

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

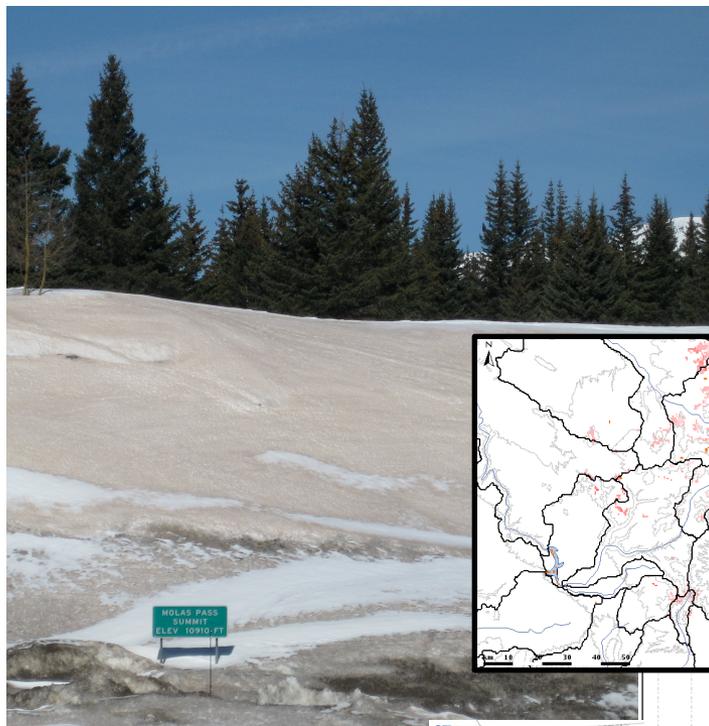
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Brent Bernard, John Lhotak,
and Craig Peterson

NOAA/National Weather Service
Colorado Basin River Forecast Center
Salt Lake City, UT

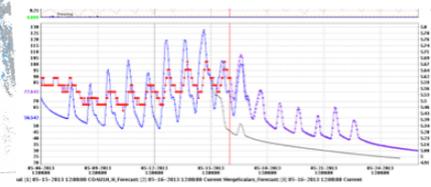
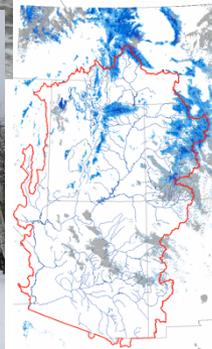
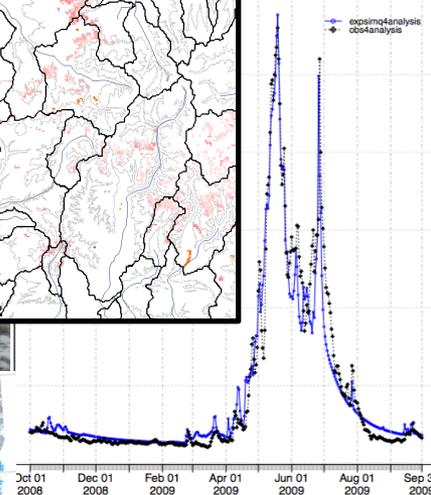
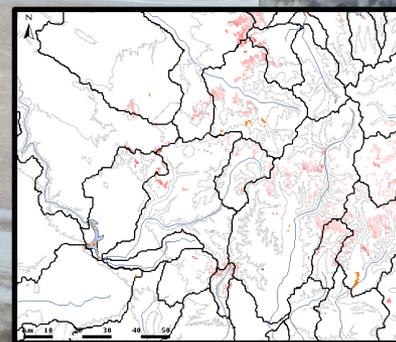
Western Water Assessment
Snowpack Monitoring Workshop

West Jordan, UT

August 11, 2015



Credit: CSAS/CODOS





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- CBRFC
- Importance of Snow Info
- Operational CBRFC Modeling
- CBRFC Uses of Surface Observations
- CBRFC Uses of Remote Sensing
- Future Directions
- Questions and Comments

Colorado Basin River Forecast Center (CBRFC)

Full staff: 3 mgmt, 9 hydrologists, 1 admin, 1 IT

Operational streamflow forecasts across the Colorado River basin and eastern Great Basin

Operational forecast types:

- short-term streamflow, out 10d in future
- seasonal peak streamflow
- seasonal runoff volume



National Weather Service River Forecast Centers

www.cbrfc.noaa.gov

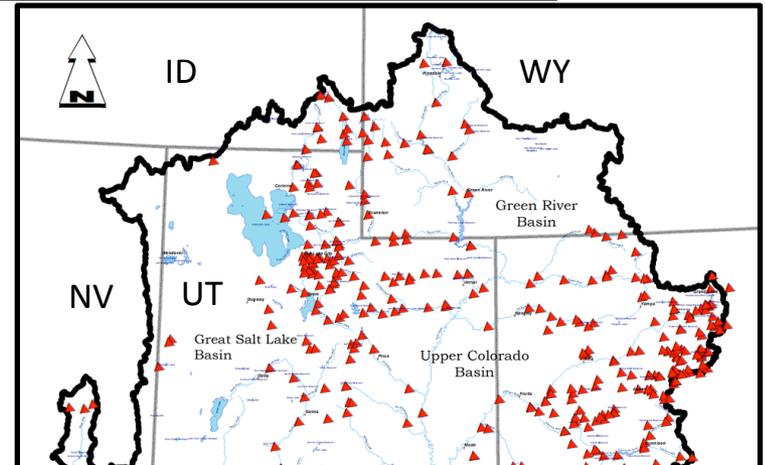
Colorado Basin River Forecast Center (CBRFC)

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

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Operational CBRFC Modeling

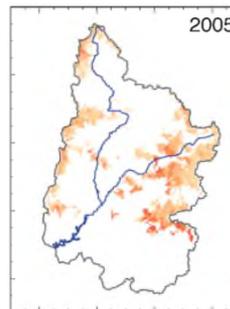
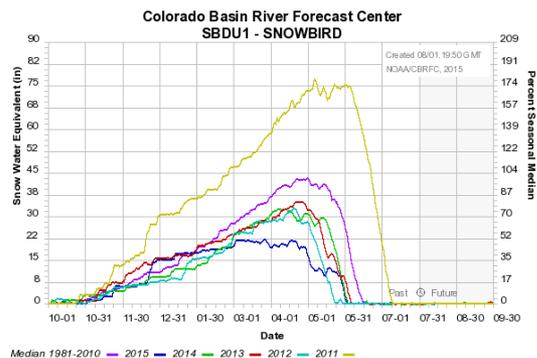
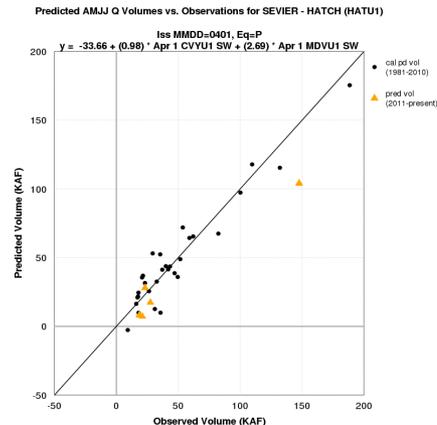
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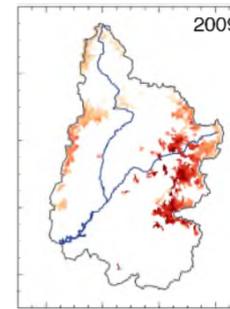
Future Directions

Questions and Comments

- ~60-80% of precipitation in CBRFC's area of responsibility (AOR) falls as snow
- Snow (especially water equivalent) is a primary predictor of seasonal runoff volume in much of CBRFC's AOR
- Snowpack of recent years has exhibited extremes in both directions
 - mostly dry (☹) and, sometimes, wet (generally ☺)
 - sometimes heavy dust deposition, sometimes a clean snowpack surface

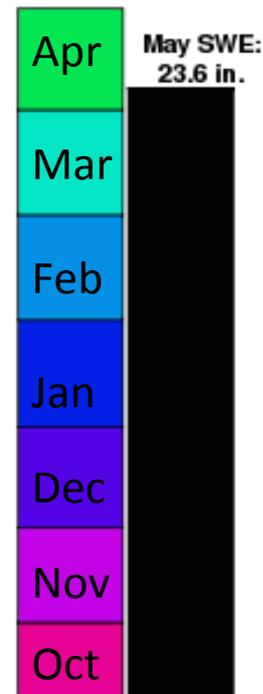


Map credit: Bryant-Burgess, 2014



Map credit: Bryant-Burgess, 2014

Total precip through April 30:
26.8 in



Average (WY81-WY10)

Average (81-10) precip thru April 30 vs May 1 SWE at Trial Lake SNOTEL

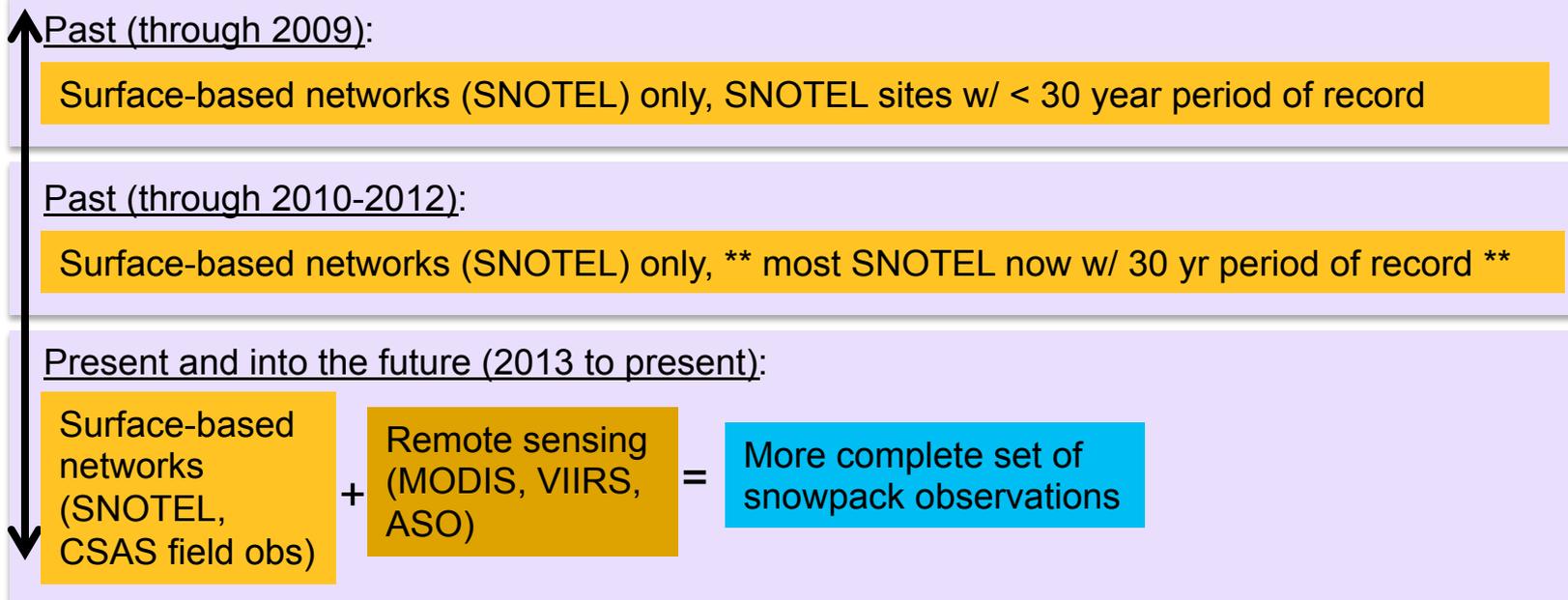


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Additional datasets and information about snowpack conditions assists CBRFC hydrologists with more informed forecasting decisions.

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



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

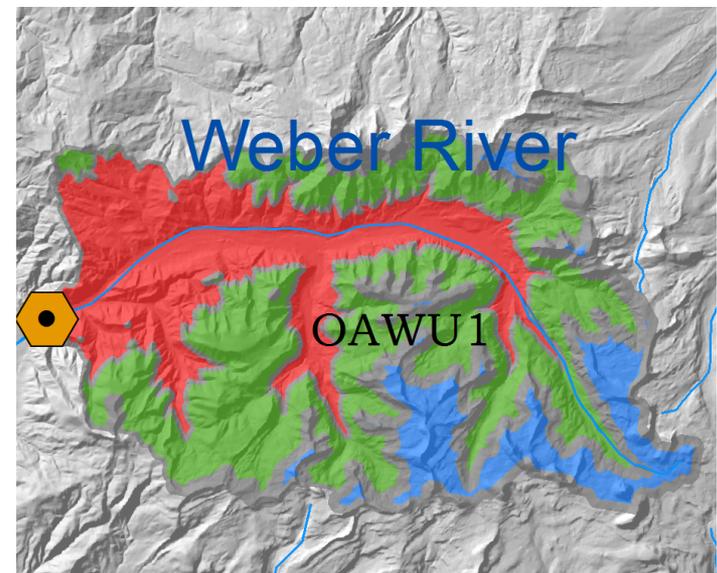
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CBRFC's operational models:

- Modeling units = elevation bands or zones
- each "zone" gets its own set of SNOW17 and Sac-SMA parameters via model calibration

EXAMPLE: Weber River headwaters in northern UT (NWS ID = OAWU1)

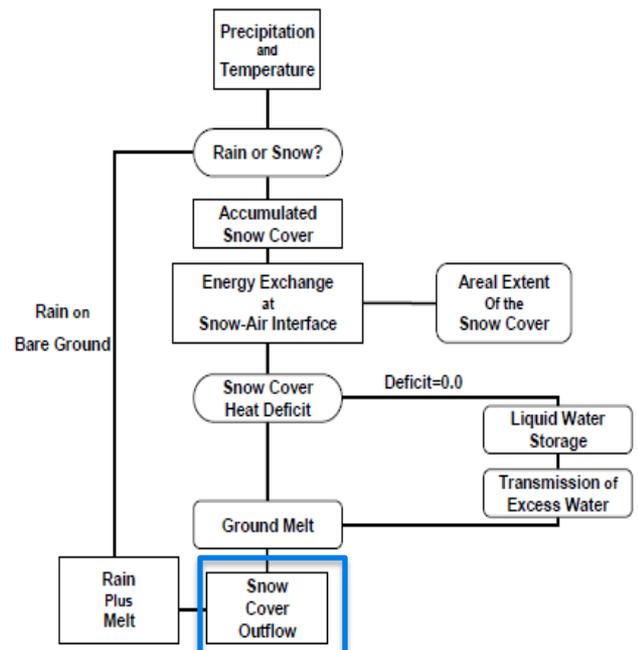
Elevation Zone	Mean Elevation (ft)
OAWU1HUF (Upper)	10333
OAWU1HMF (Middle)	9318
OAWU1HLF (Lower)	7831



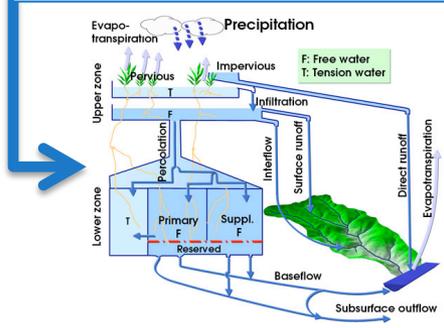
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Operational Snow Model at CBRFC: SNOW17

- minimum inputs and computational power needed
- manually calibrated at CBRFC using 1981-2010 historical data
- temperature-index model (air temperature used as proxy for energy/radiation)
- forecasts snowmelt pretty well under near-normal conditions of the calibration period
- *doesn't* do so hot when conditions deviate from near-normal – manual adjustments needed



Water output from SNOW17 is then input to the soil moisture model (Sac-SMA)

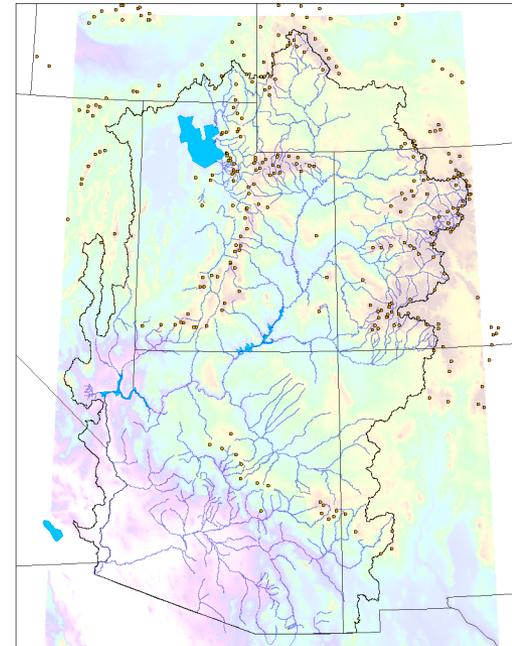


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NRCS's SNOTEL network = primary source of surface-based snowpack information for CBRFC

- 1st-of-month SWE data - used in statistical modeling for seasonal runoff volume forecasting
- SNOTEL precipitation data :
 - Real-time values - used to initially build the simulated snowpack in SNOW17
 - monthly values – used to “update” the snowpack simulated by SNOW17

More details on next few slides



Map: NRCS SNOTEL network for CBRFC AOR

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

Photo (right): Several inches of clean snow above D4 dust layer, as of the morning of April 4, 2014. Courtesy Center for Snow and Avalanche Studies, Colorado Dust-on-Snow Program, Silverton, CO (<http://www.codos.org/sbb-4-04-14>)



Photo (above): Parleys Summit SNOTEL

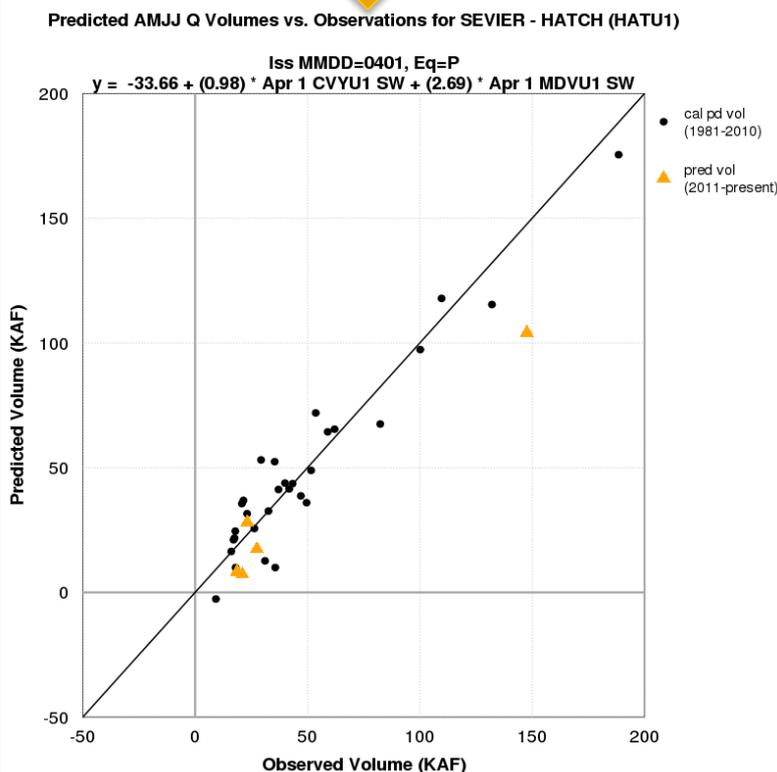


Surface Measurements: SNOTEL SWE

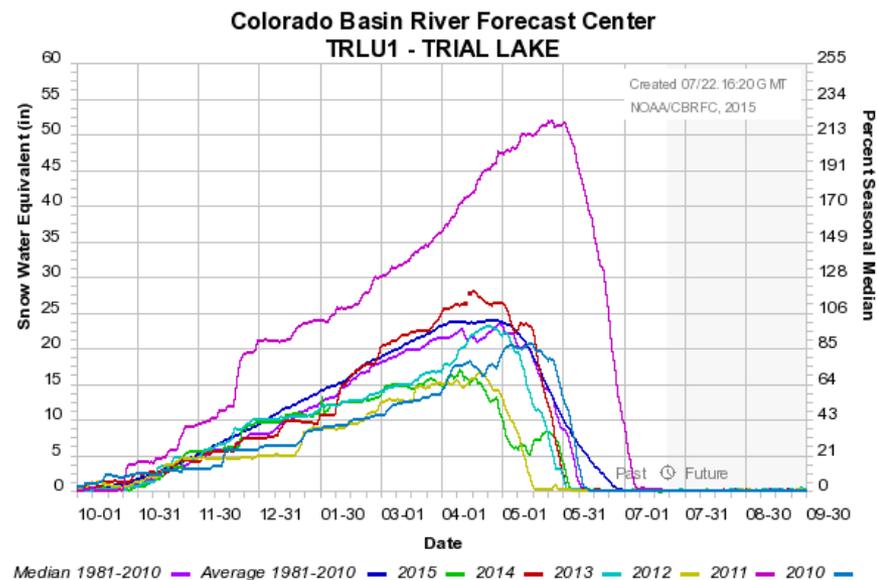


SNOTEL SWE: used on the 1st of the month for water supply forecasting

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.)



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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

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***CBRFC Uses of
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Surface Measurements: SNOTEL Precip



Building the simulated snowpack with real-time SNOTEL precipitation

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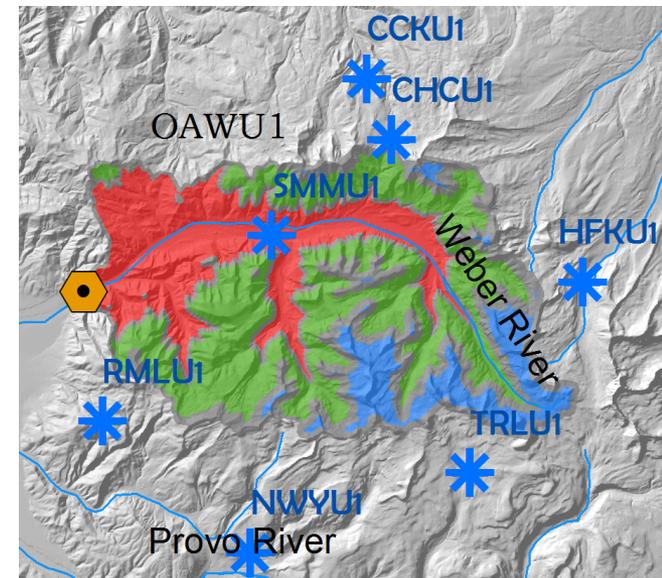
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Each real-time model run involves:

1. Gather point precipitation data from SNOTEL stations.
2. Generate mean areal precipitation value (MAP) for each elevation zone/modeling unit, using the point precipitation data from SNOTEL.
3. Input MAP values to SNOW17.
4. SNOW17 types the precipitation as *snow* or *rain*, depending on T_{air} .
5. SNOW17 (temperature index model) then runs snowpack computations and determines snowpack state.

Elevation Zone	SNOTEL Stations Used to Compute MAP Value
OAWU1HUF (Upper)	HFKU1 (Hayden Fork) TRLU1 (Trial Lake)
OAWU1HMF (Middle)	HFKU1 (Hayden Fork) SMMU1 (Smith & Morehouse)
OAWU1HLF (Lower)	SMMU1 (Smith & Morehouse) NWYU1 (Beaver Divide)





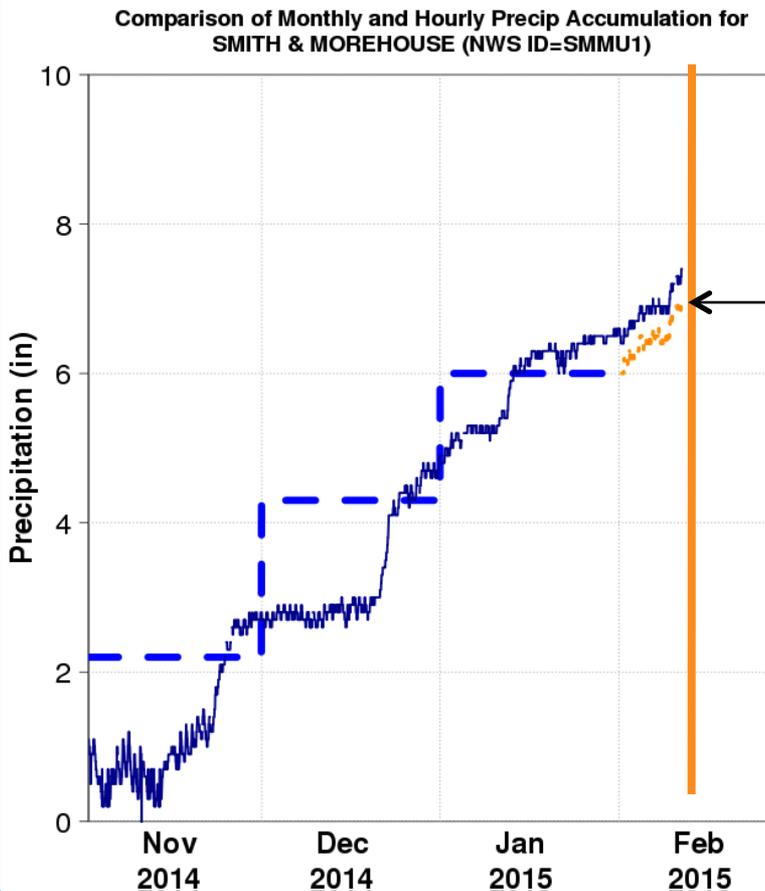
Surface Measurements: SNOTEL Precip



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.

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Measurements from Remote Sensing



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Remotely-sensed snow datasets currently used by CBRFC:

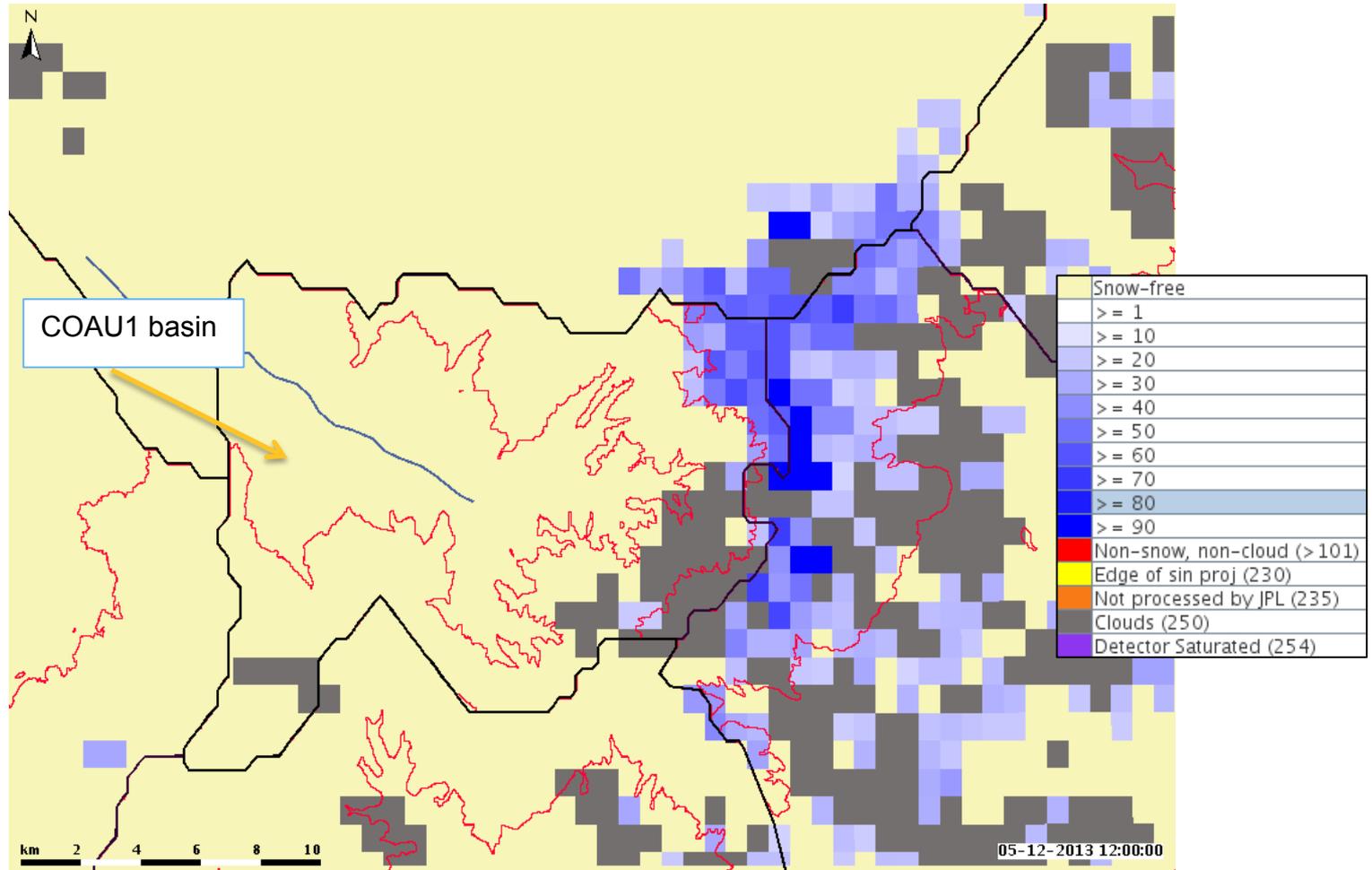
- Data provider = NASA/JPL
- Satellite (instrument = MODIS) fractional snow-covered area (fSCA)
 - used to adjust SNOW17 model SWE as snowpack dwindles
- Satellite (instrument = MODIS) “dust-on-snow” data
 - used to adjust melt rates in SNOW17

Remotely-sensed snow datasets on the horizon for CBRFC:

- Data provider = NASA/JPL
- Airborne Snow Observatory SWE, fSCA
 - already ongoing in CO
 - will be starting in WY in next 1-2 years
 - not yet in UT
 - CBRFC is just starting with ASO data (have mostly focused on satellite data so far)
- Satellite-based (instrument = VIIRS) fSCA and “dust-on-snow” data
 - VIIRS is the follow-on instrument to MODIS

Detailed info and more examples in following slides...

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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.



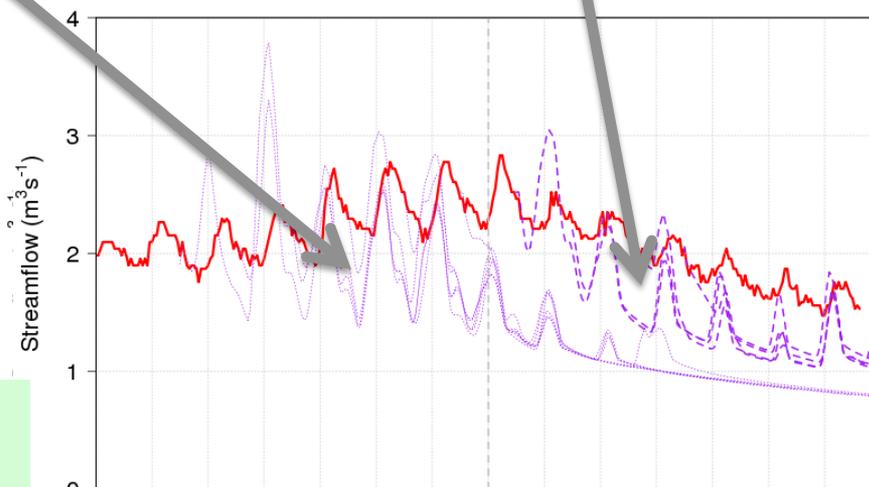
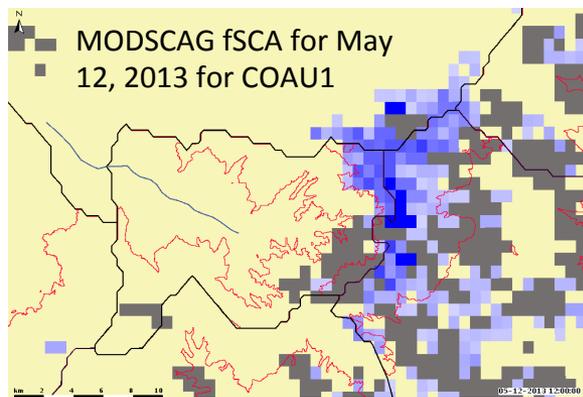
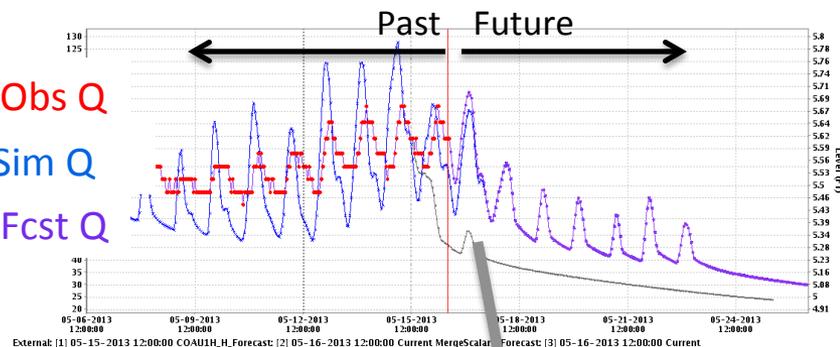
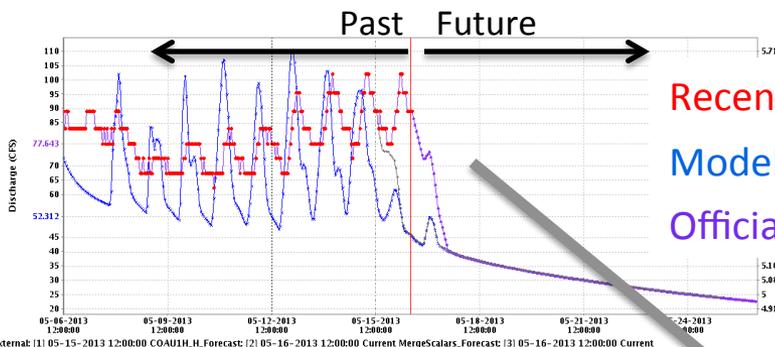
May 16, 2013 CBRFC forecast modifications informed by MODSCAG fSCA



Coal Creek, near Cedar City, UT, NWS ID: COAU1/USGS ID: 10242000

Before small SWE adjustment:

After small SWE addition:



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).

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2014 Dust-on-snow Example



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Current operational CBRFC forecasting system:

- includes a temperature-index snow model
- allows (and usually requires) manual adjustment to model simulation by forecasters

To address snowmelt potentially accelerated by dust-on-snow, 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
→ improved Q forecasts

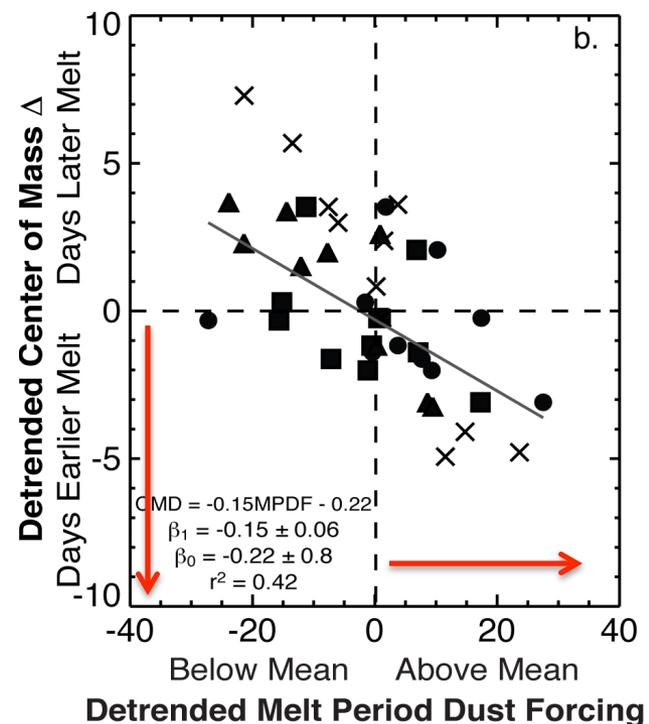
Historical Analysis

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Dust in the snowpack primarily impacts timing of snowmelt (and timing of subsequent snowmelt-driven streamflow peaks)

Analysis shows that a dustier than average snowpack results in center of mass that is observed *earlier* than predicted (esp. SW CO)

Very dusty years coincide with larger streamflow prediction errors



REFERENCE:

Bryant, A. C., T. H. Painter, J. S. Deems, and S. M. Bender (2013), Impact of dust radiative forcing in snow on accuracy of operational runoff prediction in the Upper Colorado River Basin, *Geophys. Res. Lett.*, 40, 3945–3949, doi:10.1002/grl.50773.

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Senator Beck Basin CODOS Update for April 4, 2014:

“... dust layer D4 may emerge in the coming week, absorbing solar radiation and accelerating the warming of the underlying snowcover at higher elevations, or enhancing snowmelt rates at lower elevations where the snowcover was already isothermal.”

(CSAS, <http://www.codos.org/sbb-4-04-14>)



Photo: 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>)

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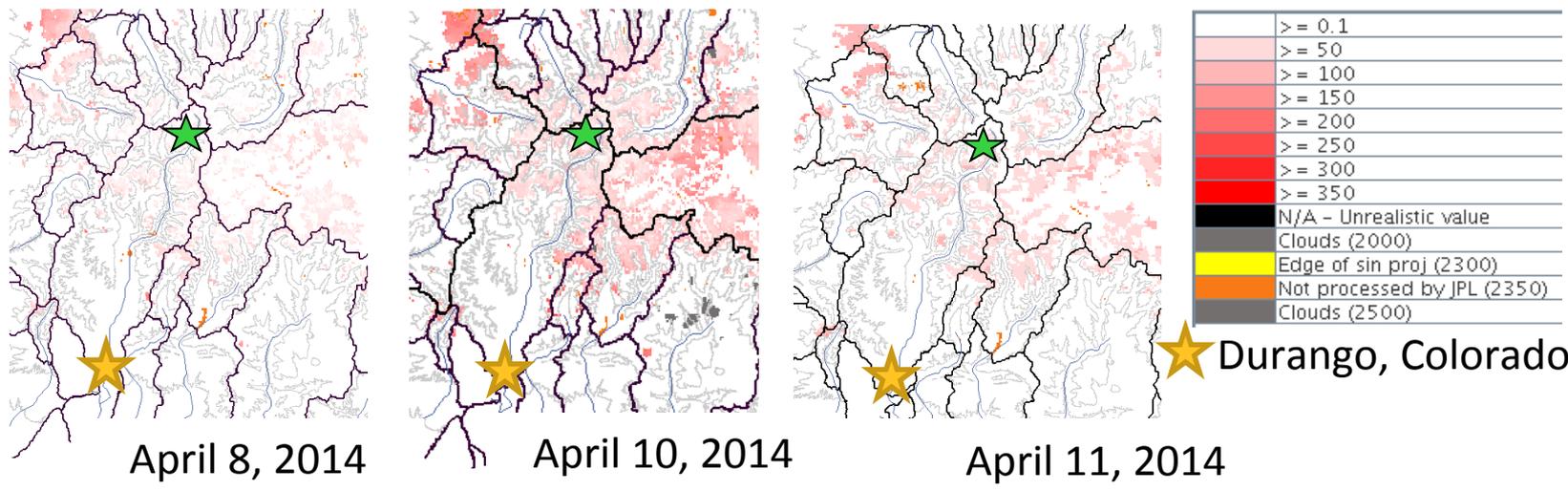
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MODDRFS Dust Radiative Forcing ($W m^{-2}$)



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

Weather Forecasts

- CBRFC relies on a temperature-index snow model
- Forecasters anticipated clear, sunny weather and a period of above normal air temperatures
- Knew that dust layer(s) were present in the snowpack



Potential for accelerated snowmelt rates

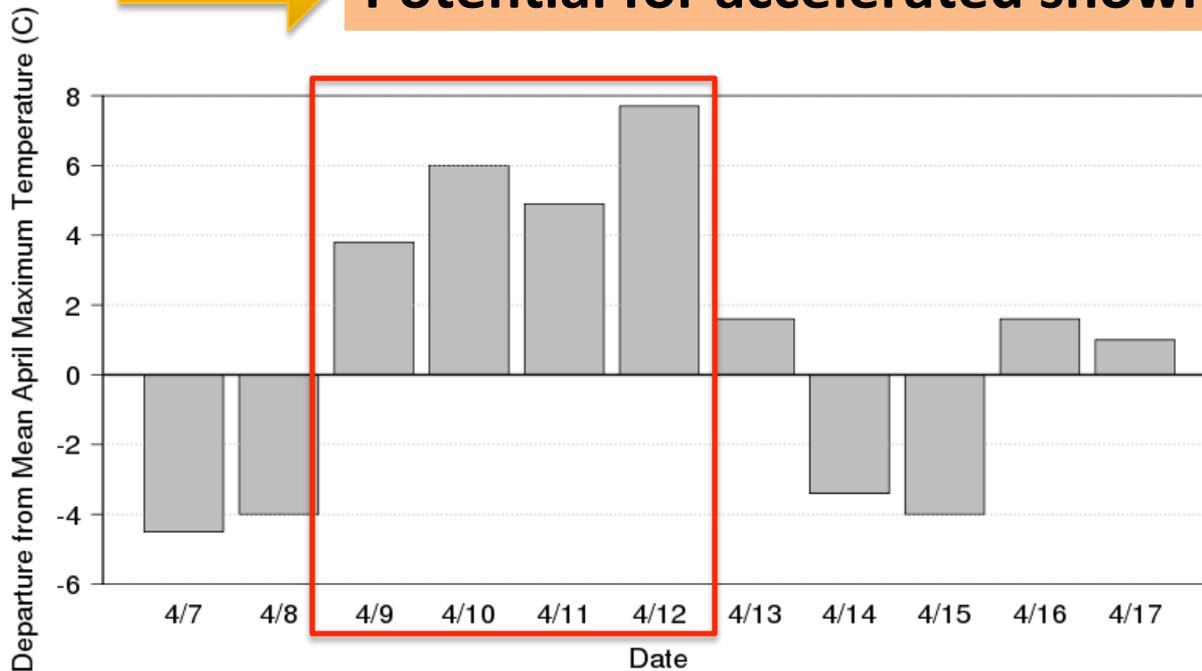


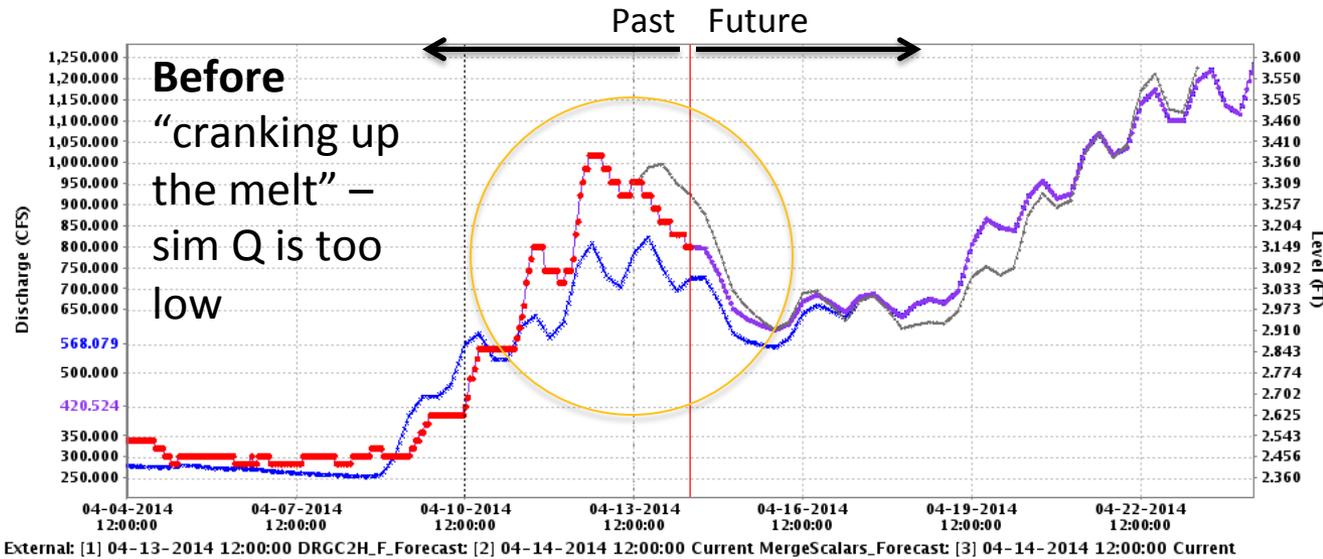
Figure: Departures of daily maximum air temperature from mean April maximum temperature for Silverton, CO (NWS ID: SLVC2) for mid April 2014

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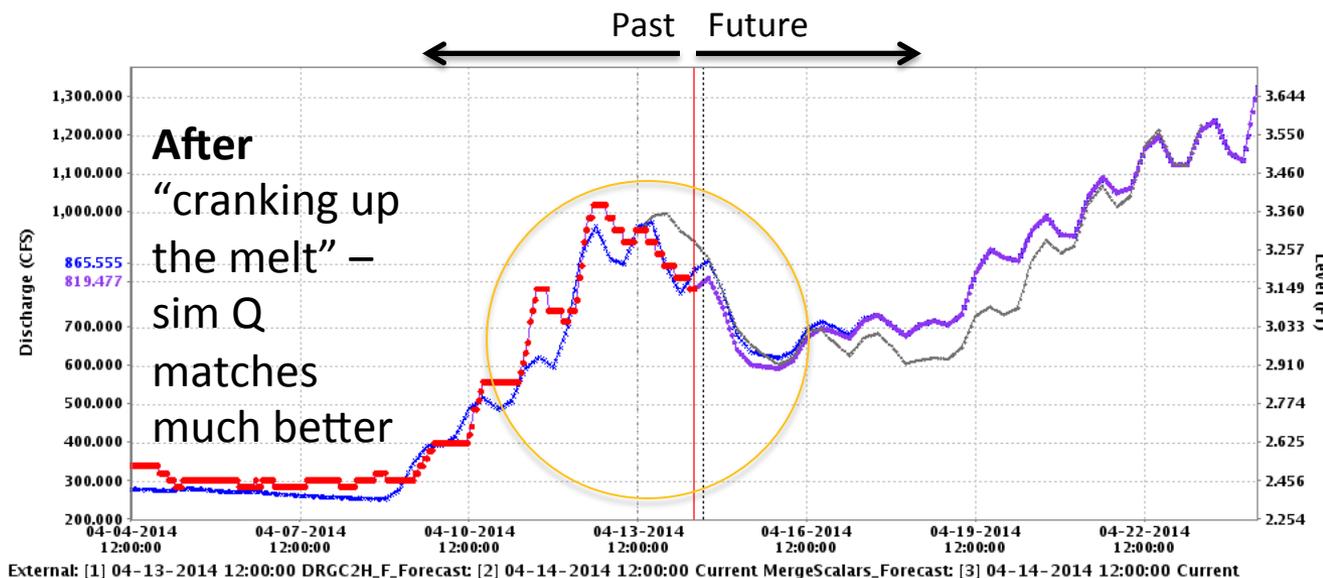


Manual Adjustments by Forecasters

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Recent Obs Q
 Model Sim Q
 Official Fcst Q



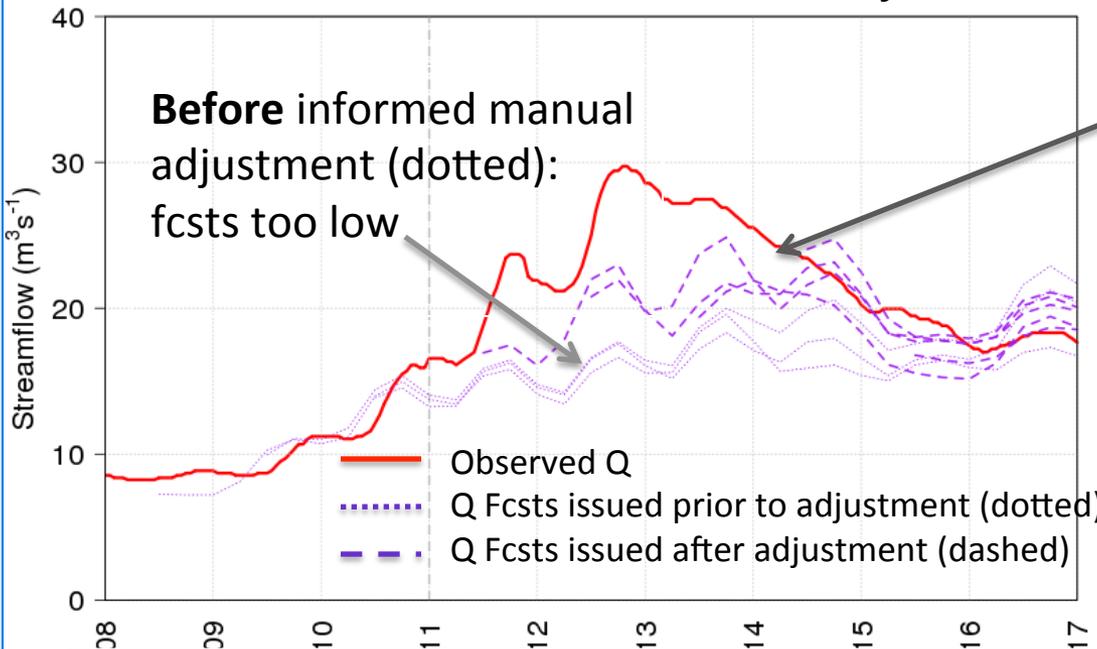
Recent Obs Q
 Model Sim Q
 Official Fcst Q

Credit: plots courtesy B. Bernard (CBRFC)

How did we do in this April 2014 case?

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Solid line: Mid April 2014 observed streamflow for the Animas R. at Durango, CO
Dotted lines: CBRFC streamflow forecasts *before* manual adjustment
Dashed lines: CBRFC streamflow forecasts *after* manual adjustment



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

Perfect? No.

Though, still an improvement!

Average Forecast Error for Mid April 2014 Case:
 (for forecasts valid between 4/11 and 4/17):

Lead time (days)	Before adjustment	After adjustment
1	-6.4 m ³ s ⁻¹	-2.6 m ³ s ⁻¹
2	-8.3 m ³ s ⁻¹	-2.7 m ³ s ⁻¹
3	-9.2 m ³ s ⁻¹	-0.7 m ³ s ⁻¹



DRFS-informed MAT



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MODDRFS-informed manual adjustments to snowmelt rate by CBRFC forecasters are helpful (see previous example) but subjective and time-consuming.

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

Process historical data and identify patterns that quantitatively relate MODDRFS “dust-on-snow” data to mean areal temperatures (MAT) input to SNOW17.

Develop statistical relationship that allows computation of an “adjusted MAT” that is informed by remotely-sensed MODDRFS “dust-on-snow” data

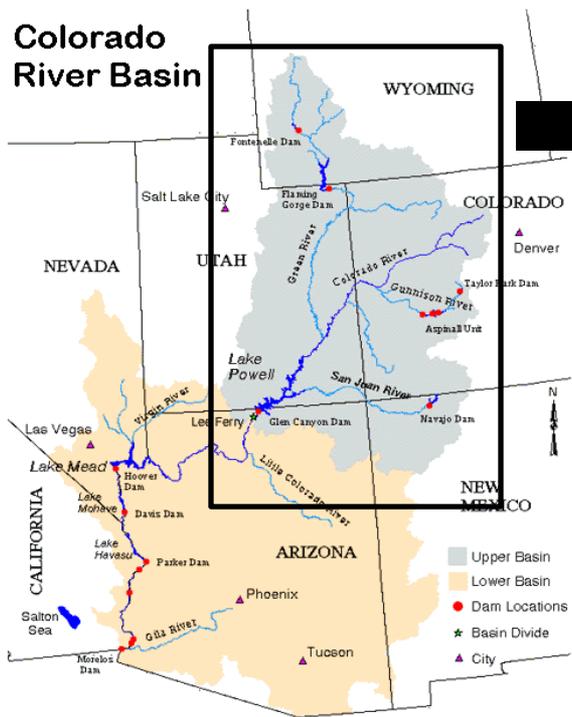
- $MAT_{adjust} = MAT_{orig} + (M_{mean}/10) \times (0.75) \times EGREEN$

where, for each “elevation zone”:

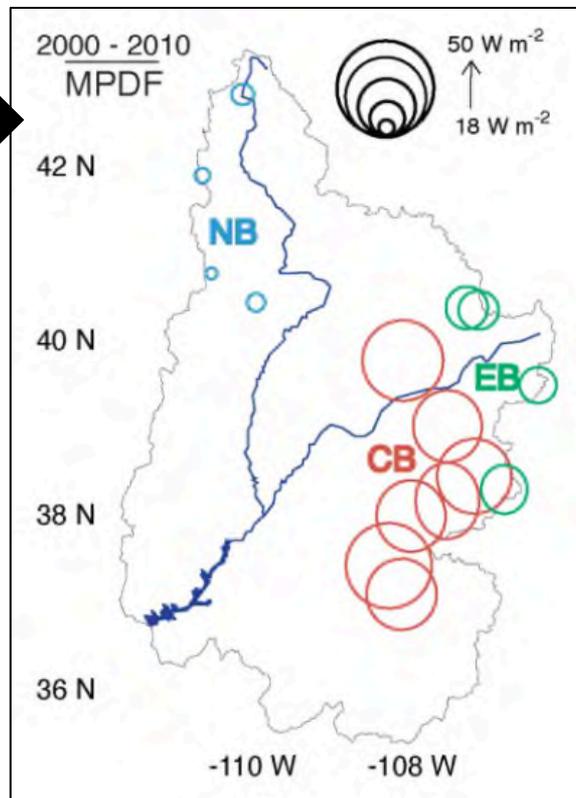
- MAT_{adjust} = MODDRFS-informed, adjusted MAT value (input to SNOW17)
- MAT_{orig} = original, unadjusted MAT value (computed from point data)
- M_{mean} = mean of MODDRFS values for most recent few days
- EGREEN = fraction of elevation zone covered in coniferous vegetation

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Choosing a region for initial experiments w/ DRFS-informed SNOW17 MAT-adjustment method



Map credit: Colorado River Commission of NV, available via http://crc.nv.gov/images/colorado_river_basin.gif



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

→ **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...) – will look at UT and WY in more detail in coming weeks

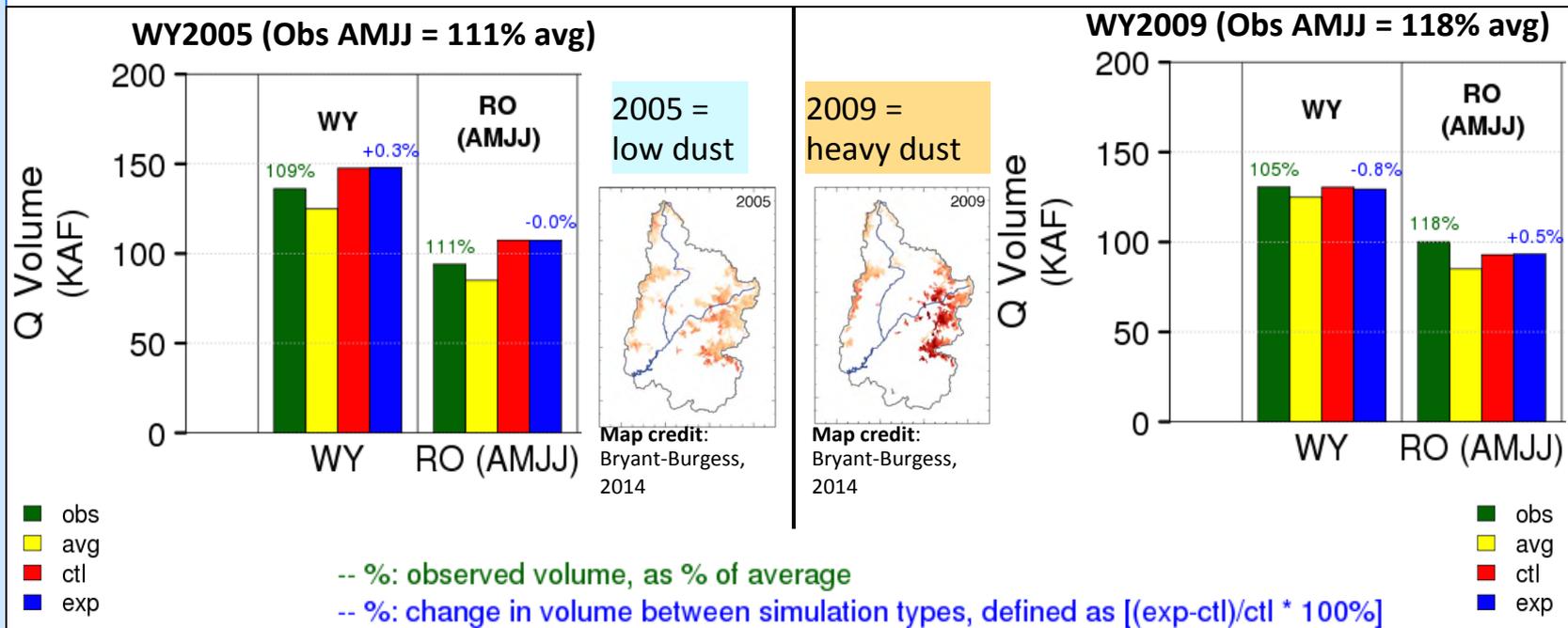


DRFS-informed MAT



Outcomes for example basin in sw CO (Uncompahgre R. – NWS id = UCRC2)

- Water year and seasonal runoff **volumes** (Apr-Jul) are minimally impacted, regardless of dust conditions in the 2000-2010 period of record
 - Differences of (+/- 3%) in 2000-2010 “control” (*without* MODDRFS dust info) vs. “experimental” (*with* MODDRFS dust info) streamflow simulations
 - 2005 and 2009 = similar WY and AMJJ volumes, but different dust conditions



- Timing** of melt (and snowmelt-driven streamflow) within the April-July runoff period is altered by incorporation of MODDRFS data into SNOW17 via temperature inputs – timing example on next slide

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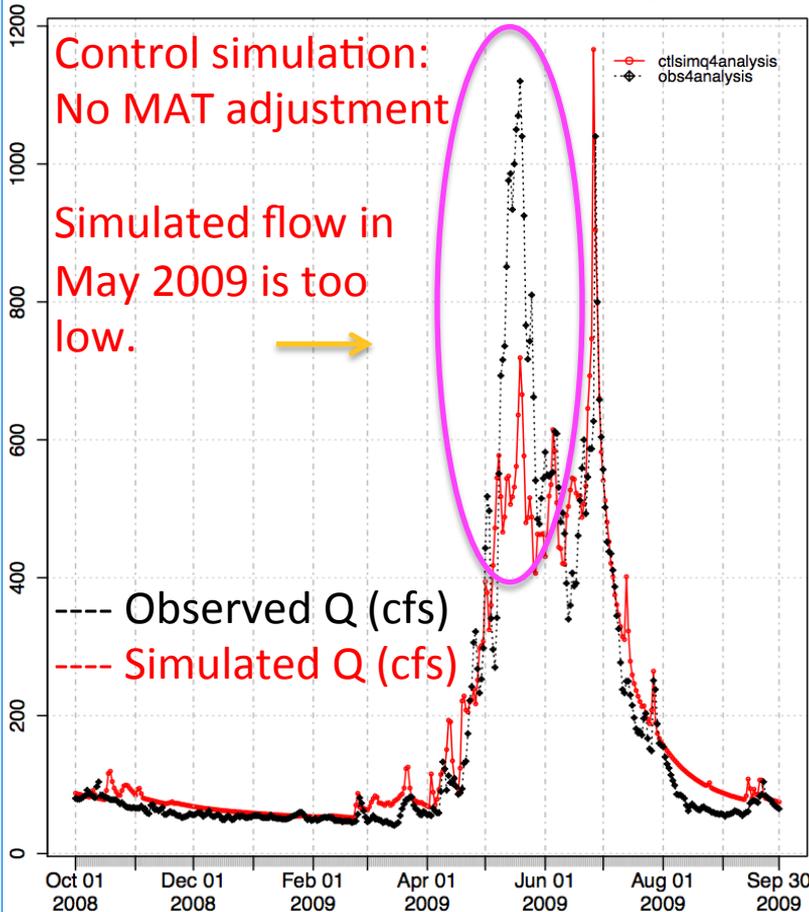
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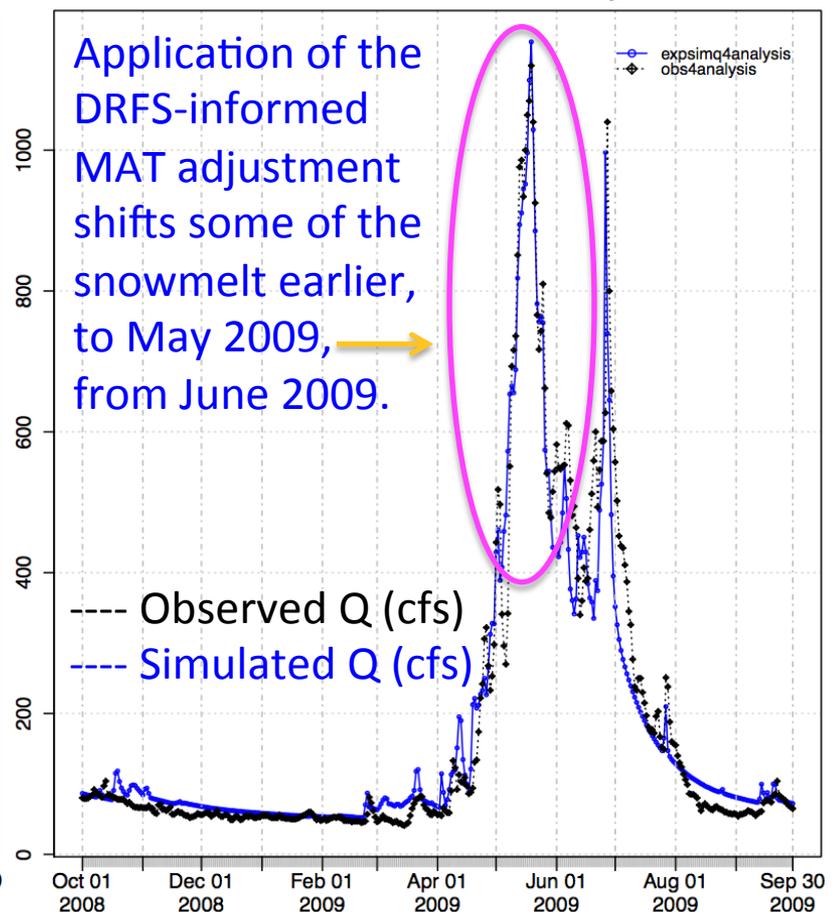
Example from initial results:

- Uncompahgre River in southwestern CO (NWS ID = UCRC2)
- WY2009 – “heavy dust” year

Sim. Q **without** DRFS-informed MAT adjustment



Sim. Q **with** DRFS-informed MAT adjustment



DRFS-informed MAT

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Outcomes for example basin in sw CO (Uncompahgre R. – NWS id = UCRC2)

- Timing of melt (and snowmelt-driven streamflow) *within the April-July runoff period* is altered by incorporation of MODDRFS data into SNOW17 via temperature inputs

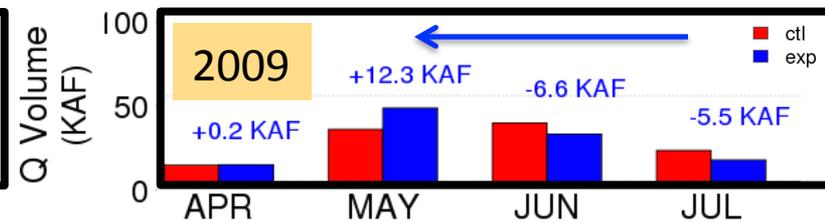
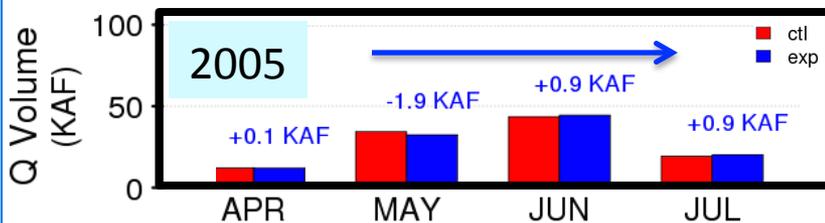
2005 (minimal dust) - **Experimental runoff timing:**

- slightly less runoff in May Slight delay in melt
- slightly more in June and July

2009 (heavy dust) - **Experimental runoff timing:**

- much more runoff in May Accelerated melt
- much less in June and July

-- KAF: change in volume between simulation types, defined as (exp-ctl)

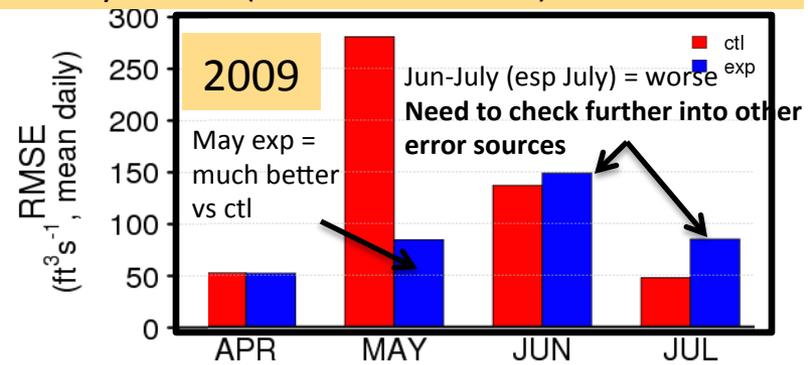
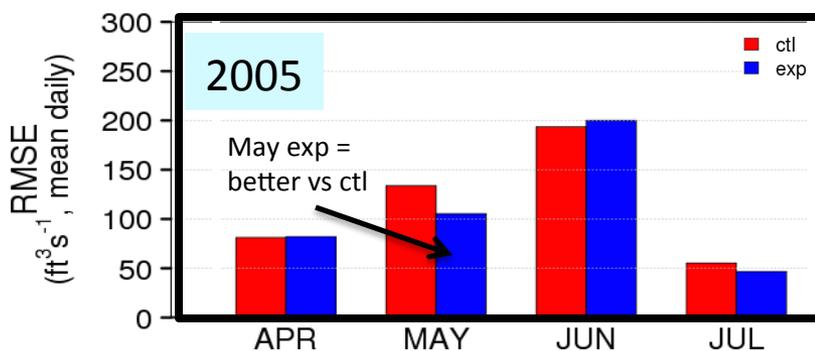


2005 (minimal dust) – Which q sim did better vs. obs?

- April: toss-up
- May: **exp** sim (with MODDRFS data) May = most improvement
- June: **ctl** sim (no MODDRFS data)
- July: **exp** sim (with MODDRFS data)

2009 (heavy dust) – Which q sim did better vs. obs?

- April: toss-up
- May: **exp** sim (with MODDRFS data) May = most improvement
- June: **ctl** sim (no MODDRFS data)
- July: **ctl** sim (no MODDRFS data)





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
- Assimilation of additional remote sensing datasets (more MODIS datasets, VIIRS, ASO from NASA/JPL) and associated assim. methods
- Incorporate energy balance snow modeling into CBRFC system
 - K. Andreadis data assimilation and VIC work through JPL
 - Utah State partnership (UEB snow model)
- And other projects

CBRFC
Importance of
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Operational
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Modeling
CBRFC Uses of
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CBRFC Uses of
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Future
Directions
Questions and
Comments



Questions, Comments, and Acknowledgements



- CBRFC
- Importance of Snow Info
- Operational CBRFC Modeling
- CBRFC Uses of Surface Observations
- CBRFC Uses of Remote Sensing
- Future Directions
- Questions & Comments**

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