can be input to SNOW17

**Preliminary Results for Uncompahgre R. in SW CO – NWS id = UCRC2:**
- Minimal (+/- 3%) impacts on water year and seasonal runoff **volumes** (Apr-Jul)
- **Timing** of melt (and snowmelt-driven streamflow) **within the April-July runoff period** is altered by incorporation of MODDRFS data into SNOW17

**Example cases of runoff timing for SW CO: 2005, 2009**

- **2005 Dust:**
  - Lighter/less than normal
  - **2005 AMJJ runoff volume:**
  - 111% average

- **2009 Dust:**
  - Heavier/more than normal
  - **2009 AMJJ runoff:**
  - 118% average

Map credit: Bryant-Burgess, 2014
Example from initial results:
- Uncompahgre River in southwestern CO (NWS ID = UCRC2)
- WY2009 – “heavy dust” year

No DRFS-informed MAT adjustment
May 2009: simulated flow = too low!

WITH DRFS-informed MAT adjustment
May 2009: snowmelt is earlier and simulated flow = much improved!
Breaking down results within the April-July runoff period:

2009 (heavy dust) Case:
Including “dust on snow” remote sensing info → accelerated melt
• much more runoff in May
• much less in June and July

May = most improvement in error

2005 (minimal dust) Case:
Including “dust on snow” remote sensing info → slight delay in melt
• less runoff in May
• slightly more in June and July

May = most improvement in error

Note: for 2009: Jun-July (esp July) = exp simulation has larger error than ctl
→ to check further into other error sources
What’s Next?

For the rest of 2015 (and beyond):

- Work with stakeholders, forecast users, and water managers to share knowledge of snow observations and measurements from perspectives external to CBRFC

- Evaluation of snow model state updating methods (including documentation)
  - SNOTEL-based methods
  - Remote sensing-based methods

- Continue to support expansion of NRCS SNOTEL and other surface-based networks

- Review additional remote sensing datasets (more MODIS datasets, VIIRS, ASO from NASA/JPL) and investigate their best uses at CBRFC

- Investigate more advanced snow modeling

- And other projects
Questions, Comments, and Acknowledgements

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NRCS: www.nrcs.usda.gov/wps/portal/nrcs/main/wy/snow
WY Snow Survey – Lee Hackleman

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