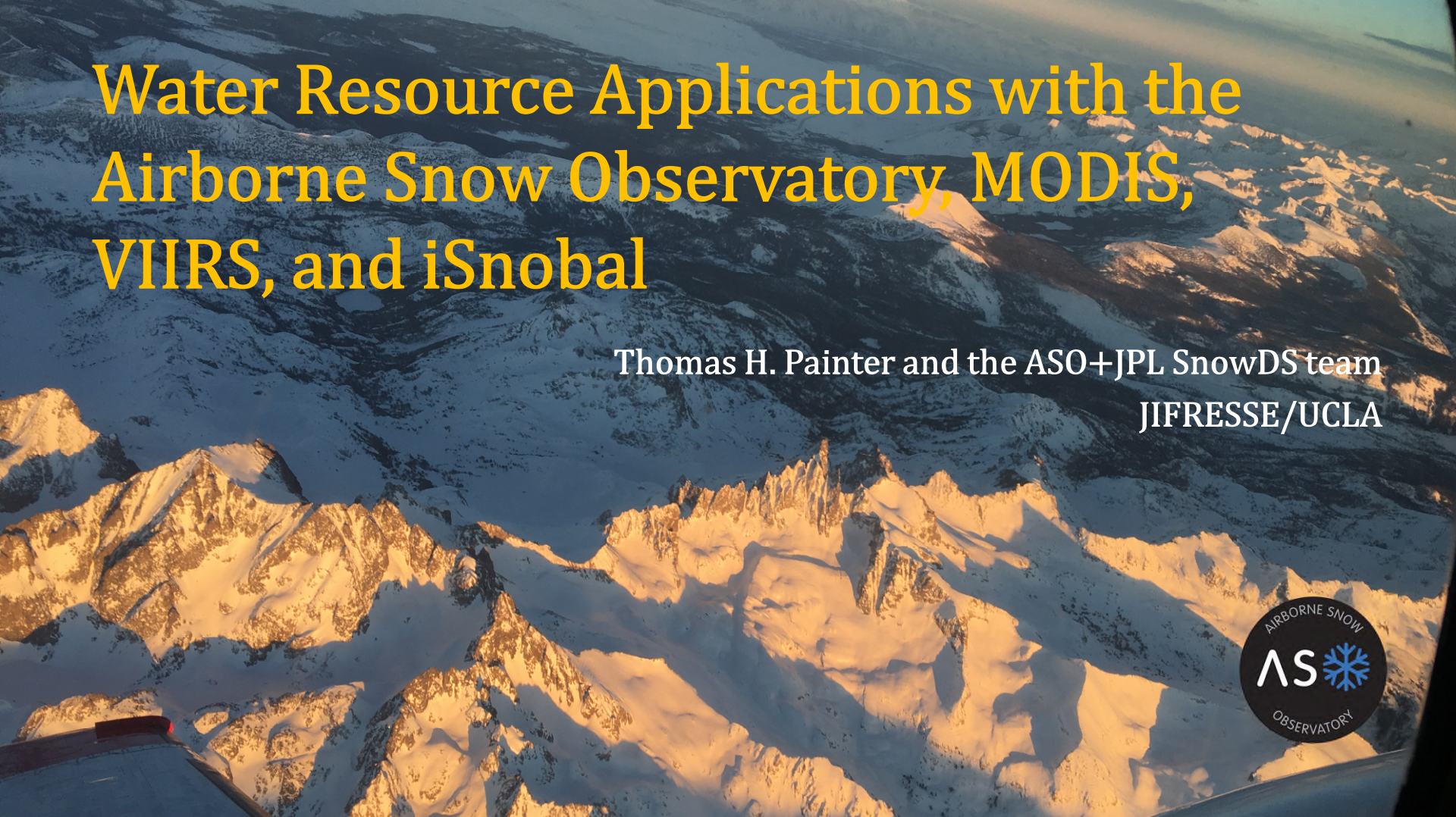
Water Resource Applications with the Airborne Snow Observatory, MODIS, VIIRS, and iSnobal

Thomas H. Painter and the ASO+JPL SnowDS team
JIFRESSE/UCLA



Outline

1. Motivation: forecast & management challenges
2. ASO overview & highlights
3. ASO projects & partnerships in California, Colorado, and Europe
4. MODIS + VIIRS constraint of operational forecast modeling

The communities with which we partner



Water Supply
- Less hedging in water supply decisions
- Increase wet year allocations for groundwater recharge
- Avoid being overly conservative in dry years
- Better information for environmental allocations and management
- Benefits across dry and wet years

Flood Management
- Defensibility of decisions
- Avoided litigation
- Avoided property loss
- Avoided false alarms

Hydropower
- Optimization
- Value of foreseeable opportunities

Indirect
- Forest Management: fire management, tree mortality, ecosystem health
- Recreation and transportation: trail maintenance, ski area, Caltrans
- Landslide and avalanche risk assessment

“What you’ve done there is created essentially new reservoir space, without need for environmental impact statements or decades of lawsuits!” – *Wes Monier, Turlock Irrigation District*

Our Driving Goal

Reduce uncertainties in water resource and physical process understanding in snowmelt-dominated systems around Earth

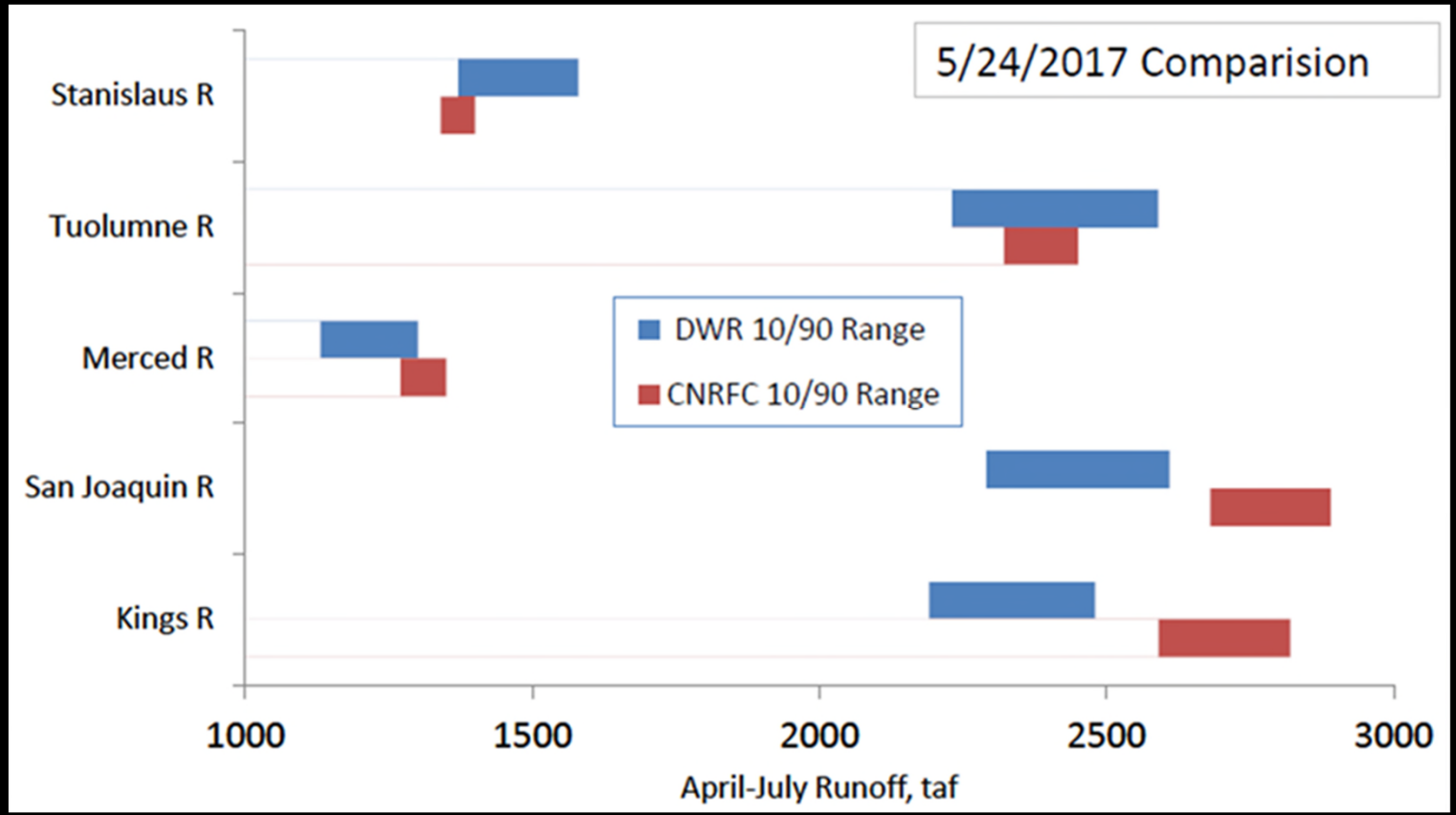


"We've got to get the water out of there because we have all this snow and we don't know what's going to happen," Glen Pearson said.

South Feather Water and Power water district manager Matt Colwell also talked about balancing the water level and said predicting how much water would come into the reservoir is a stochastic process, which means random variables can affect the reliability of the prediction.

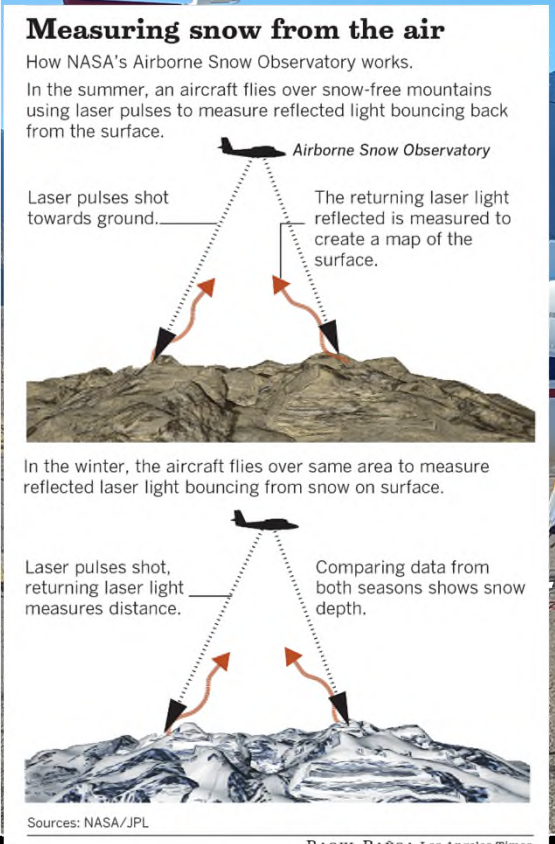
The Mercury News, 24 March 2017

Present Discrepancies between B-120 and CNRFC



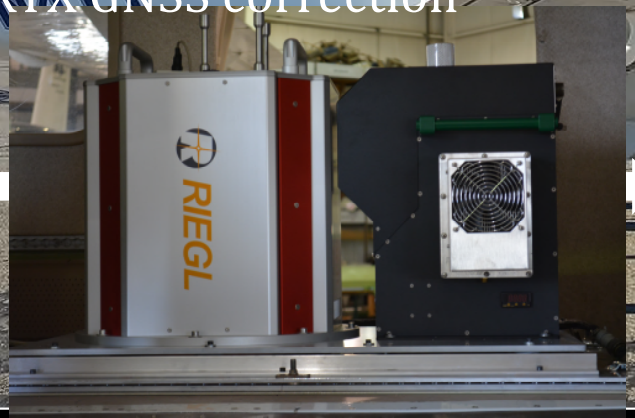
Source: Wes Monier (TID)

NASA's Airborne Snow Observatory



- Wall to wall mapping of SWE and albedo
- Weekly flights in winter and spring
- < 24 hour turnaround of distributed products and modeling/management distillations

GNSS/IMU – Applanix AP60
RTX GNSS correction

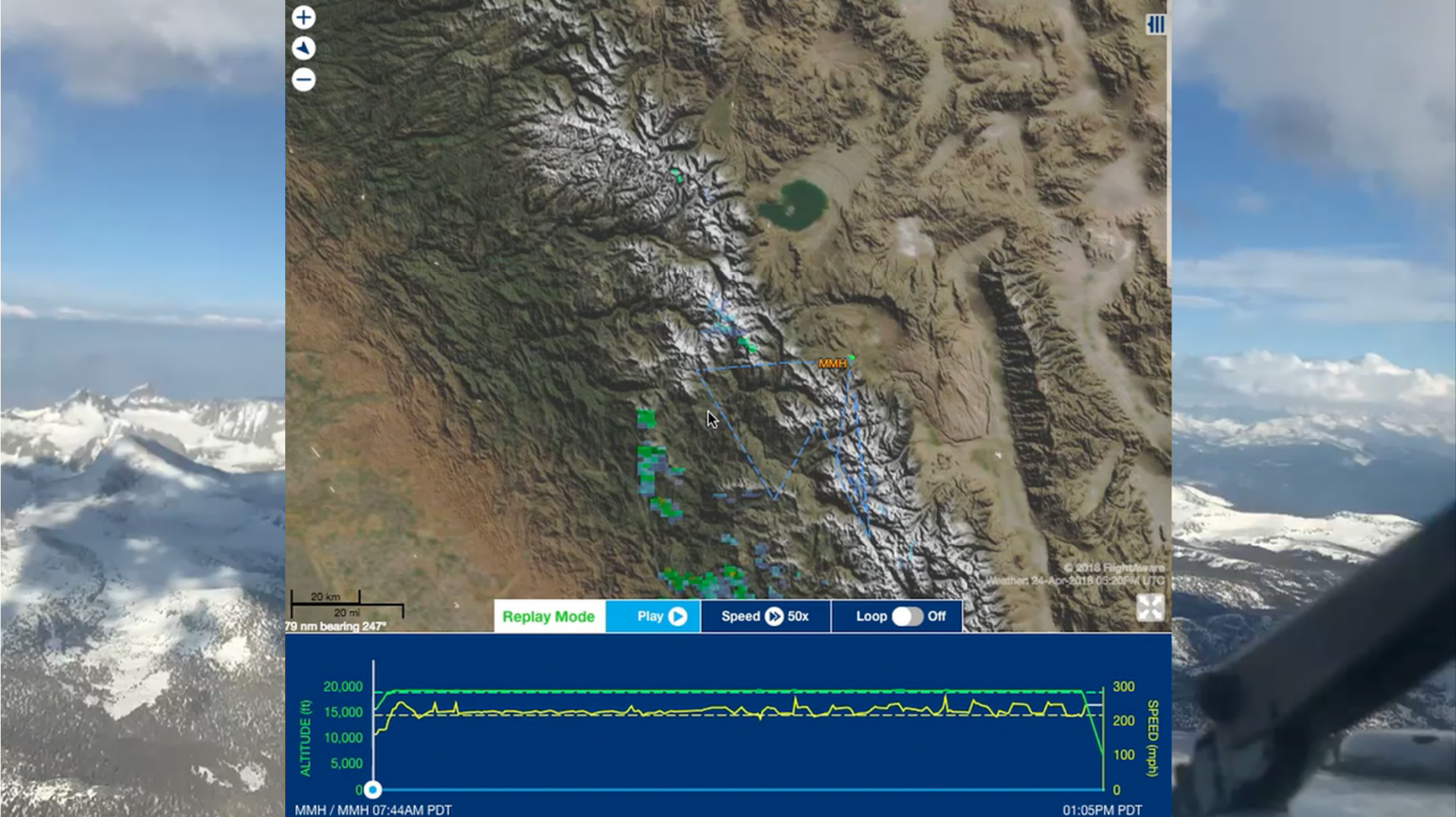


Snow albedo

- *CASI-1500 Imaging Spectrometer*
- *72 bands between 0.35 and 1.05 µm*
- *40° field of view*

History of ASO program

- Considered in 2009
- Startup commitment by JPL in 2010
- Partnership with DWR initiated in 2011
- Funding committed by NASA in 2012
- First snow-free flights Aug 2012 (Tuolumne)
- First snow-on acquisition Apr 3 2013 (Tuolumne)
- First 24 hour turnaround late April 2013
- Expansion of California to include Lakes, Merced, Kings, Rush in 2014
- Expansion to include Cherry/Eleanor (2016) and San Joaquin (2017)
- 50th full Tuolumne acquisition (2018)
- 250 snow-on acquisitions by ASO (2013-2018)

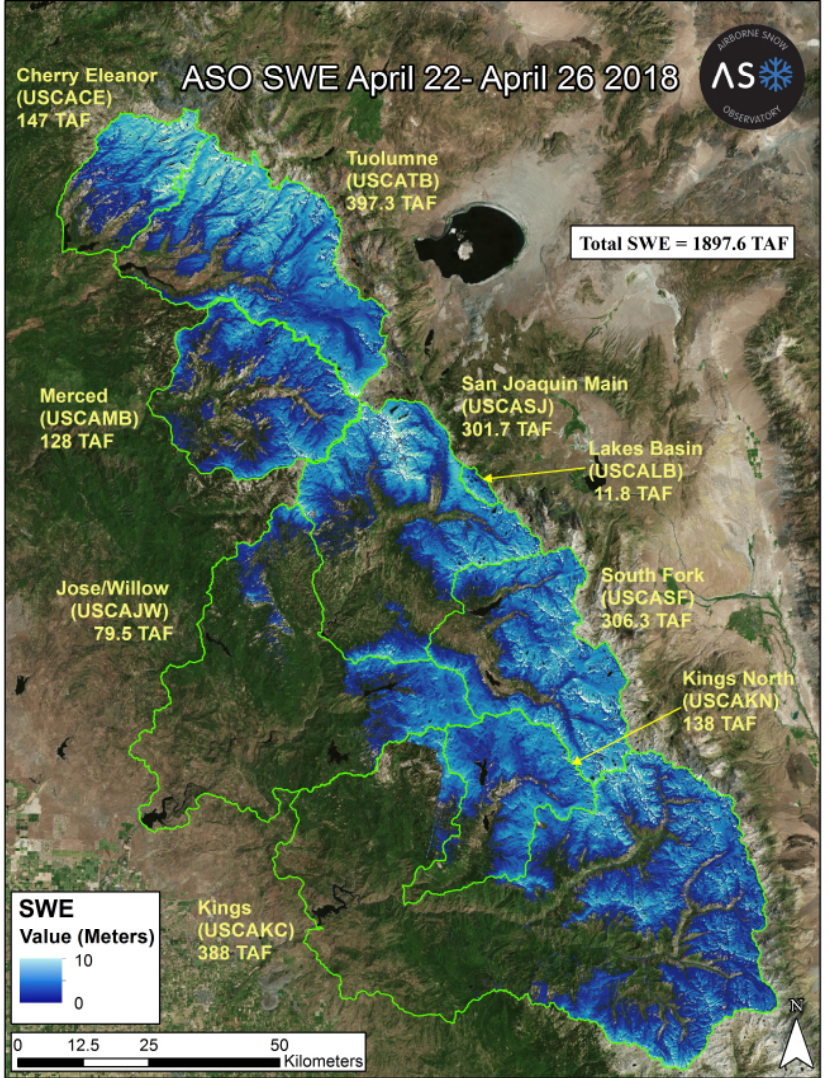

MMH
20 km
20 mi
79 nm bearing 247°
Replay Mode
Play
Speed 50x
Loop Off
© 2018 FlightAware
Weather: 24-Apr-2018 05:20PM UTC
ALTITUDE (ft)
20,000
15,000
10,000
5,000
0
SPEED (mph)
300
200
100
0
MMH / MMH 07:44AM PDT
01:05PM PDT

ASO April 2018

April 22 - 26

- San Joaquin
- Tuolumne/Cherry/Eleanor
- Lakes Basin
- Kings Basin
- Merced

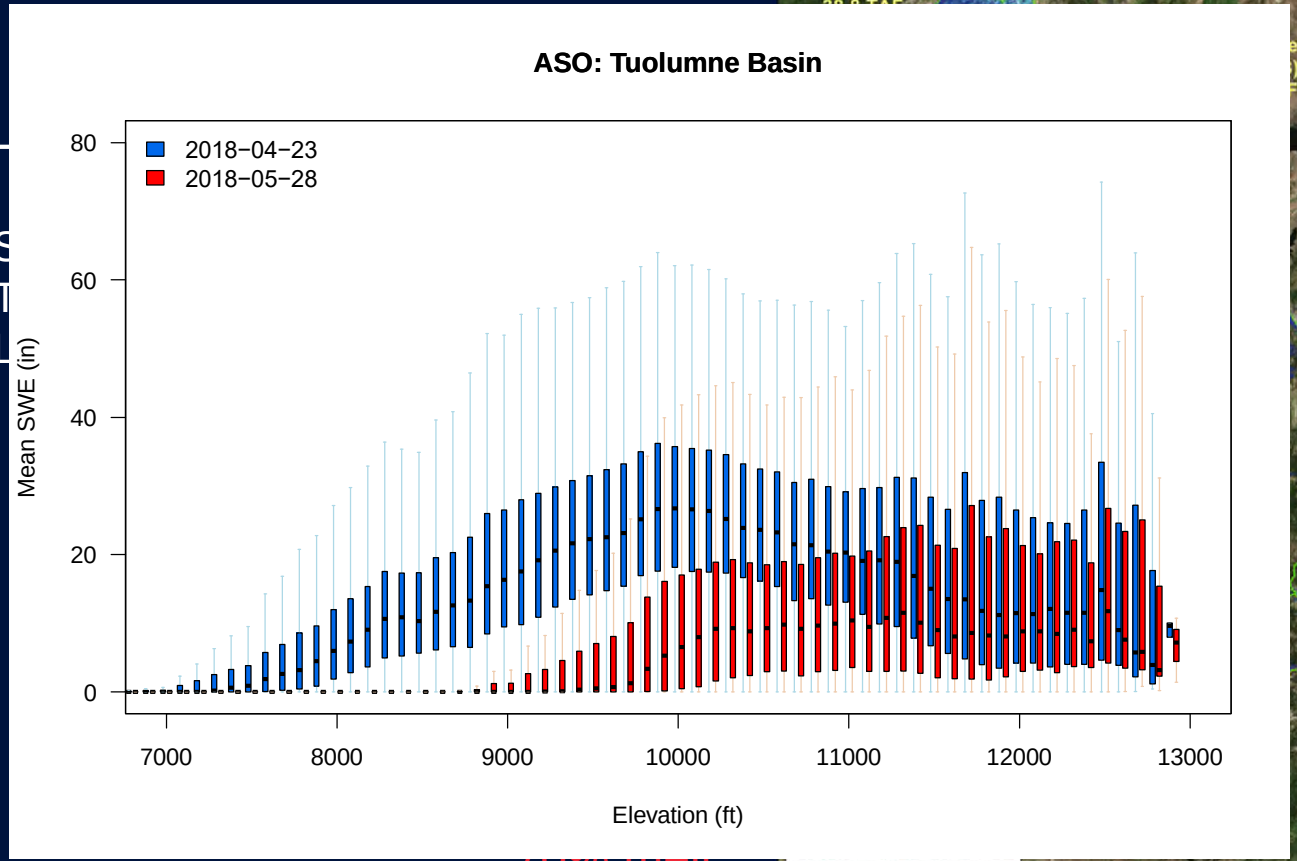
1,243.6 TAF



ASO June 2018

May 28 –

- S
- T
- L



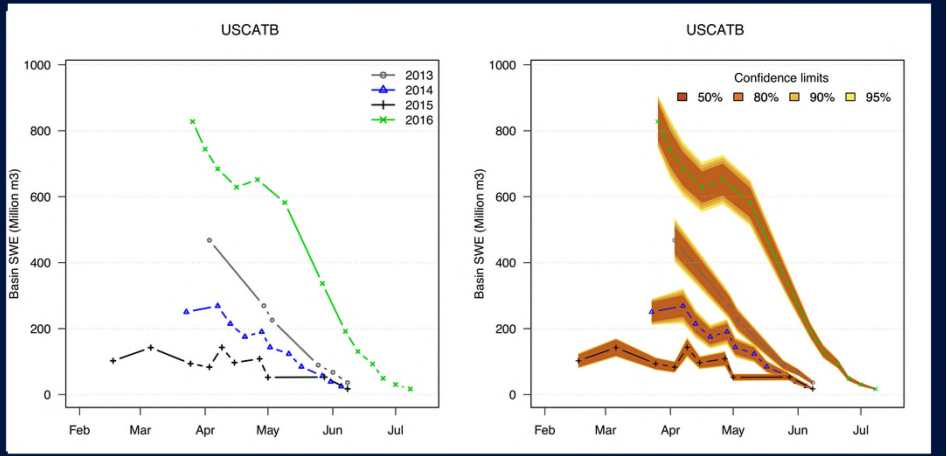
70% melt

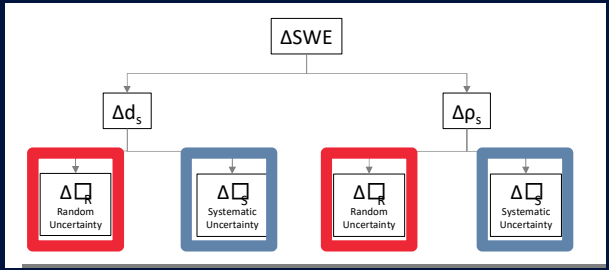
ASO 2018 Overview

2018 Operations

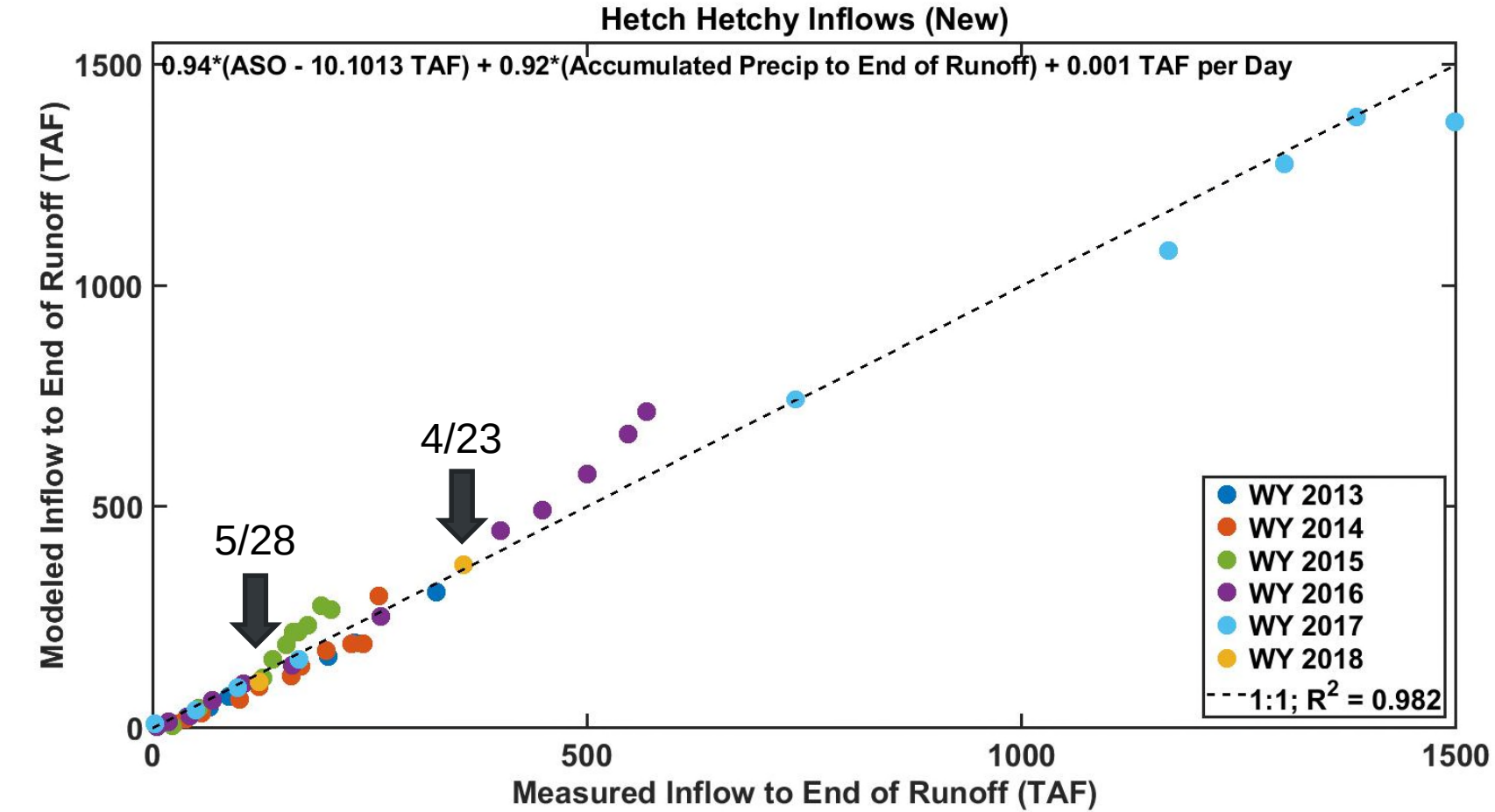
- 23 operational surveys
  - San Joaquin x 3
  - Tuolumne/Cherry/Eleanor x 2
  - Lakes Basin x 3
  - Kings x 1
  - Merced x 1
  - *Gunnison (CO) x 2*

Tuolumne above Hetch Hetchy





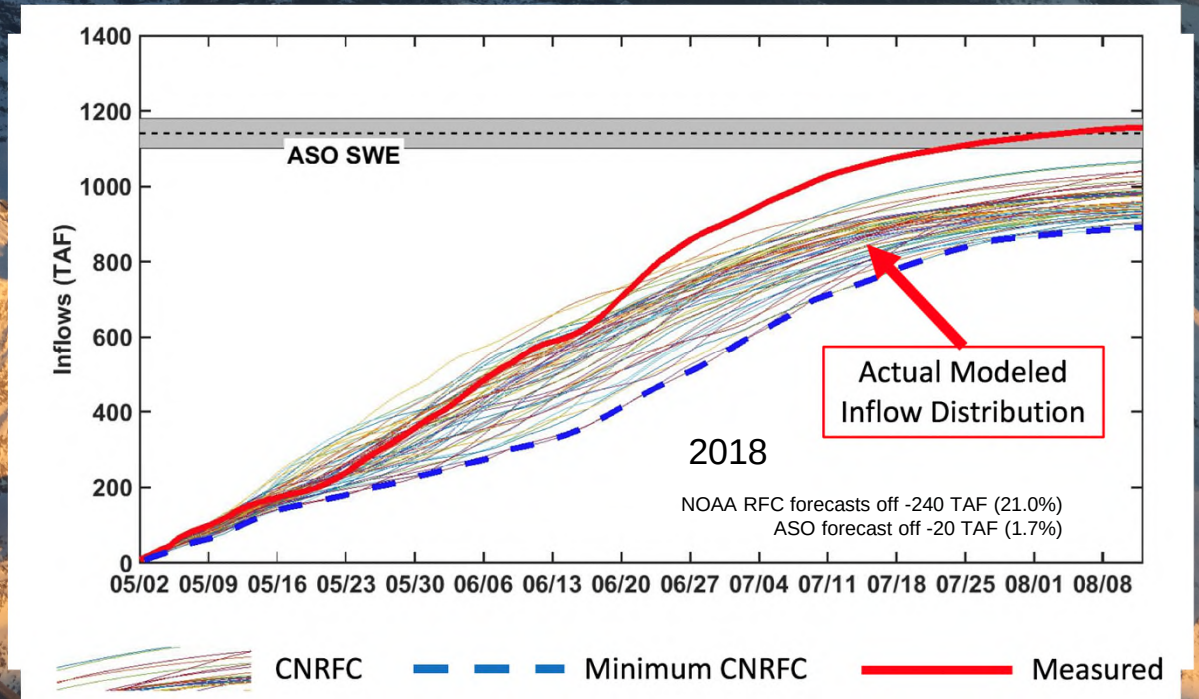
ASO SWE estimates and Inflows – Hetch

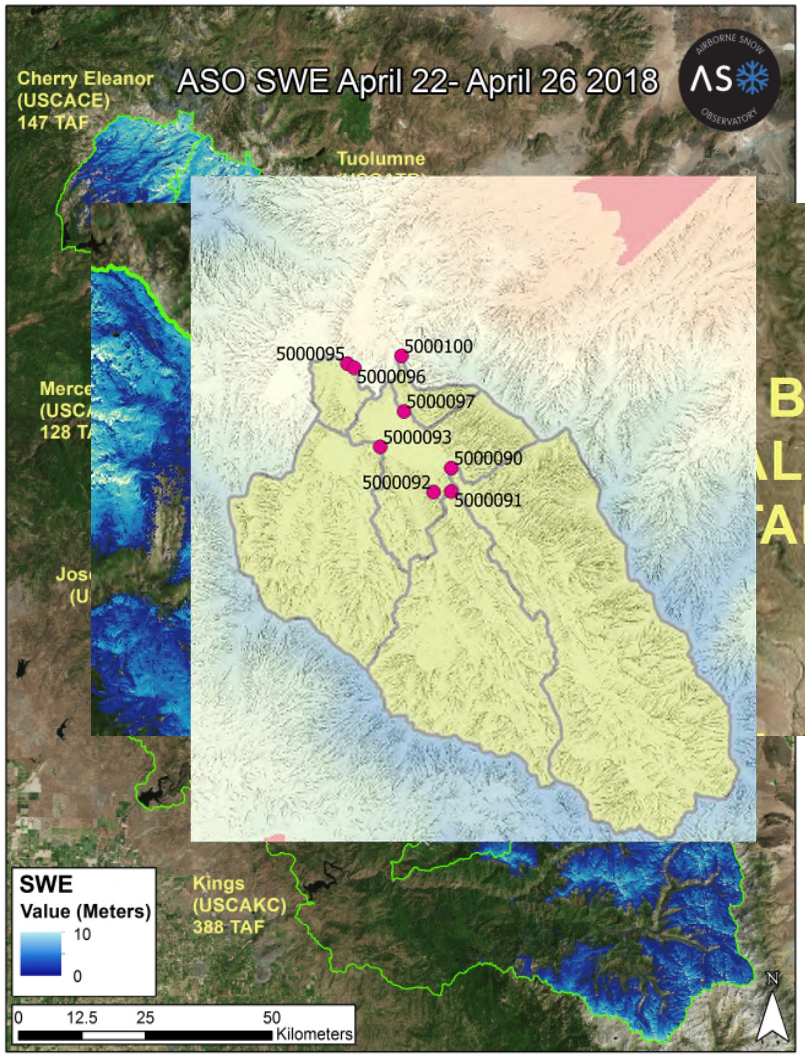


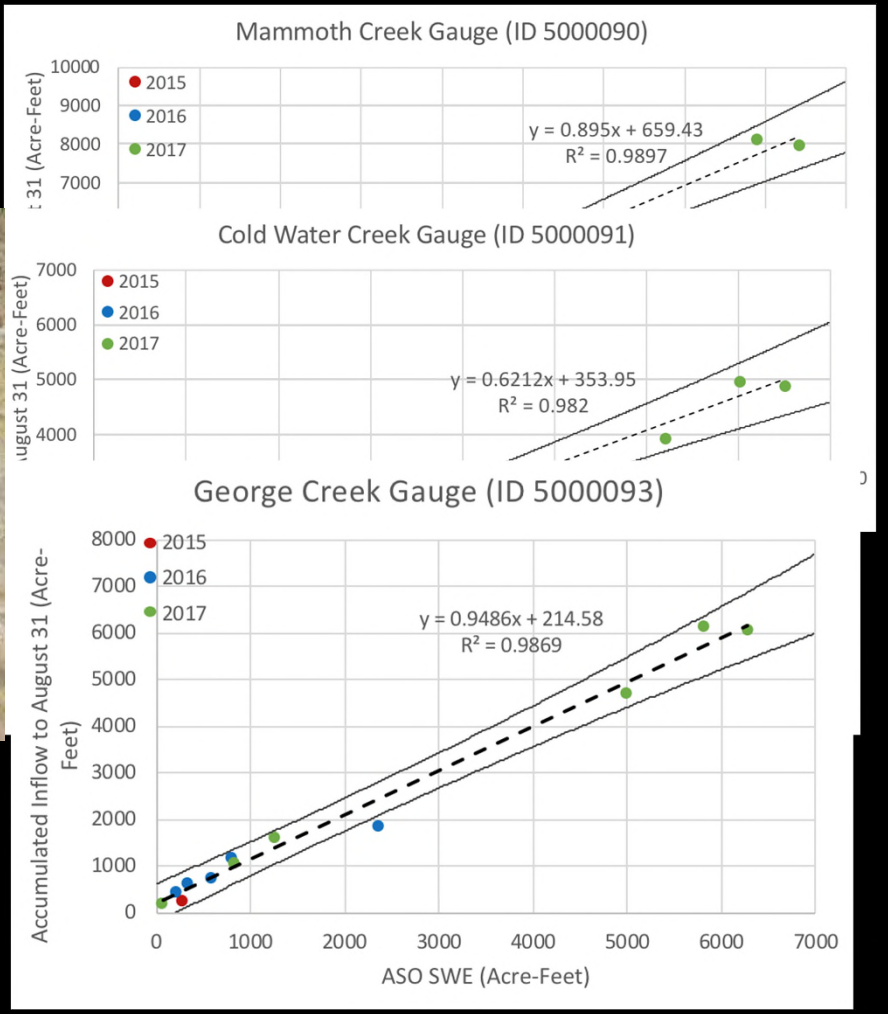
ASO advances streamflow forecasting

Previous seasonal snowmelt runoff forecasting based on traditional methods of snow tubes and snow pillows had > 20% forecast errors in half of years and > 40% forecast errors in 1 in 5 years.

With ASO, across 6 years seasonal forecast errors were consistently less than 2%. *This largely removes the springtime uncertainty and stress for water management and has led to adoption by California operations.*




ASO SWE April 22- April 26 2018
Cherry Eleanor
(USCACE)
147 TAF
Tuolumne
Merce
(USC
128 TA
Jos
(U
Kings
(USCAKC)
388 TAF
5000095
5000100
5000096
5000097
5000093
5000090
5000092
5000091
Basin
LB)
AF
SWE
Value (Meters)
10
0
0
12.5
25
50
Kilometers
N


Mammoth Creek Gauge (ID 5000090)
2015
2016
2017
y = 0.895x + 659.43
R² = 0.9897
Cold Water Creek Gauge (ID 5000091)
y = 0.6212x + 353.95
R² = 0.982
George Creek Gauge (ID 5000093)
y = 0.9486x + 214.58
R² = 0.9869
Accumulated Inflow to August 31 (Acre-Feet)
ASO SWE (Acre-Feet)

Direct Insertion to Distributed Model

DRAFT SUBJECT TO CHANGE

Tuolumne River Basin Snowpack Summary
ASO Update, April 23-24
Water Year 2018
April 23 to April 30

USDA Agricultural Research Service, Boise, Idaho
NASA Jet Propulsion Lab, Pasadena, California
in cooperation with NRCS National Water and Climate Center, Portland, Oregon
and U.S. Bureau of Reclamation, Sacramento, California

Summary

This is the Tuolumne River Basin Snowpack Summary for the period between April 23 and April 30, based on iSnobal model simulation and ASO depth fields from overflights on April 23-24. The flights were applied as a model state update for snow depths on April 23, which is the initialization point for this model run. The effect of updating the iSnobal snow depths with ASO depths was to decrease the total basin storage by approximately 8%, most of which occurred between 7,000-9,000 ft.

The reporting domain covers the Tuolumne River basin upstream of Hetch Hetchy reservoir, the Cherry Creek basin upstream of Cherry Lake and Eleanor basin upstream of Lake Eleanor. Extended Tuolumne refers to the total of all three basins. The total amount of water stored in the snowpack as of April 30 is estimated to be **387.7 KAF**, which represents a change of **-91.7 KAF** of snow storage during the reporting period.

Water Year Precipitation Inputs

Basin	ppt (mean) [in]	Rain [%]
Extended Tuolumne	34.7	~37
Tuolumne	31.9	~33
Cherry	42.4	~39
Eleanor	39.7	~48

Snow Storage and Surface Water Inputs

Basin	SWE [KAF]	SWE (avail) [KAF]	SWE (mean) [in]	ΔSWE [KAF]	SWI [KAF]
Extended Tuolumne	387.7	374.9	11.3	-91.7	738.6
Tuolumne	200.8	281.8	12.1	-61.0	419.5
Cherry	72.4	69.5	11.8	-22.2	187.0
Eleanor	24.0	23.0	5.8	-8.3	130.2

SWE: Snow Water Equivalent, snow storage in the basin

Results

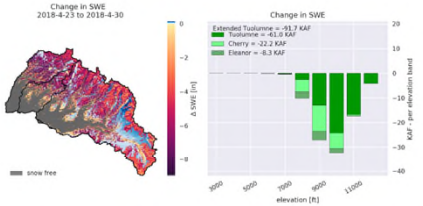


Figure 1: Change in SWE during the reporting period, as a depth (left) and as a function of elevation band (right).

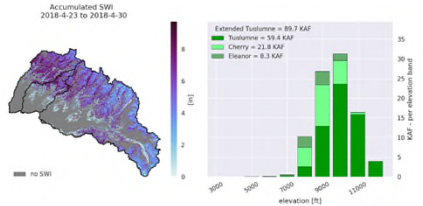


Figure 2: Current Surface Water Inputs (SWI) for the reporting period, as a depth (left) and as a function of elevation band (right).

DRAFT SUBJECT TO CHANGE

Tuolumne River Basin Snowpack Summary
ASO Updates, Apr 23, May 28
Water Year 2018
May 29 to June 10

USDA Agricultural Research Service, Boise, Idaho
NASA Jet Propulsion Lab, Pasadena, California
in cooperation with NRCS National Water and Climate Center, Portland, Oregon
and U.S. Bureau of Reclamation, Sacramento, California

Summary

This is the Tuolumne River Basin Snowpack Summary for the period between May 29 and June 28. The reporting domain covers the Tuolumne River basin upstream of Hetch Hetchy reservoir, the Cherry Creek basin upstream of Cherry Lake and Eleanor basin upstream of Lake Eleanor. Extended Tuolumne refers to the total of all three basins. The total amount of water stored in the snowpack as of June 10 is estimated to be **47.3 KAF**, which represents a change of **-114.7 KAF** of snow storage during the reporting period.

Water Year Precipitation Inputs

Basin	ppt (mean) [in]	Rain [%]
Extended Tuolumne	36.3	~26
Tuolumne	33.6	~21
Cherry	43.9	~29
Eleanor	41.0	~41

Snow Storage and Surface Water Inputs

Basin	SWE [KAF]	SWE (avail) [KAF]	SWE (mean) [in]	ΔSWE [KAF]	SWI [KAF]
Extended Tuolumne	47.3	47.3	1.4	-114.7	1179.1
Tuolumne	36.5	36.5	1.6	-86.3	742.6
Cherry	7.3	7.3	1.2	-21.0	272.6
Eleanor	3.3	3.3	0.8	-7.0	160.9

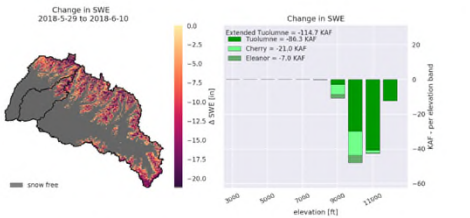


Figure 1: Change in SWE during the reporting period, as a depth (left) and as a function of elevation band (right).

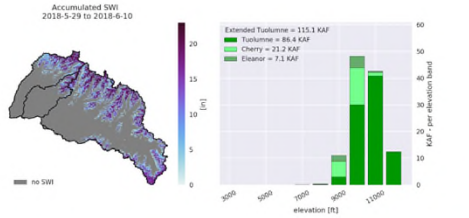


Figure 2: Current Surface Water Inputs (SWI) for the reporting period, as a depth (left) and as a function of elevation band (right).

AGU PUBLICATIONS

Water Resources Research

RESEARCH ARTICLE

10.1002/2017WR020473

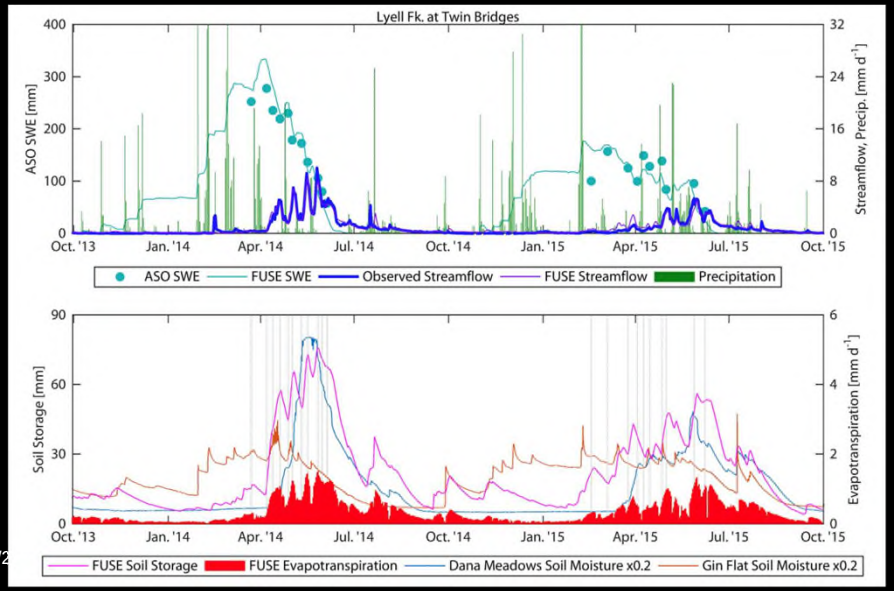
Key Points:

- Distributed streamflow and lidar-based SWE observations are used to close alpine basins' water balance during 2013–2015 California drought
- Estimates of the residual ET term (snowmelt plus precipitation minus streamflow) are consistent between lidar flights and across basins
- Basin-mean ET from peak SWE to end of summer averaged 168, 162 and 191 mm in 2013–2015, lower than other estimates at point locations

High-Elevation Evapotranspiration Estimates During Drought: Using Streamflow and NASA Airborne Snow Observatory SWE Observations to Close the Upper Tuolumne River Basin Water Balance

Brian Henn[1,2], Thomas H. Painter[3], Kat J. Bormann[3], Bruce McGurk[4], Alan L. Flint[5], Lorraine E. Flint[5], Vince White[6], and Jessica D. Lundquist[2]

[1]Currently, Center for Western Weather and Water Extremes, Scripps Institution of Oceanography, UC San Diego, La Jolla, CA, USA, [2]Department of Civil and Environmental Engineering, University of Washington, Seattle, WA, USA, [3]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA, [4]McGurk Hydrologic, Orinda, CA, USA, [5]United States Geological Survey, Sacramento, CA, USA, [6]Southern California Edison, Bishop, CA, USA



AGU100 ADVANCING EARTH AND SPACE SCIENCE

Water Resources Research

RESEARCH ARTICLE

10.1029/2018WR023190

Special Section:
Advances in remote sensing, measurement, and simulation of seasonal snow

Key Points:

- This is the first near-real time application of a model state variable being periodically updated using lidar-derived snow depths
- The first update in each year is most crucial since it defines the spatial

Direct Insertion of NASA Airborne Snow Observatory-Derived Snow Depth Time Series Into the *iSnobal* Energy Balance Snow Model

Andrew R. Hedrick[1,2], Danny Marks[1], Scott Havens[1], Mark Robertson[1], Micah Johnson[1], Micah Sandusky[1], Hans-Peter Marshall[2,3], Patrick R. Kormos[4], Kat J. Bormann[5], and Thomas H. Painter[5]

[1]USDA-ARS Northwest Watershed Research Center, Boise, ID, USA, [2]Department of Geosciences, Boise State University, Boise, ID, USA, [3]U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, USA, [4]Colorado Basin River Forecast Center, National Weather Service, Salt Lake City, UT, USA, [5]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

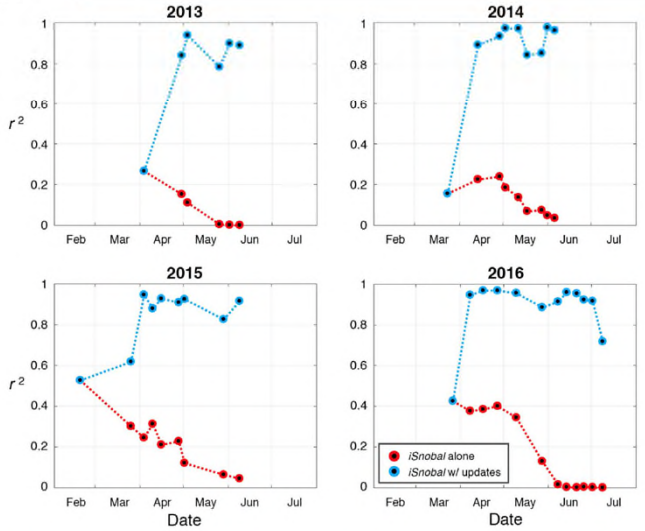
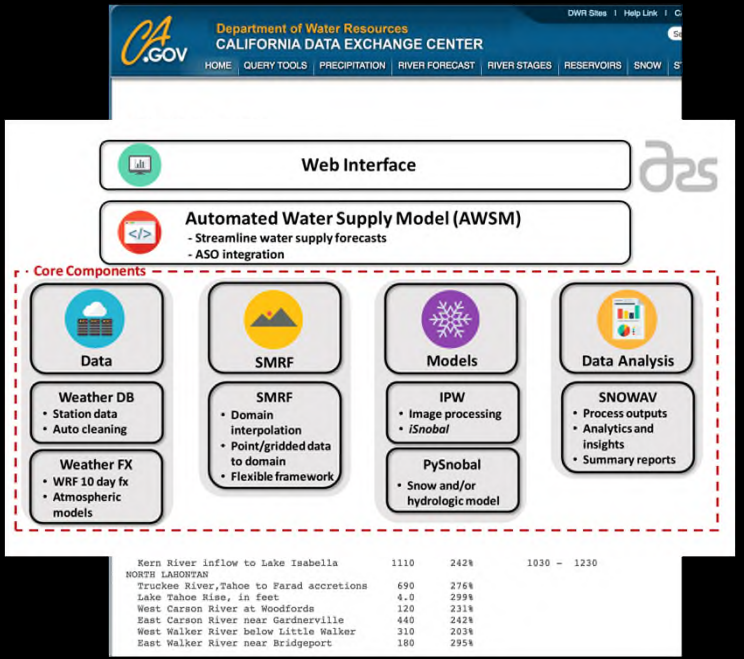


Figure 7. Coefficients of determination for each of the ASO-derived snow depth products with respect to *iSnobal* predicted snow depths on the day of the lidar acquisitions for both the previously updated (blue) and ordinary estimates without ASO (red). Once the spatial distribution is defined by the first update, the correlation to subsequent updates drastically increases.

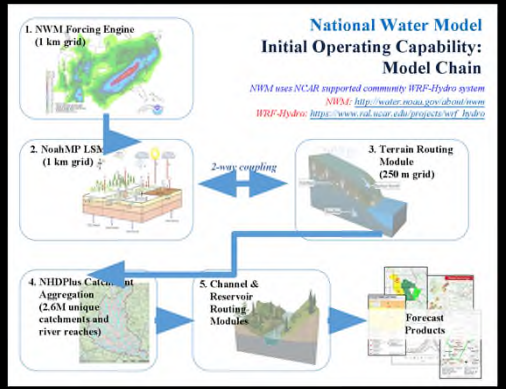
Forecast Modeling Paths – 1-10 day forecasts

Bulletin 120

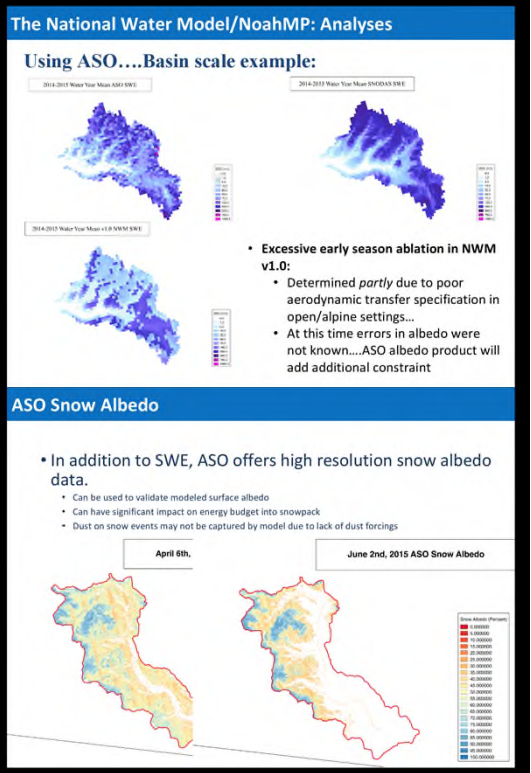


Active effort with DWR, Cooperators, etc.

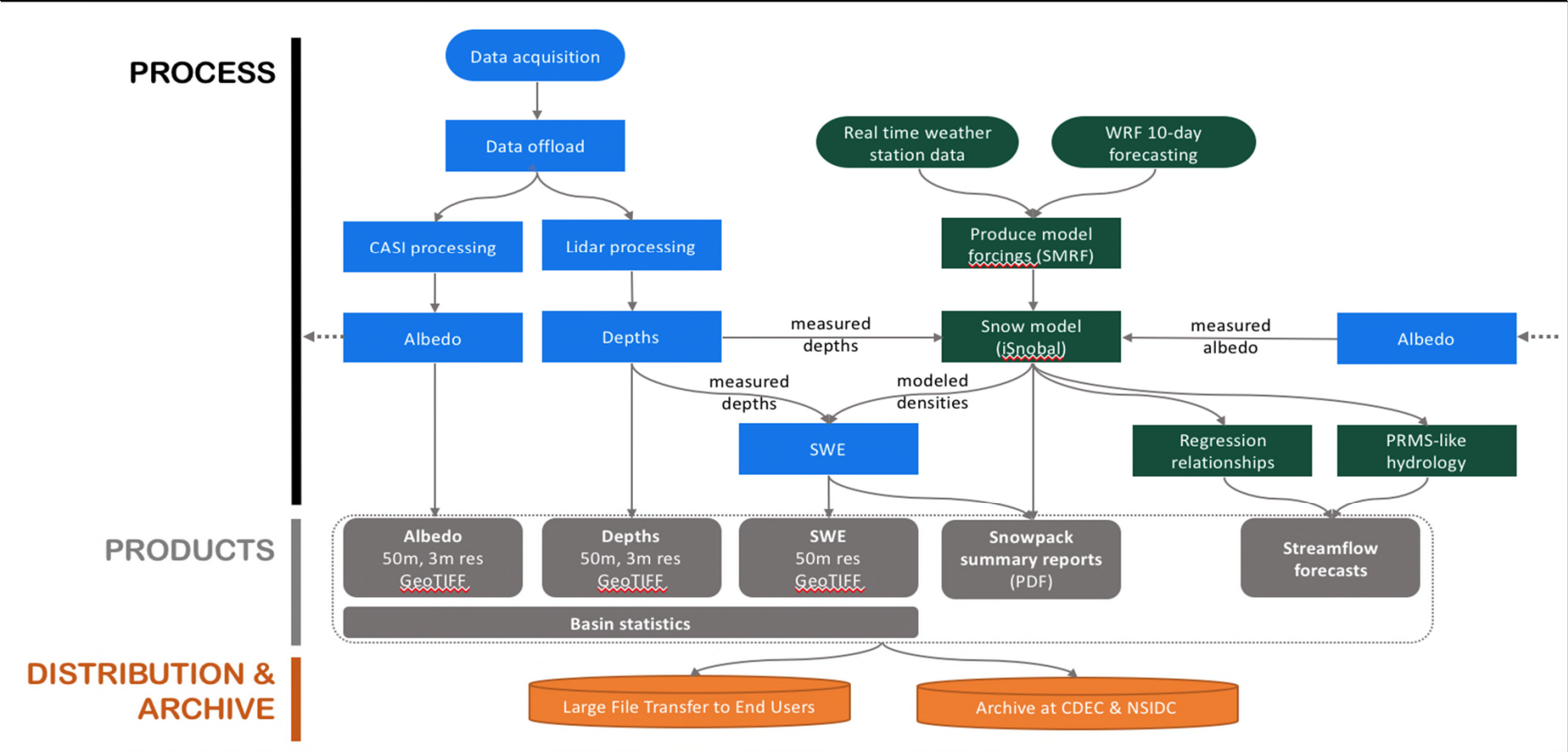
RFC Snow-17 and National Water Model



Active effort with National Water Model team at National Center for Atmospheric Research

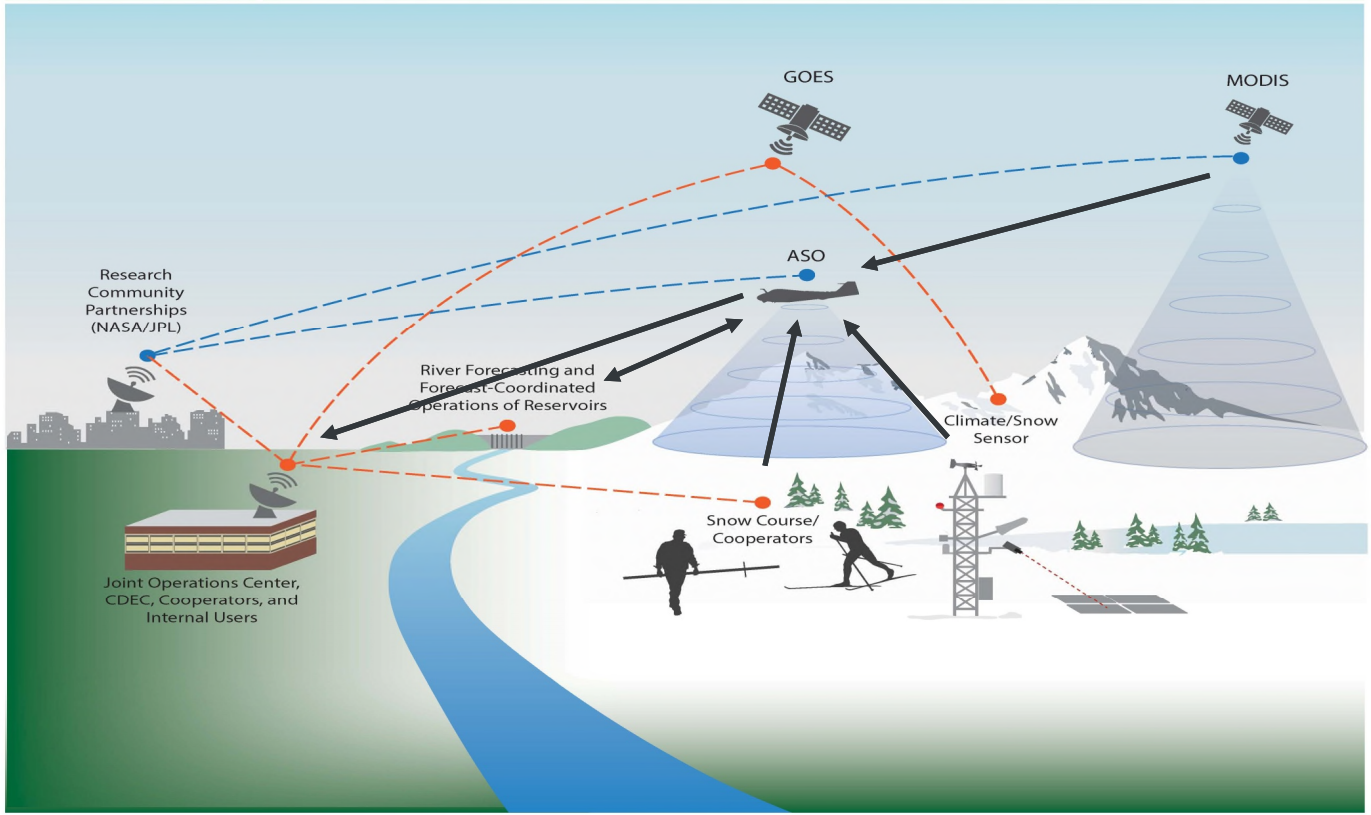


Modeling Flow – Daily to 10-day Forecasting



62ND ANNUAL MEETING
CALIFORNIA COOPERATIVE SNOW SURVEYS PROGRAM

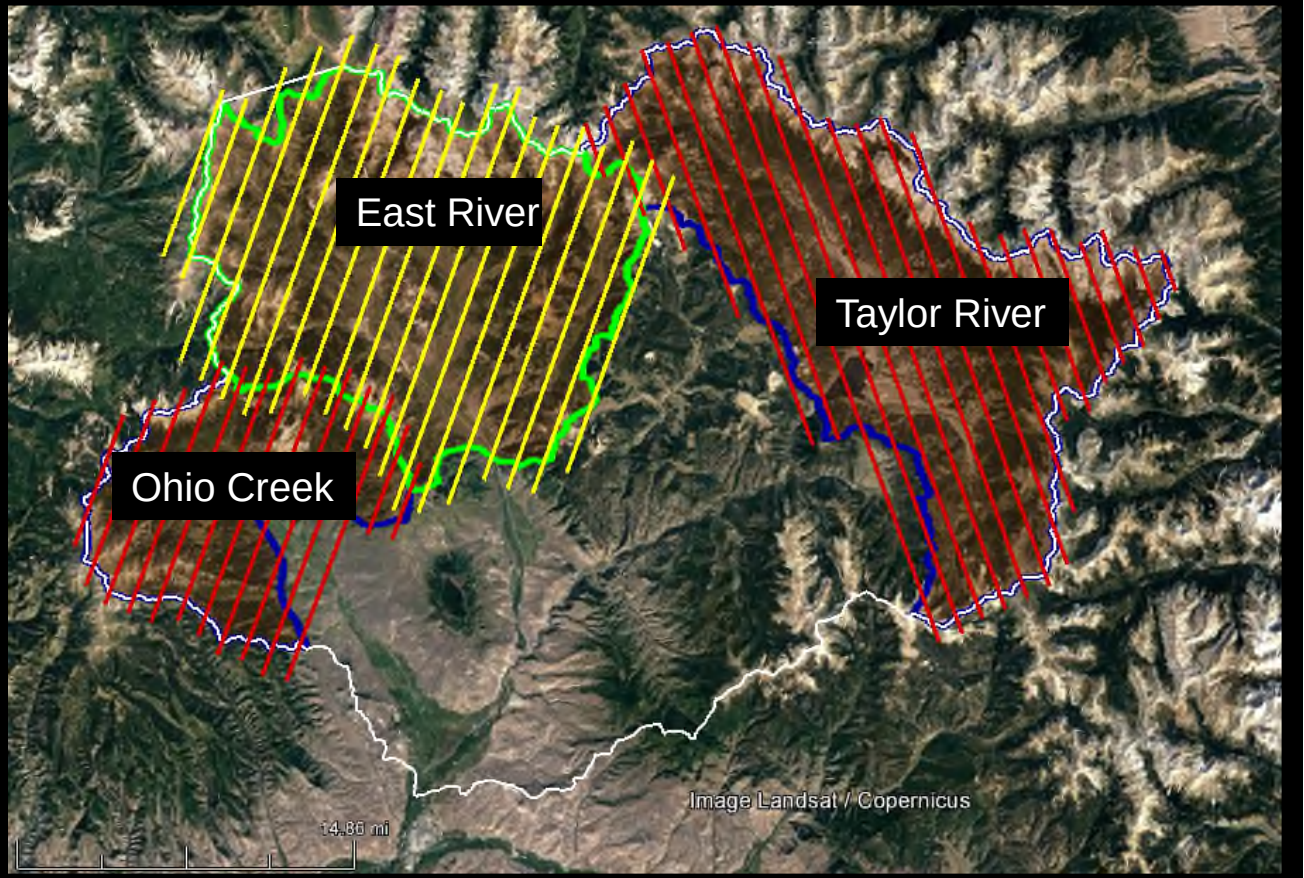
California's Upper Watershed Remote Hydrologic Data Collection Network



JPL

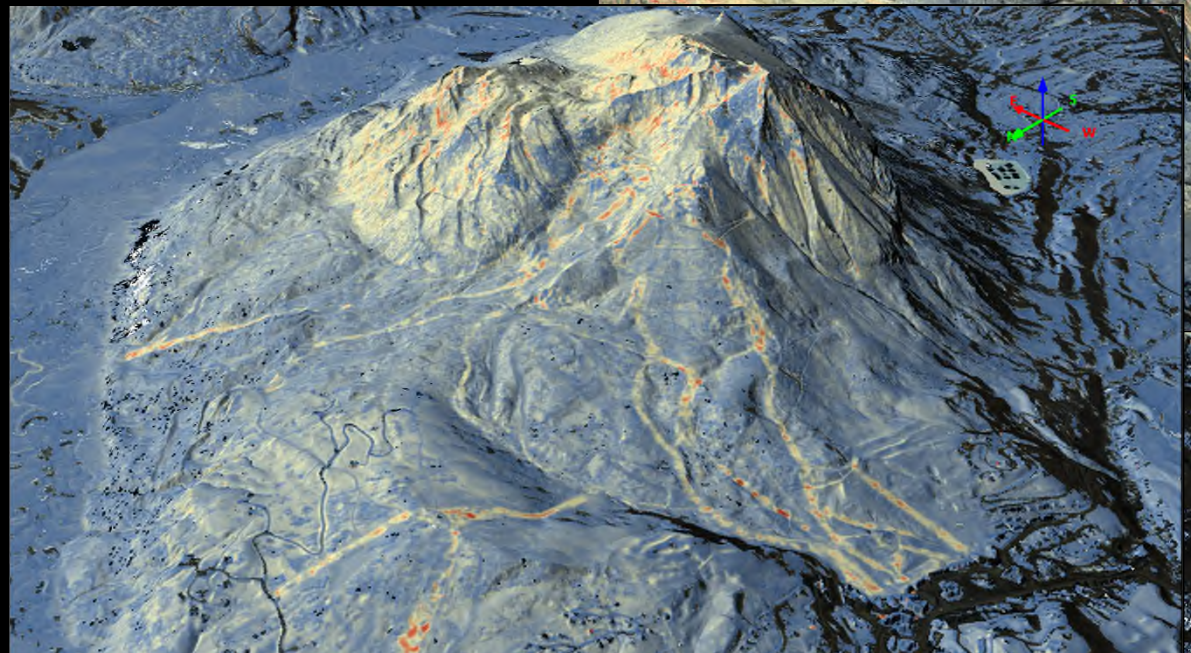
Upper Gunnison project

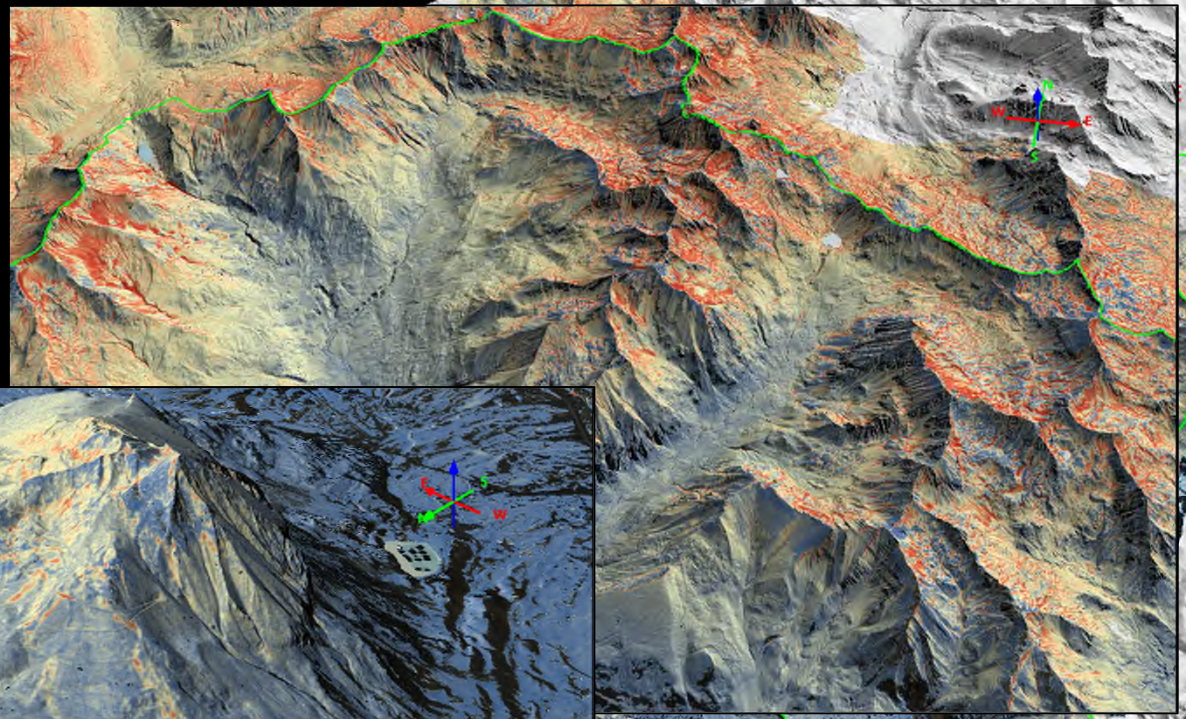
- Colorado Water Conservation Board support
- Collaboration with:
  - UGRWCD
  - DOE WFSFA
  - NCAR WRF-HYDRO forecasting project
- Snow-on flights
  - 1 Spring 2016 (East R.)
  - 2 Spring 2018 (East/Ohio/Taylor)
- Snow-off flight Fall 2018
- Planning 2 snow-on flights in melt season 2019
  - Likely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

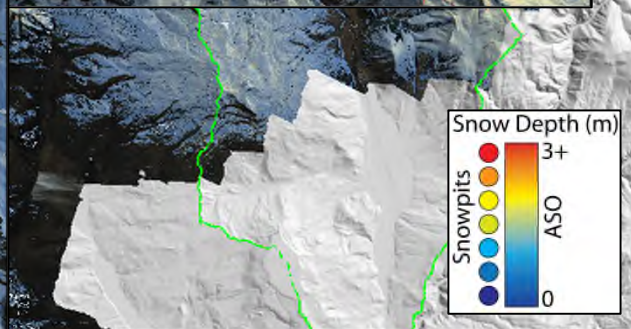


2018 results

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





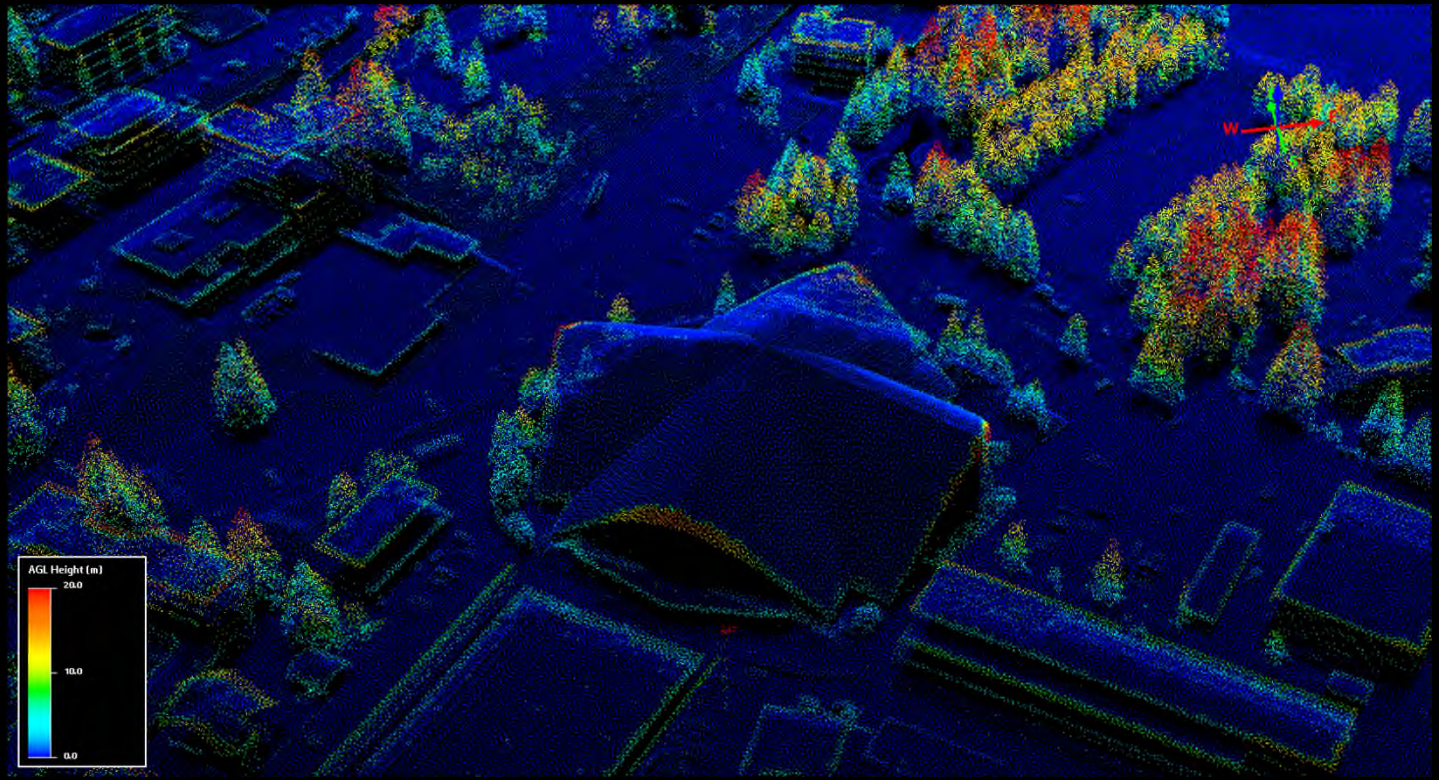


ALS demo mission in the European Alps in 2017

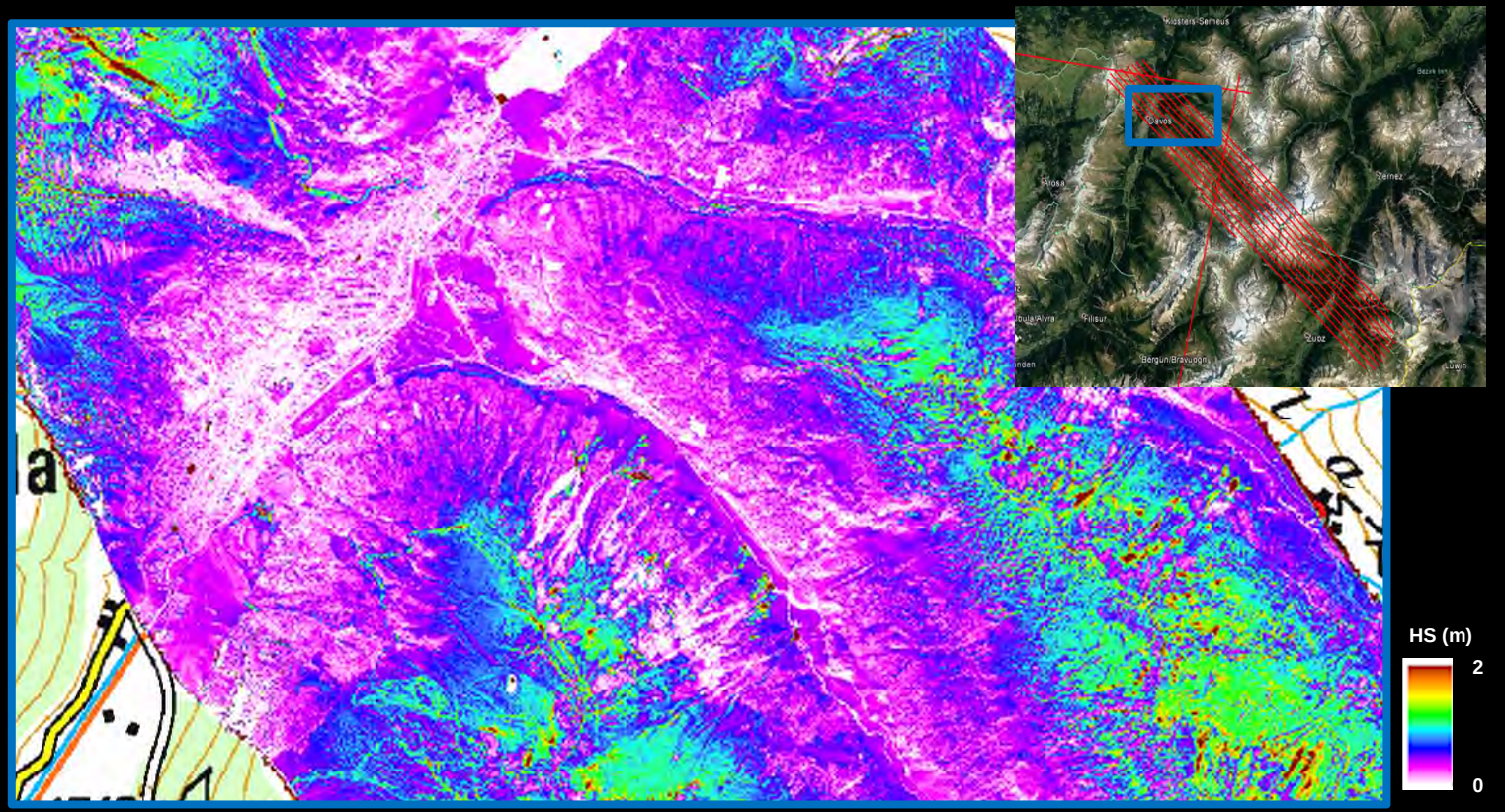


ALS demo mission in the European Alps in 2017

- LiDAR return density at the lowest point within the target area (ice hockey arena Davos)



Snow depth (derived from flights on March 31 | August 29)



Constraint of operational runoff forecasting with snow properties from MODIS and VIIRS

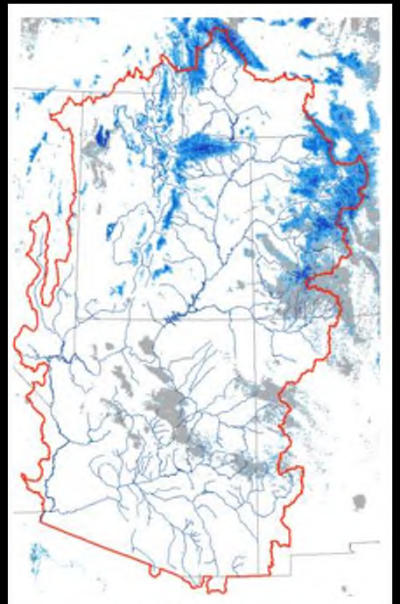


Figure 1: CBRFC area of responsibility (red outline) and gridded MODIS-derived snow cover data

NASA-sponsored partnership with NOAA CBRFC

Remote Sensing of Environment 113 (2009) 868–879

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Retrieval of subpixel snow covered area, grain size, and albedo from MODIS

Thomas H. Painter [a,*], Karl Rittger [b], Ceretha McKenzie [c], Peter Slaughter [b], Robert E. Davis [c], Jeff Dozier [b]

[a] Department of Geography, University of Utah, Salt Lake City, UT 84112, USA
[b] Donald Bren School of Environmental Science and Management, University of California, Santa Barbara, CA 93106, USA
[c] US Army Cold Regions Research and Engineering Laboratory, Hanover, NH 03755, USA

GEOPHYSICAL RESEARCH LETTERS, VOL. 39, L17502, doi:10.1029/2012GL052457, 2012

Radiative forcing by light absorbing impurities in snow from MODIS surface reflectance data

Thomas H. Painter,[1] Ann C. Bryant,[2] and S. McKenzie Skiles[3]

Received 18 June 2012; revised 18 July 2012; accepted 23 July 2012; published 11 September 2012.

Constraint of operational runoff forecasting with snow properties from MODIS and VIIRS

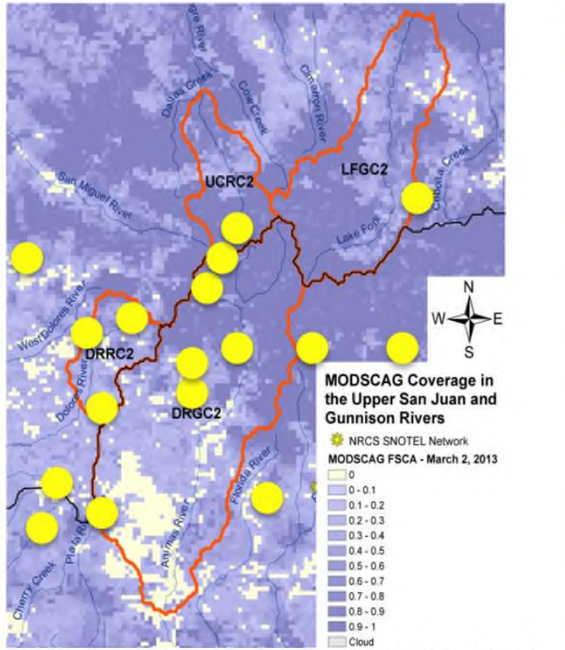


Figure 3: Spatial extent of remotely sensed fractional snow cover from MODIS (grid), with SNOTEL station locations in southwestern Colorado (yellow dots).

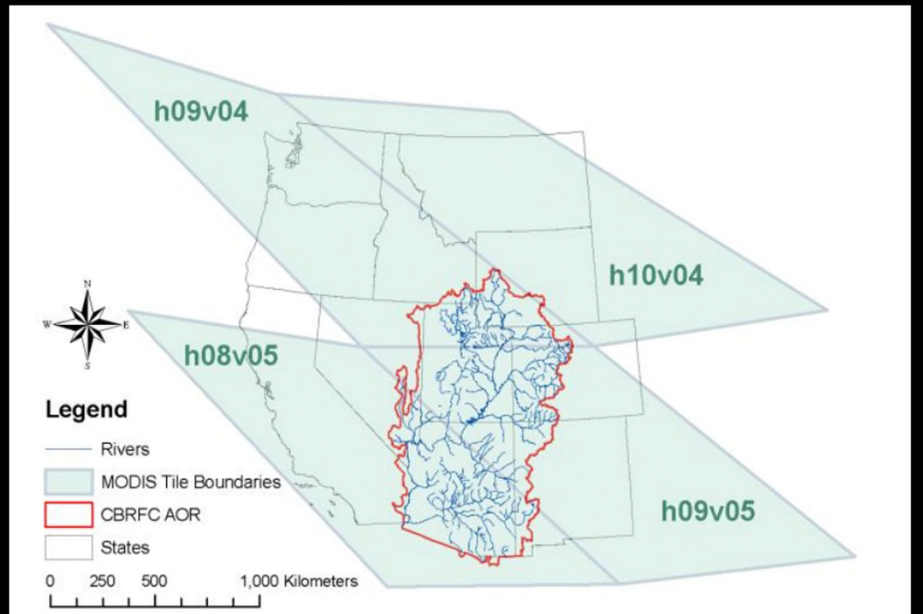


Figure 5: MODIS tiles comprising full coverage over the CBRFC area of responsibility (red outline).

Constraint of operational runoff forecasting with snow properties from MODIS and VIIRS

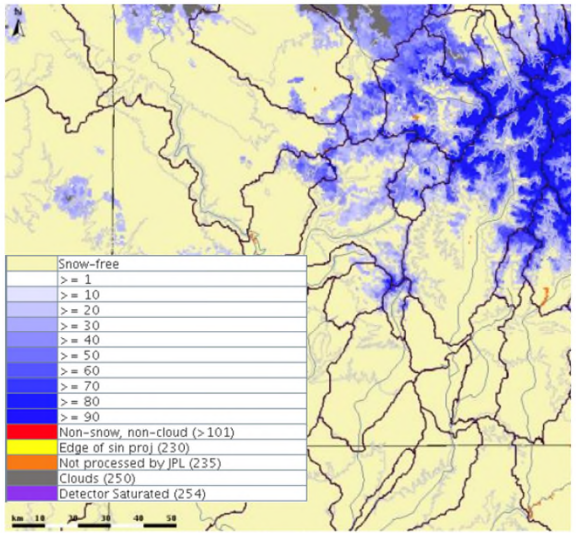
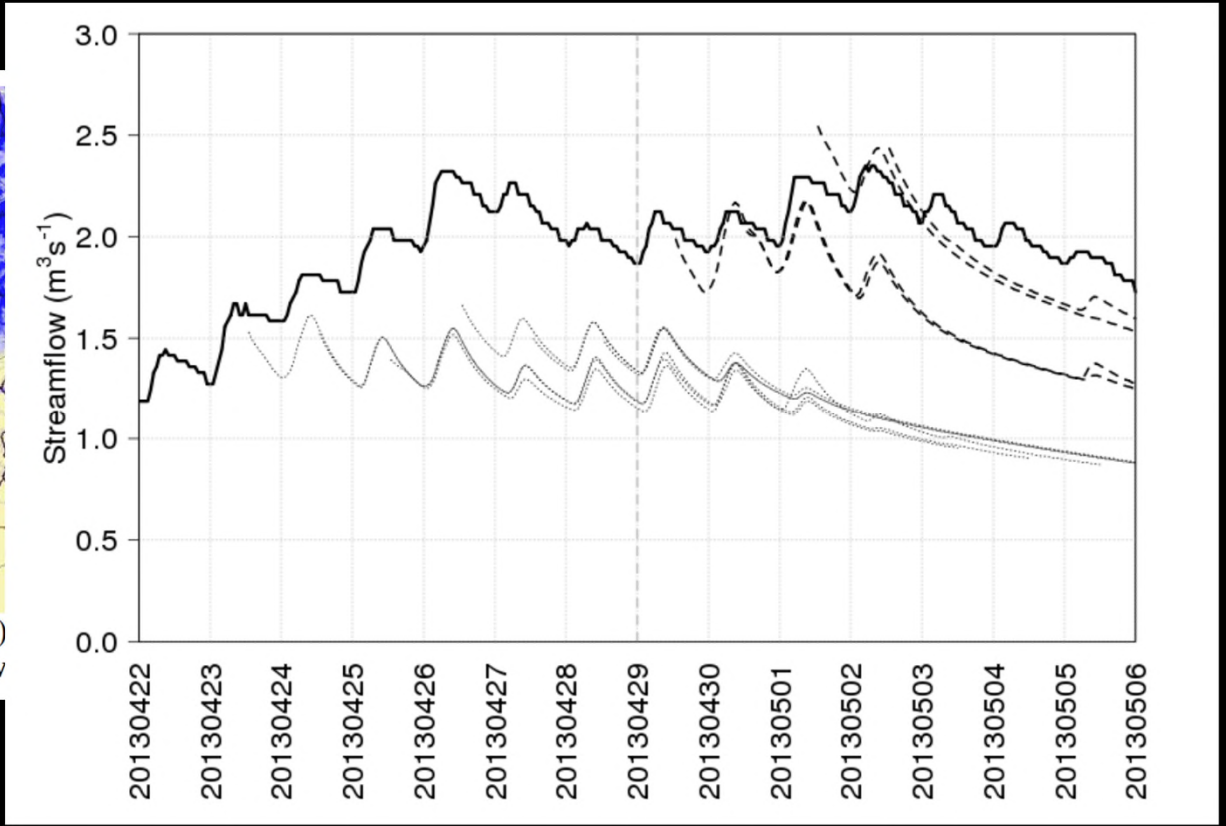
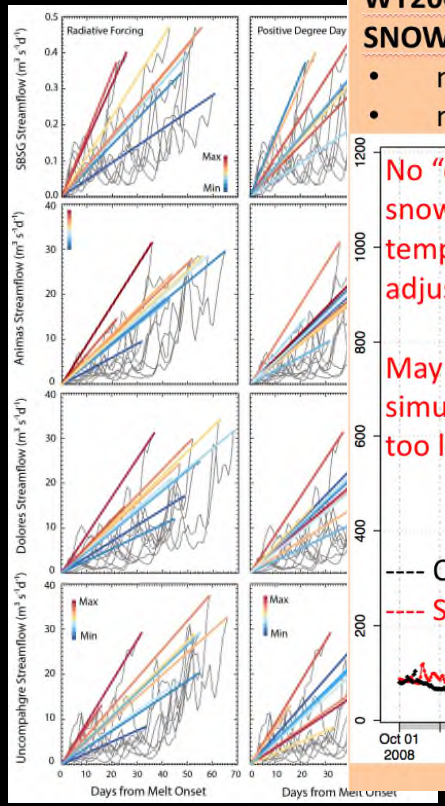


Figure 6: Graphical display of MODSCAG (a) southwestern Colorado, April 9, 2014, as view

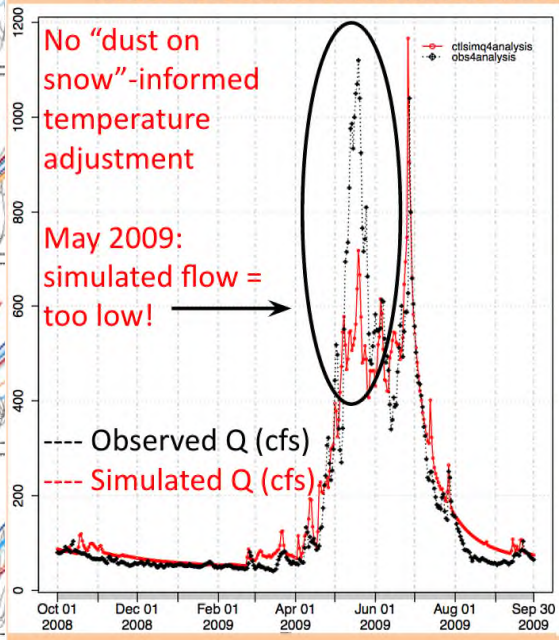


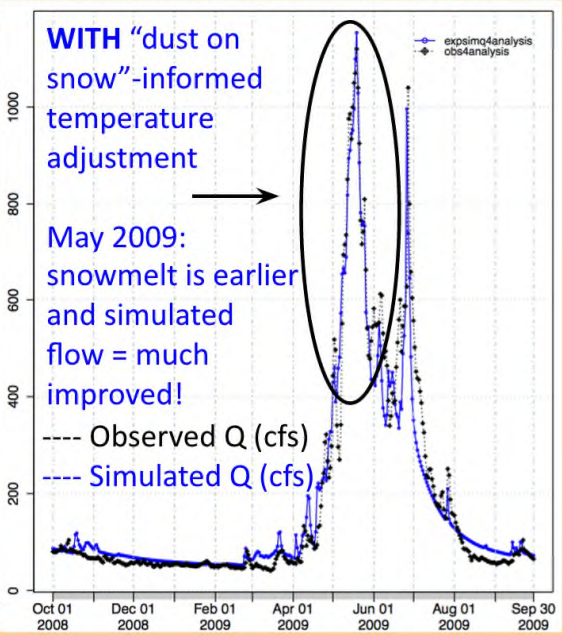
Dust Radiative Forcing (albedo perturbation)

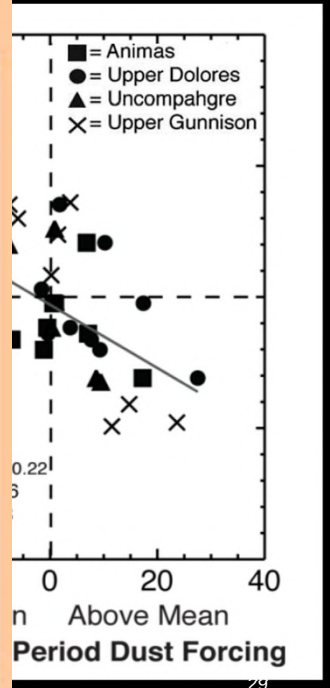


WY2009 (dusty snowpack) application of the MODDRFS-informed adjustment to SNOW17 temperature inputs:

- more prominent impacts in UCRC2 streamflow than for the "clean snowpack"
- noticeable shifts of snowmelt-driven streamflow to *earlier* in runoff season



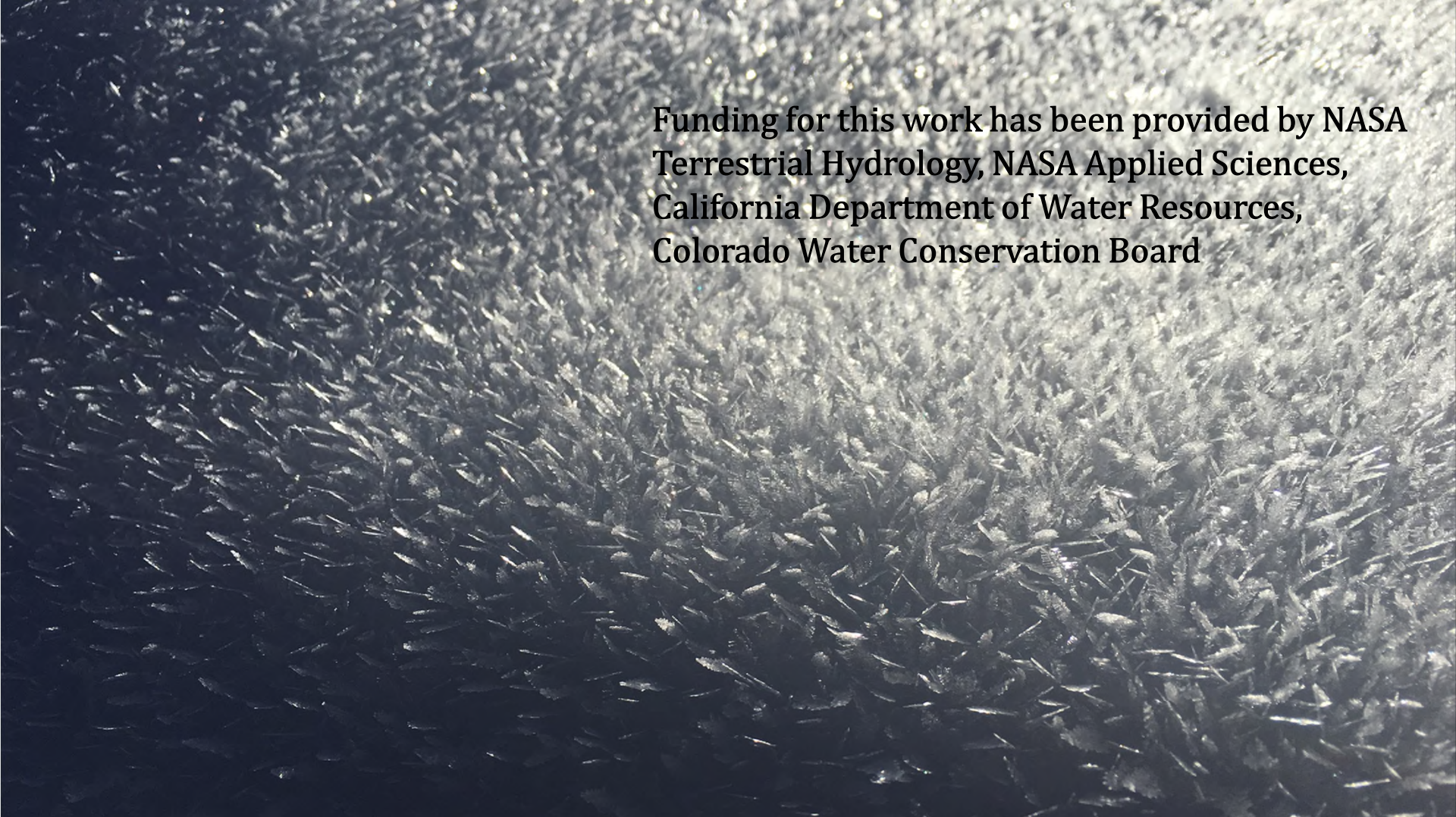




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n snow on accuracy of operational
lorado River Basin

S. Deems,[3,4] and Stacie M. Bender[5]



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