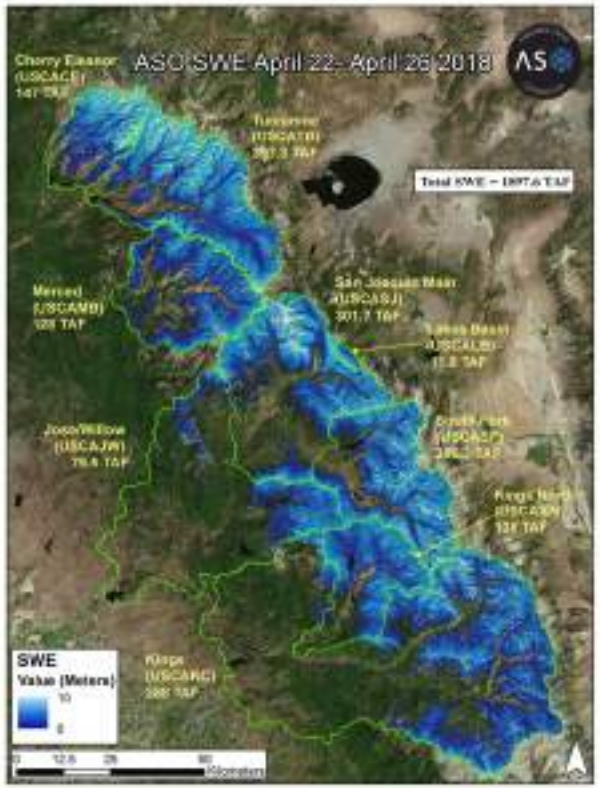
Airborne Snow Observatories: building on NASA legacy to characterize California's mountain systems for snowpack water resources and beyond

Thomas H. Painter
CEO, ASO Inc.

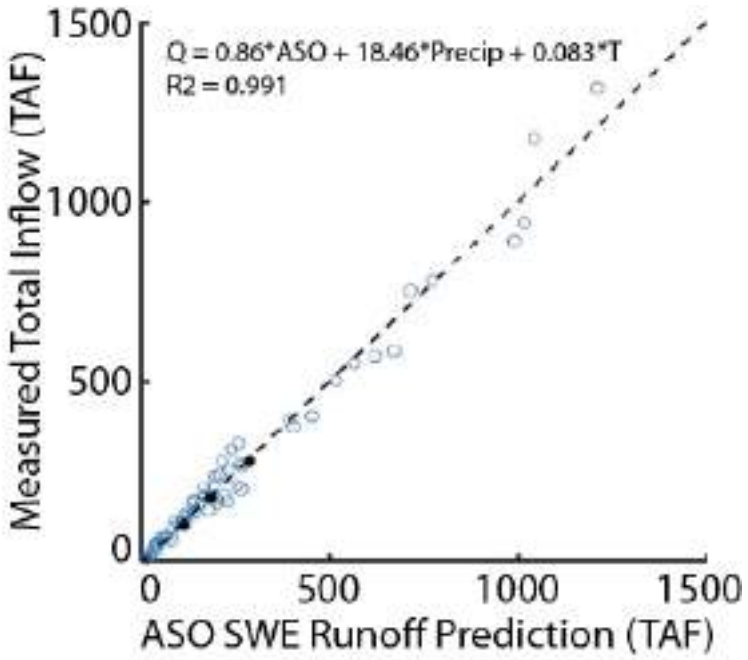
Outline

- Overview of ASO
- The successes and direction forward of ASO;
- The broad scope of the use of the repeat ASO data
- Preliminary view of our data archival and distribution system

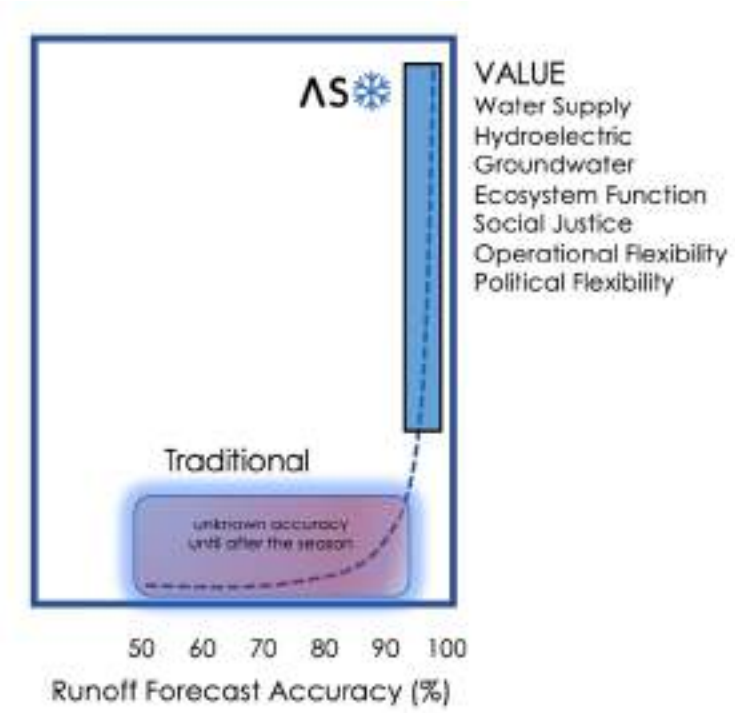
Accurate Snow Mapping Enables Unprecedented Value



NASA-legacy snow water equivalent **mapping** across entire watersheds



Unprecedented snowmelt runoff forecasting **accuracy**

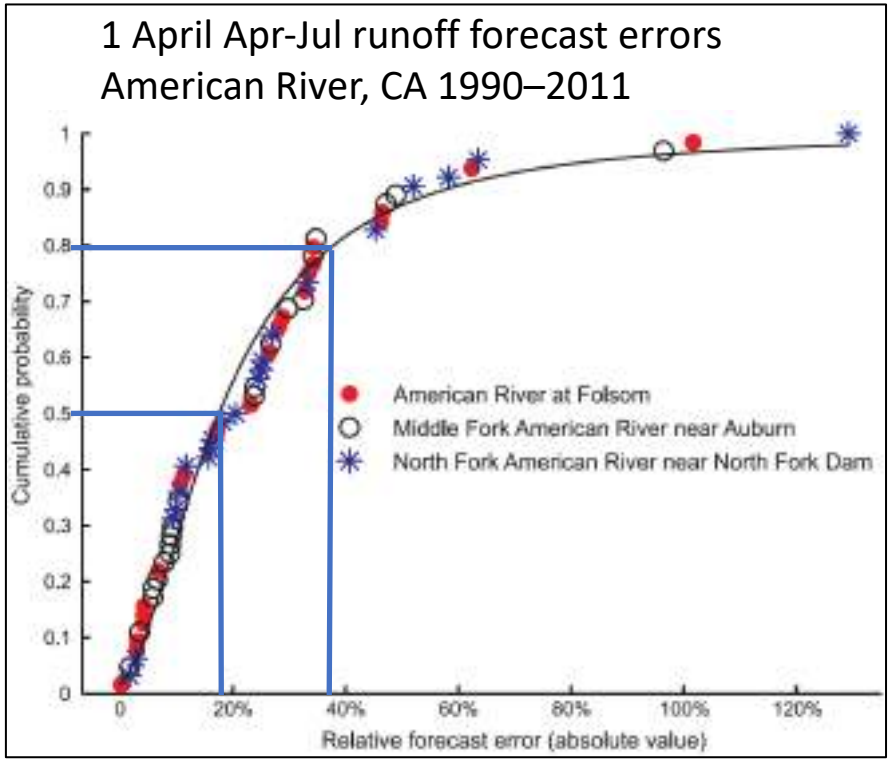


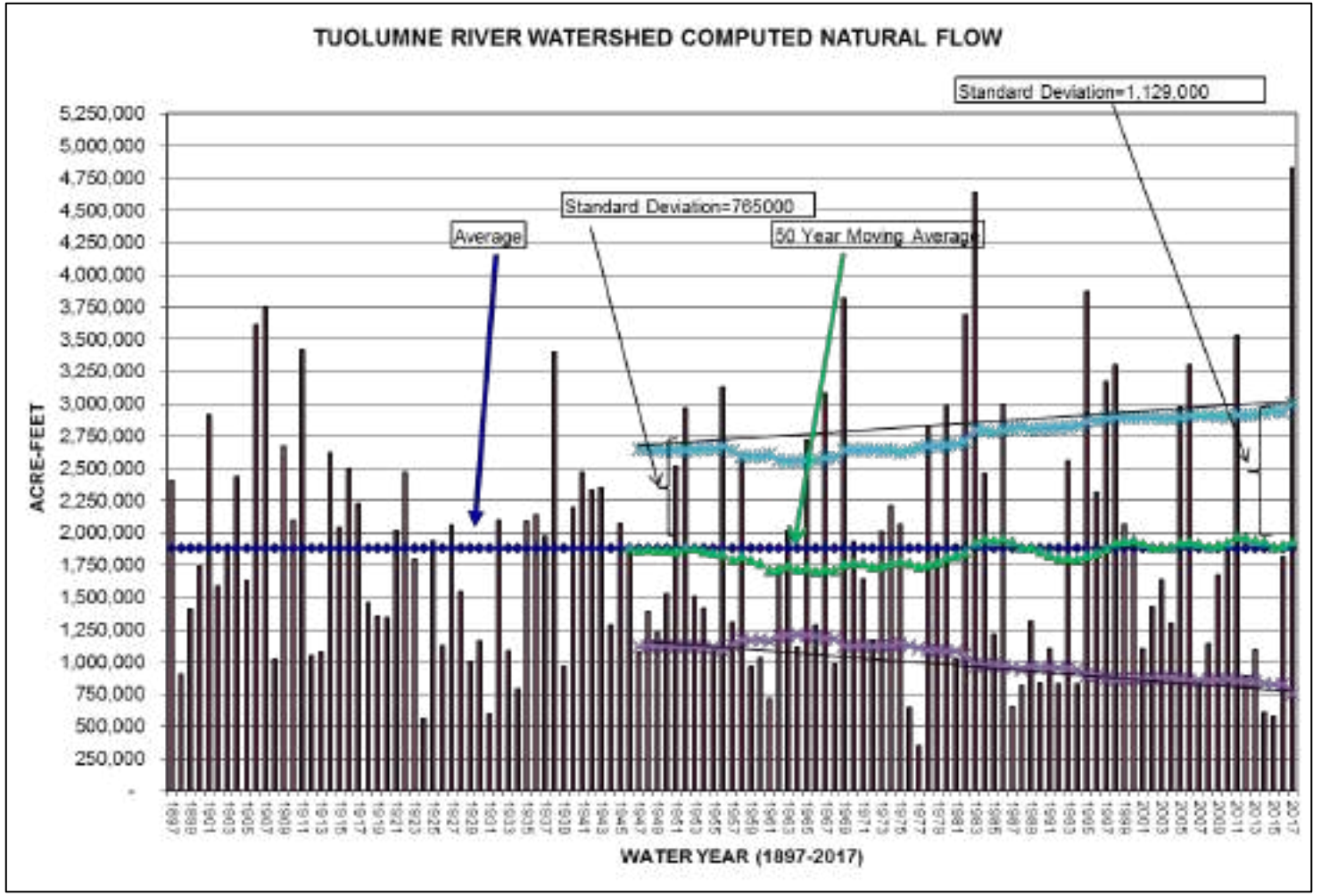
Marked improvement in consistently high accuracy translates to customer **value**

Runoff forecasts: vulnerable in current & future climate

Statistical & index runoff forecasts:

- do not consistently meet accuracy needs
- fail increasingly in a changing climate





Mote et al. 2018

How do we make water supply forecasting more robust?

- Decrease reliance on historic record
- Increase availability & use of spatial data & physically-based modeling

In other words, every year matters,
not just the average over some decades!

Airborne Snow Observatories

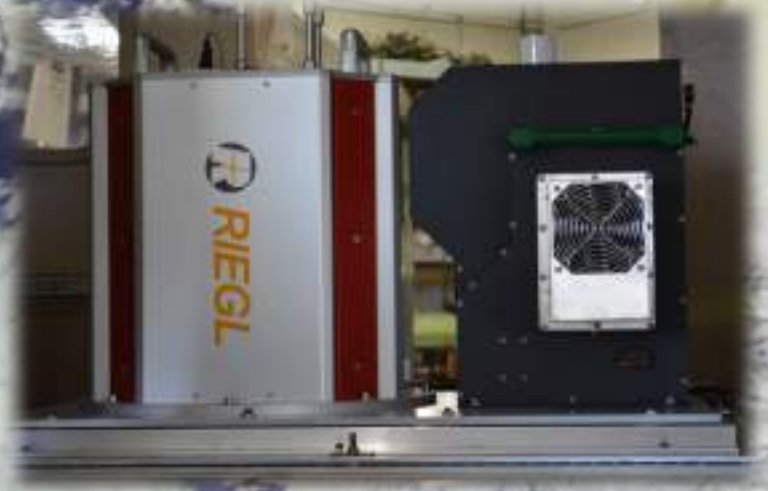
mapping the two most critical snow properties to forecast runoff volume & timing

Snow Water Equivalent

Snow depth from elevation mapping with Riegl VQ1560i
SWE from insertion of obs & modeled density

Snow Albedo

Snow albedo from CASI-1500 Spectrometer
Surface properties and controls on albedo



Physical Modeling

Coupling of lidar and spectrometer measurements
Snowpack process modeling

Operations

Unique high-altitude operations
Unique rapid product turnaround

NASA JPL AS

AIRBORNE SNOW OBSERVATORIES, INC

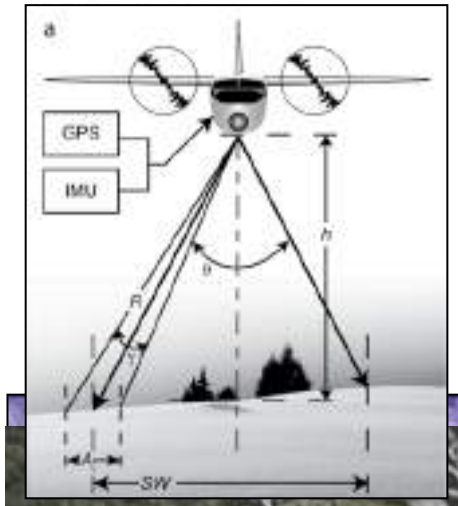
Snow depth & Water Equivalent from lidar

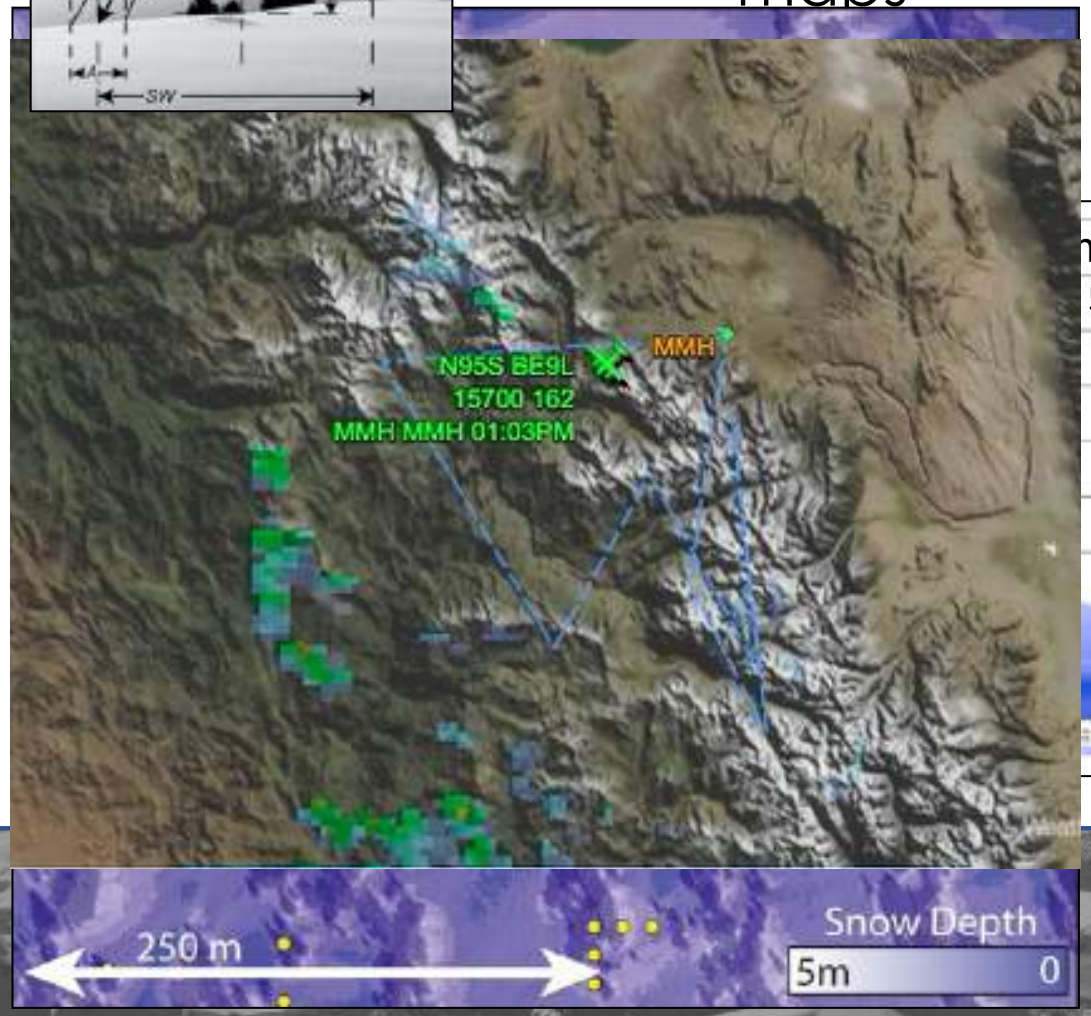
Majority of SWE variability due to snow depth

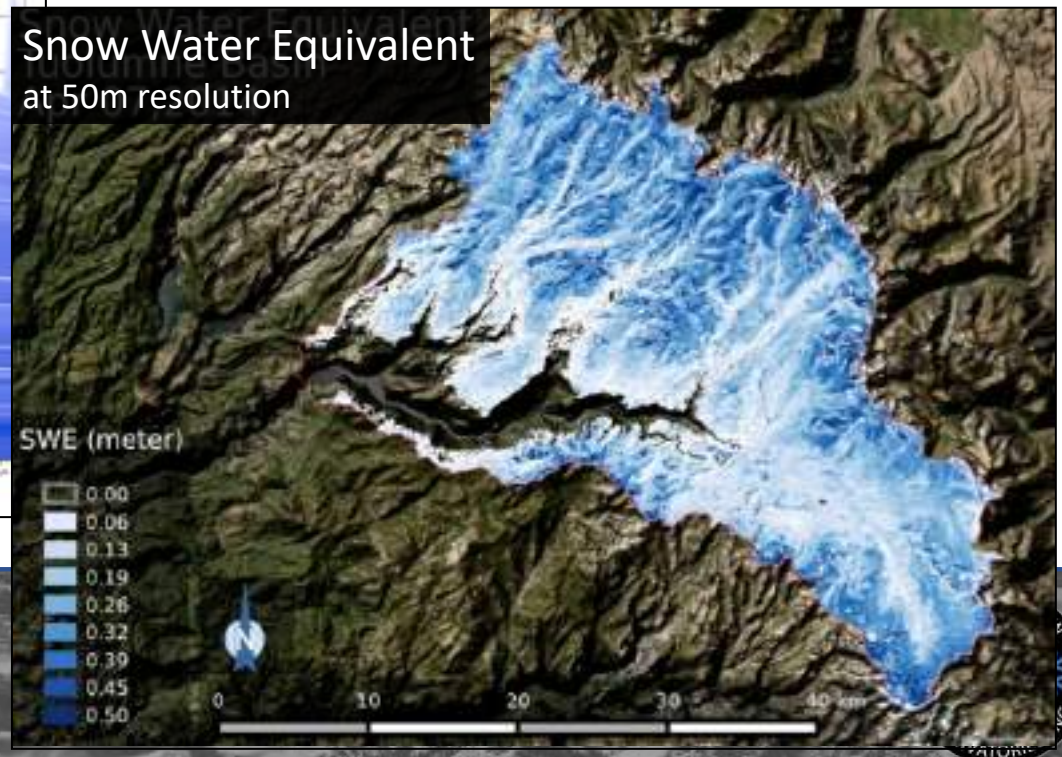
3m snow depth produced by subtracting elevation maps

Multiply snow depth by snow density

SWE = depth * density







ASO FPMS flow

Flight

- Lidar
- Spectrometer
- Visible high-res camera
- (Ka-band radar)

Flying optimized for mountain conditions

Processing

- snow depth
- snow density
- SWE
- snow albedo
- snow grain size
- radiative forcing by dust

Rapid turnaround

Modeling

M3W

NCAR

DWR
B-120

River Forecast Centers

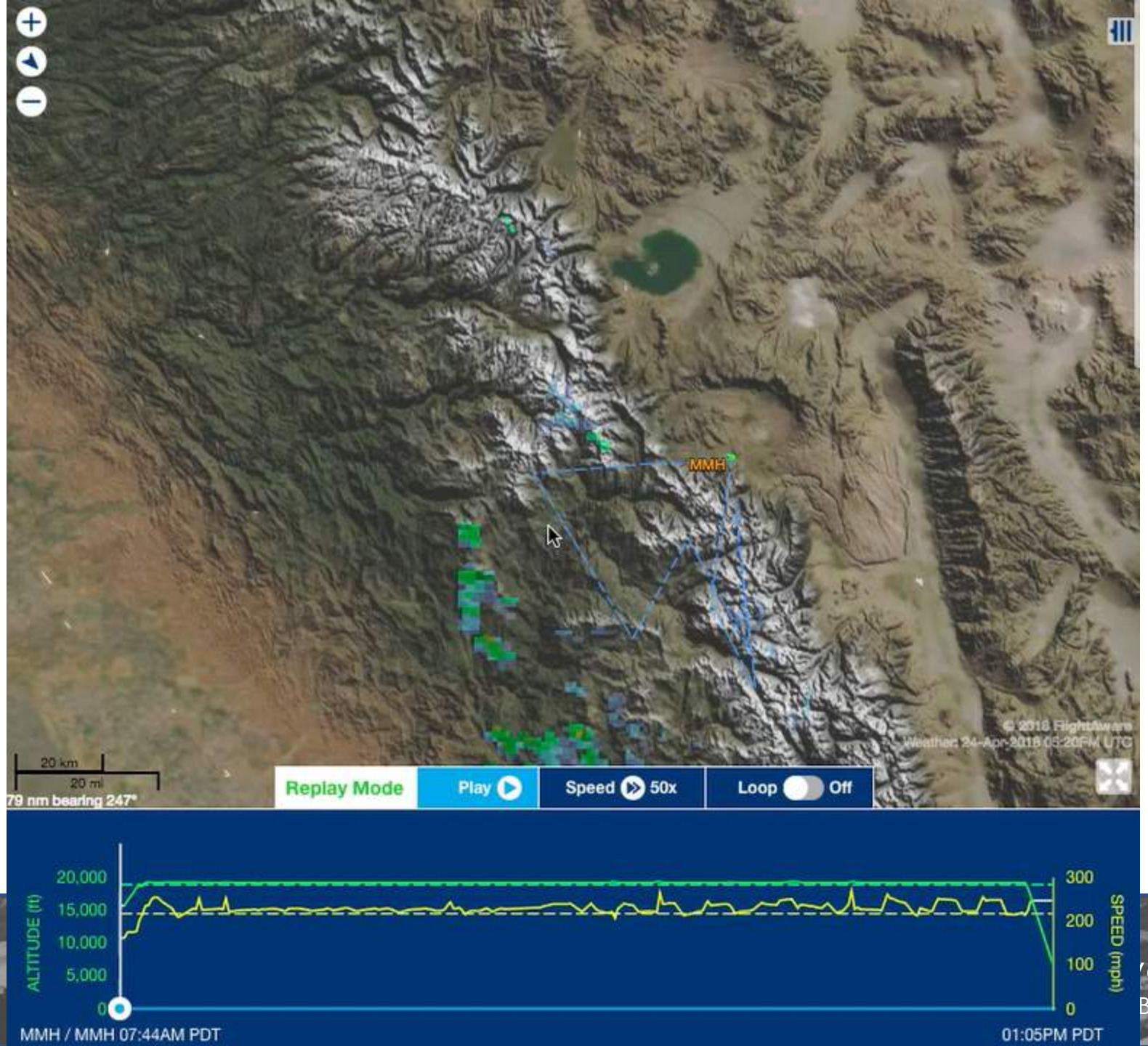
Any public or private forecast entity

SaaS Analysis & Visualization

esri
THE SCIENCE OF WHERE

Regional offices
Operations
Tech serv center

Any public or private decision-maker


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

ASO Program Evolution

2012 – First flights – partnership with NEON

2013 – First snow flights – NASA HQ support

2013 – Instrument purchases

2014 – Funding support from State of CA

2015 – Funding support from State of CO

2015 – NSIDC begins data archive & distribution

2016 – WSL/SLF & Swiss Flight Services demo project

2016 – Science support from DoE, USFS

2018 – Southern Sierra Nevada coverage

2019 – CO Acquisition partnership with Quantum Spatial

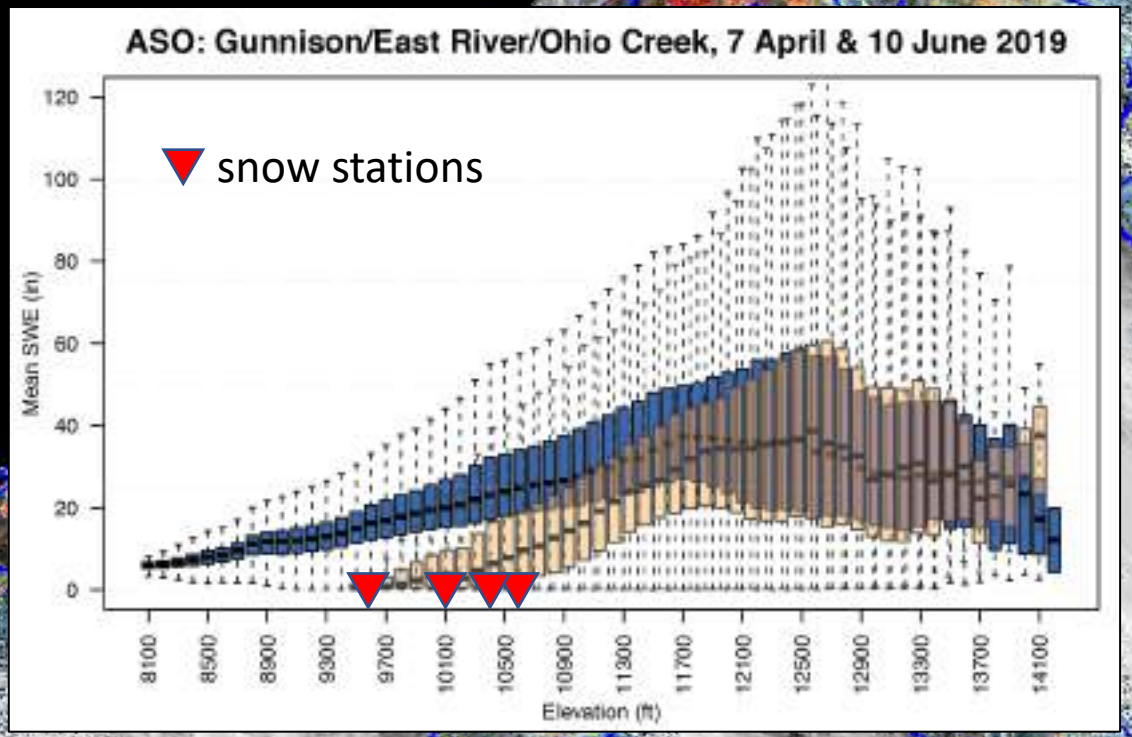
2019 – CA SB487 – pathway to CA full-state coverage

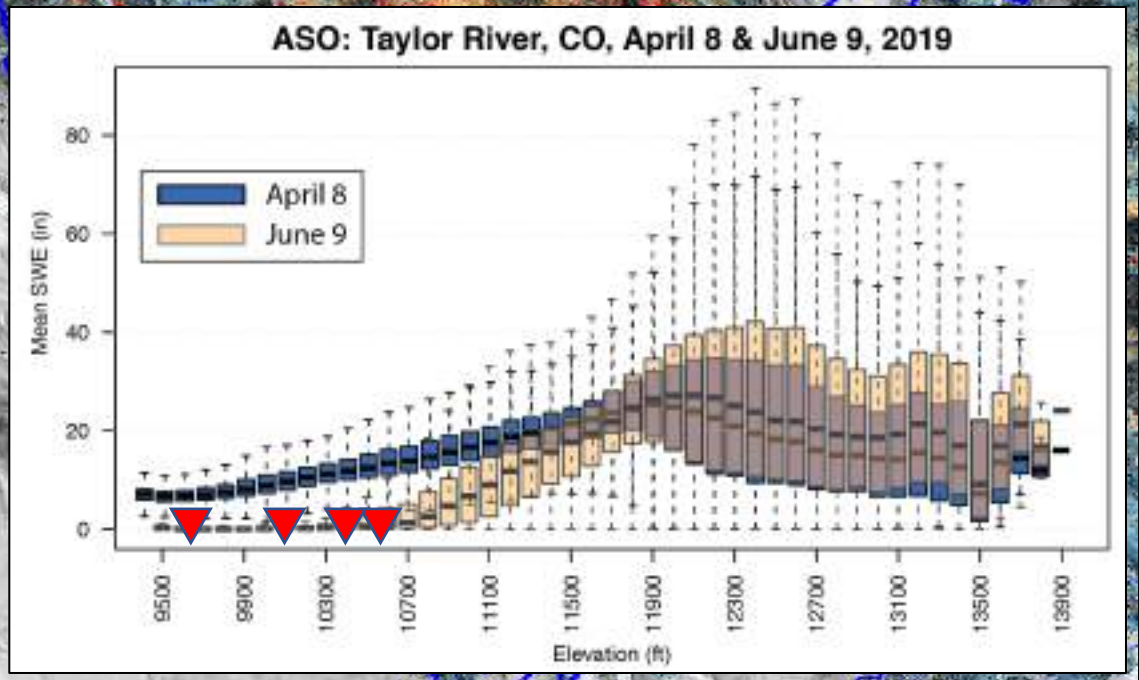
2019 – Transition to Airborne Snow Observatories, Inc

2020 – Strategic Partnership with Esri

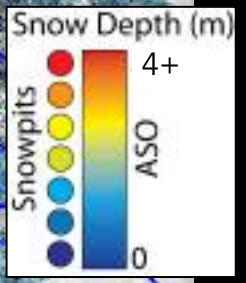
2020 – First season as ASO Inc. teaming with QSI

Upper Gunnison River
10 June 2019





contour line at elevation of highest snow station in the watershed

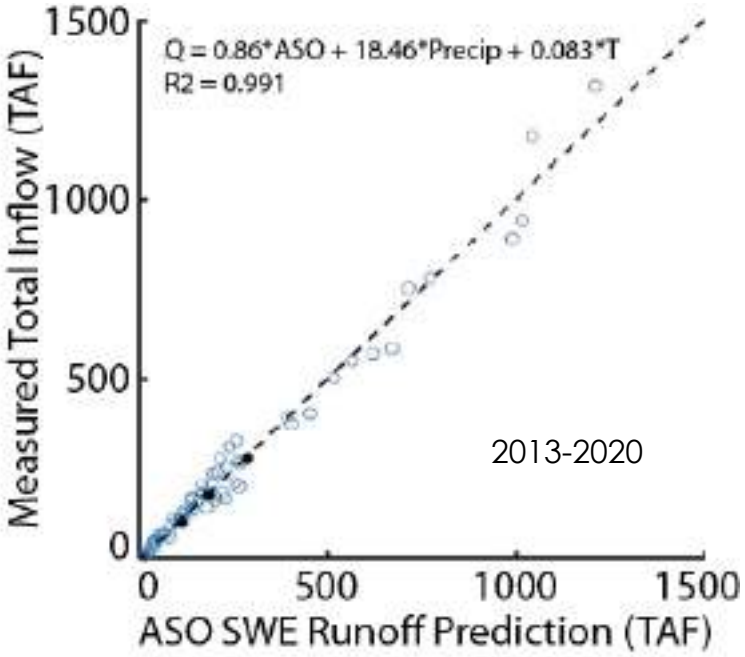


ASO is not just another hopeful SWE & albedo product

- Numerous efforts exist extrapolating **point** snow measurements, to invert snow cover maps, or to statistically model total SWE + runoff
- ASO is the **first, highly accurate, spatially-complete measurement of snow depth, snow water equivalent, & snow albedo**
  - Depth accuracy (±1 cm at 50m), Density (±3-6% at 50m)
  - SWE accuracy (±1% across basin)
- Enables forecast accuracy improvement from 50-90% to 96-99%
- California partners estimate value of ASO forecast improvement at:
  - > $600M annual for water supply only or > 40:1 ROI
  - > $1.25B annual for supply, hydro, recharge, ecosystem, operational flexibility

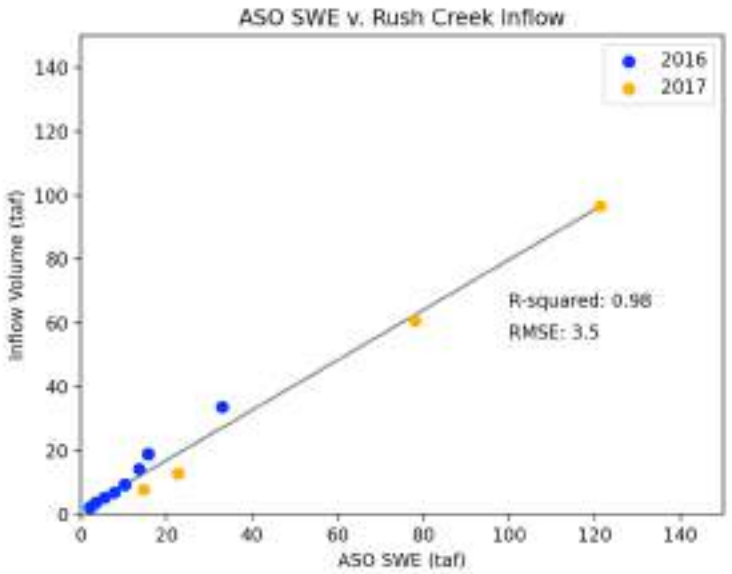
Results

Tuolumne

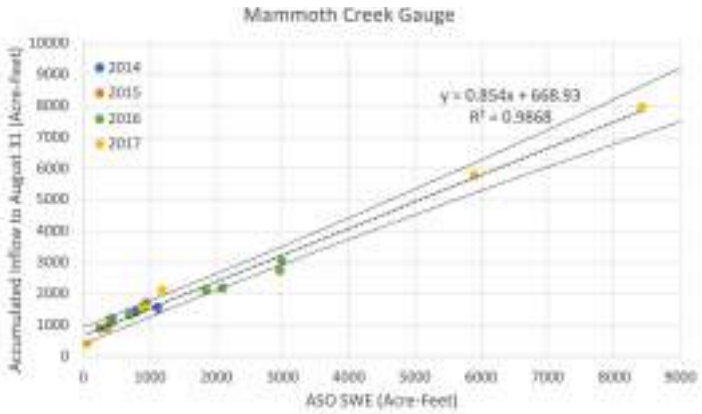


2013-2020

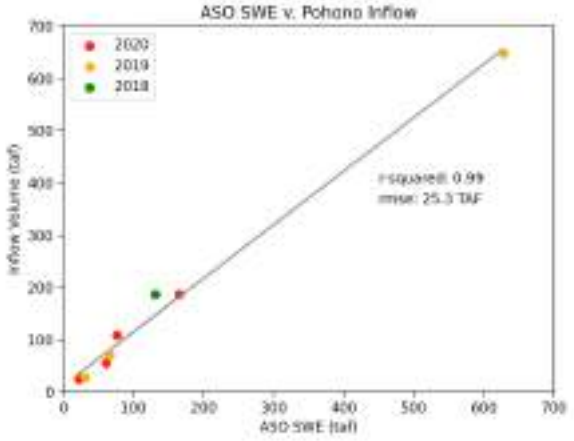
Rush Creek, Mono Basin



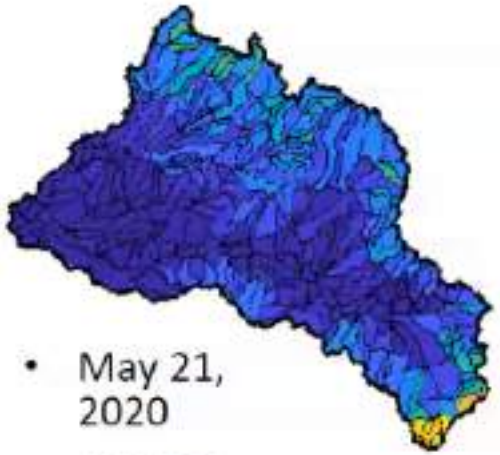
Mammoth Creek



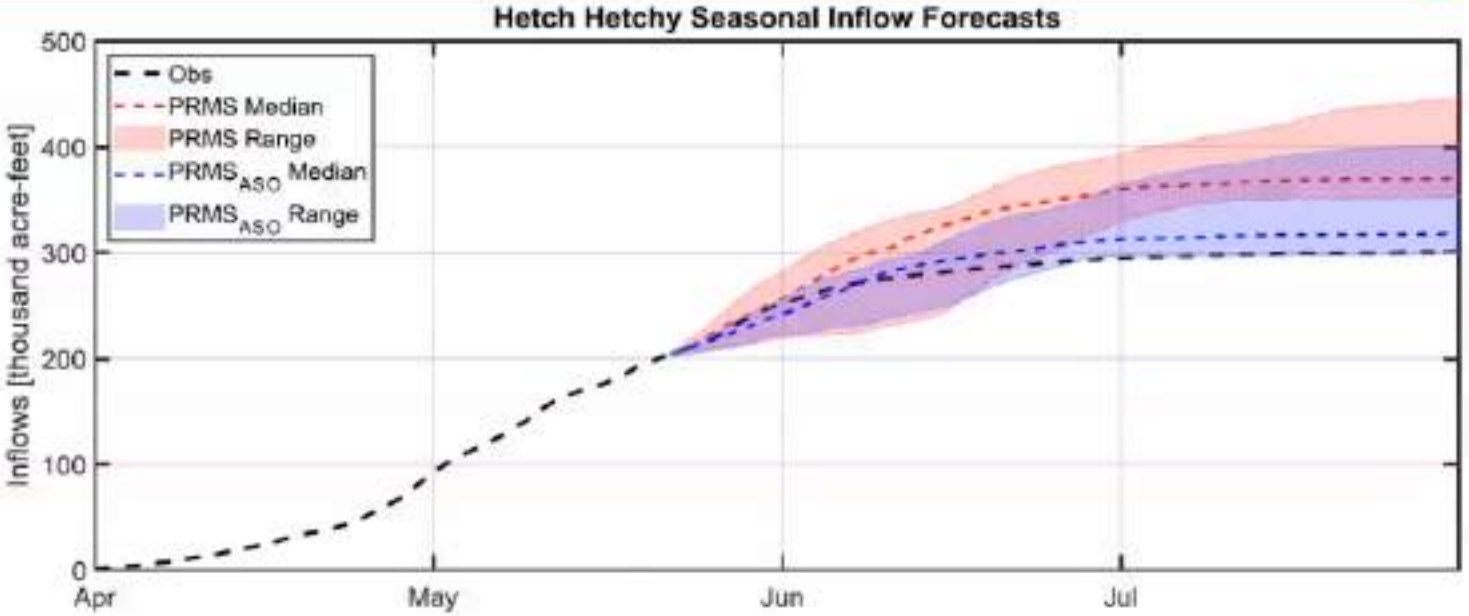
Merced

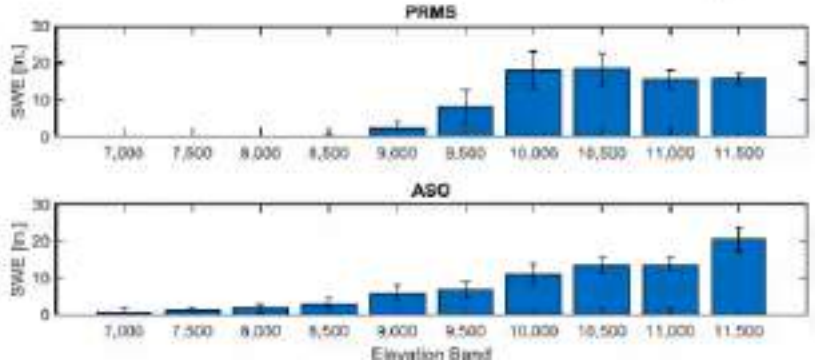


ASO Assimilation in PRMS



- May 21, 2020
- 123 TAF





- Promising improvements to internal ensemble runoff forecasting

Expanding applications with operational models

NOAA River Forecast Center testing/evaluation

- ASO SWE data nudges RFC forecast close to observed AJRO 2 months earlier than manual tuning

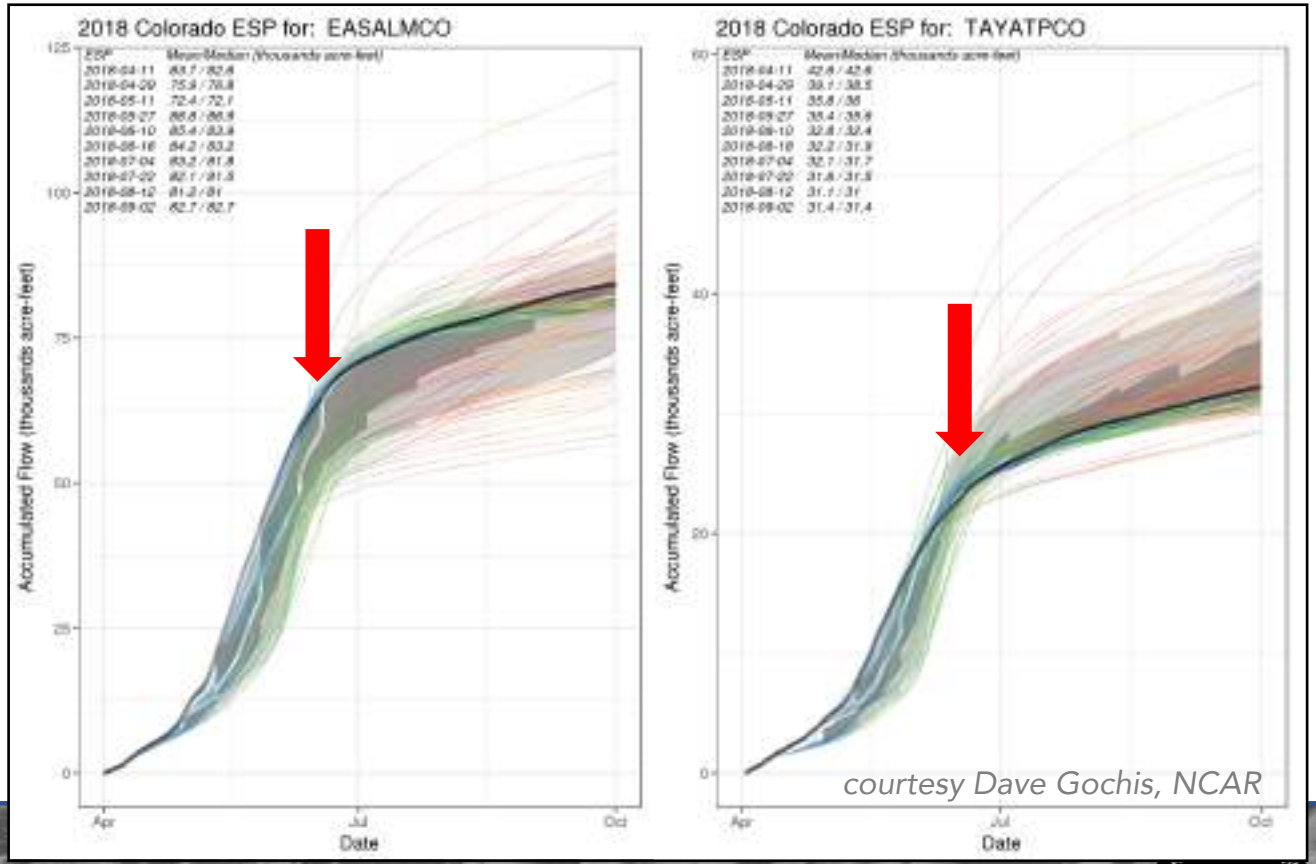
	Source / Run Type	Volume	Percent of USGS
Taylor Reservoir Inflow	USGS AJRO Volume (target)	29.1 KAF	100%
	CBRFC - unmodified	35.2 KAF	121%
	CBRFC **ASO** 3/31	30.2 KAF	104%
	CBRFC **ASO** 5/24	30.0 KAF	103%
	CBRFC **ASO** both	29.2 KAF	100%
	CBRFC FM 3/27 (added swe)	35.3 KAF	121%
	CBRFC FM through 4/28 (lz)	35.1 KAF	121%
	CBRFC FM through 5/15	33.3 KAF	114%
	CBRFC FM through 5/25	30.8 KAF	106%

courtesy Pat Kormos, CBRFC

WRF-HYDRO/National Water Model assimilation

- High elevation snow data from 24 May ASO assimilation reduces low forecast bias in ESP AJRO forecast

East River @ Almont | **Taylor River @ Taylor Park**



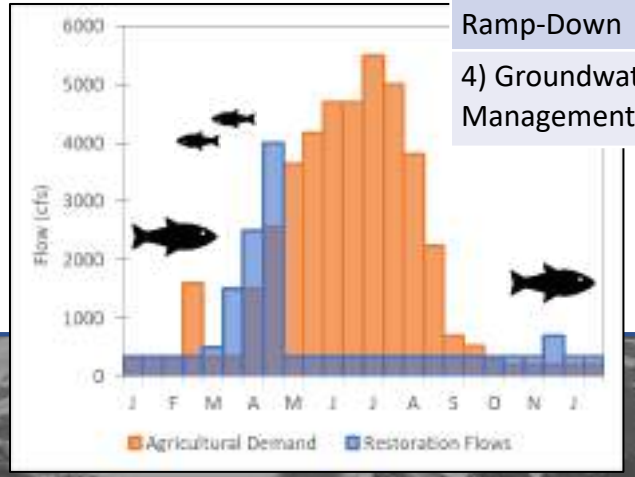
courtesy Dave Gochis, NCAR

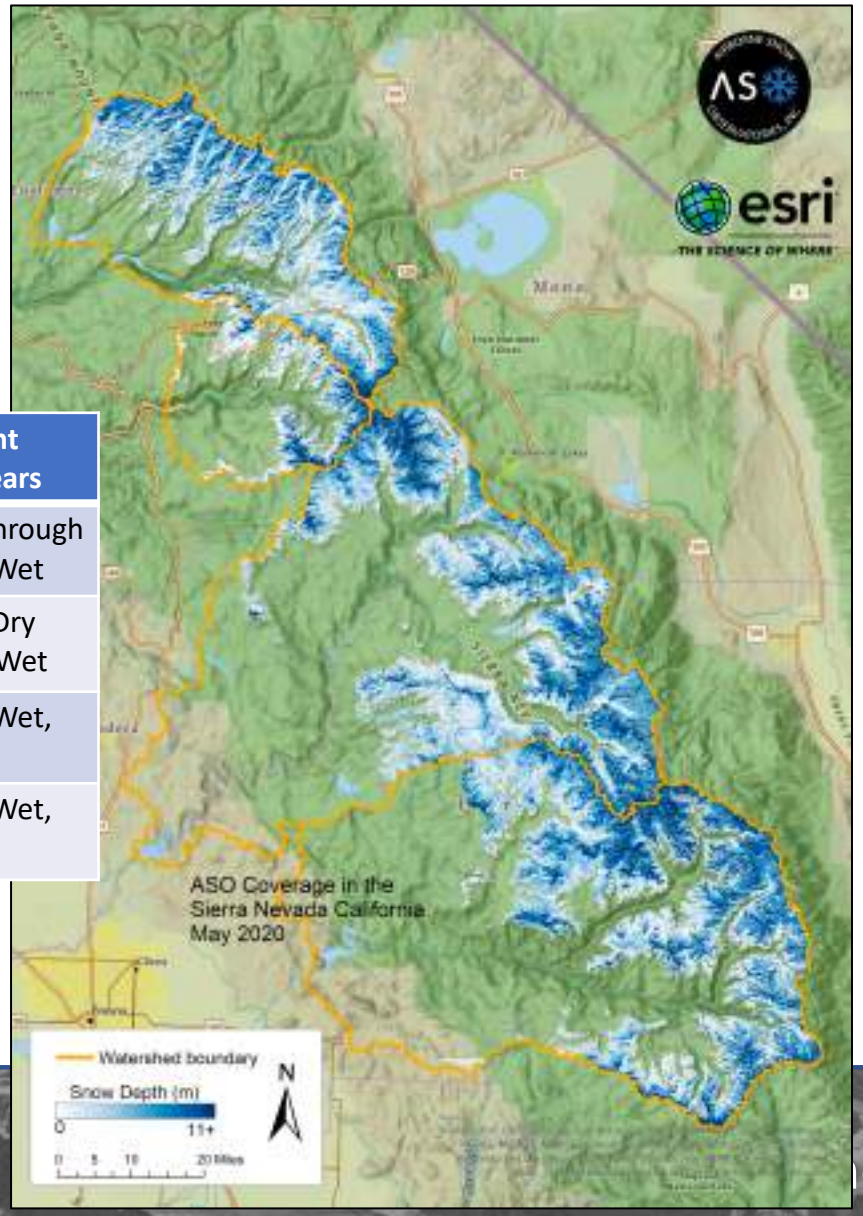
Operational support: California

San Joaquin River: Restoration flows for salmon

- ASO data used in forecast for USBR Fish Recovery Program
- Improved accuracy enables restoration flows & re-watering lower San Joaquin
- Early forecast accuracy key to achieving flow factors & summer supply reliability

Environmental Flow Factor	Important Water Years
1) Restoration Flow Scheduling	Critical through Normal-Wet
2) Temperature Management	Normal-Dry through Wet
3) Flood Flow Ramp-Down	Normal-Wet, Wet
4) Groundwater Management	Normal-Wet, Wet





Kings River 2019: Managing supply & flood risk

- Flood declaration: Army Corps takes over Pine Flat Dam ops & operates solely to protect infrastructure
- 2019: ASO forecast allowed KRWA to operate on 10% exceedance

Forecasts	Apr-Jul Runoff Forecast Exceedance		
	10%	50%	90%
CA DWR	2.1 MAF	1.8 MAF	1.6 MAF
NOAA RFC	2.3 MAF	2.1 MAF	1.9 MAF
ASO		2.5 MAF	

- *Saved 100 TAF or **~$100M** of water*

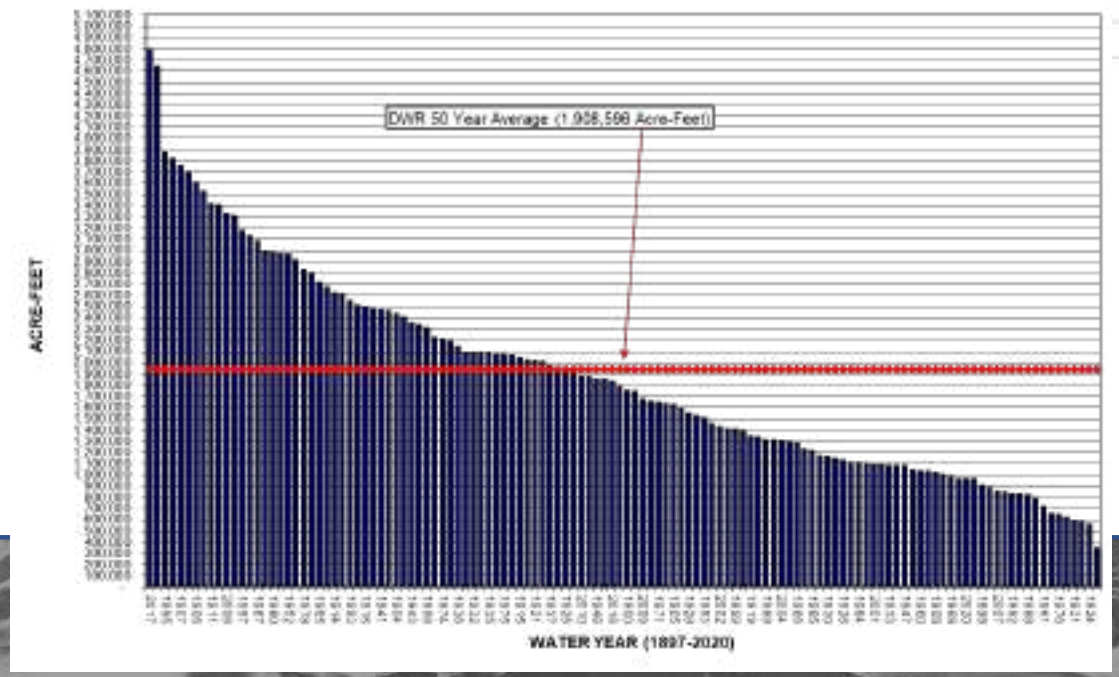
"ASO provides invaluable information that is not otherwise available, most importantly information about the rate of melt that provides a real opportunity to optimize reservoir operations for water supply, flood control, and instream requirements."

Steve Haugen, Watermaster, Kings River Water Association

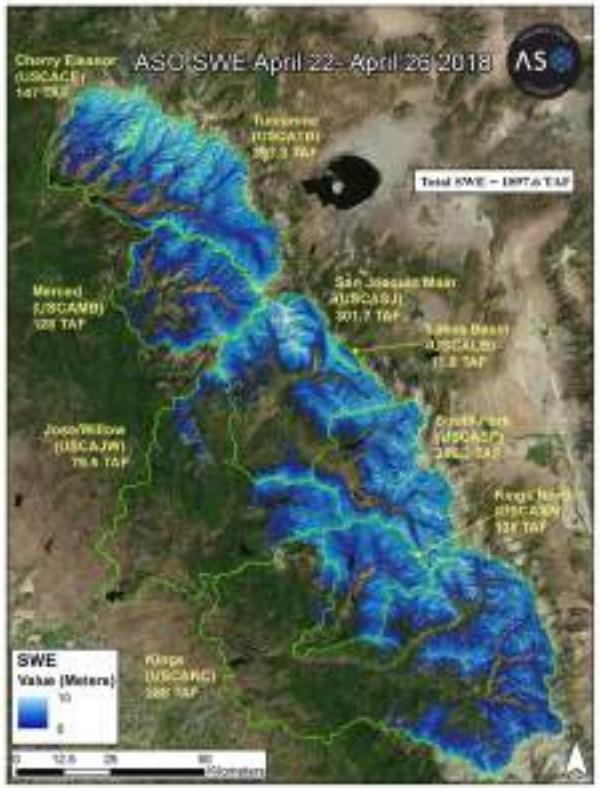
Hydroelectric Optimization is just started

Pricing on Average, Not at the Margin
Average each Year

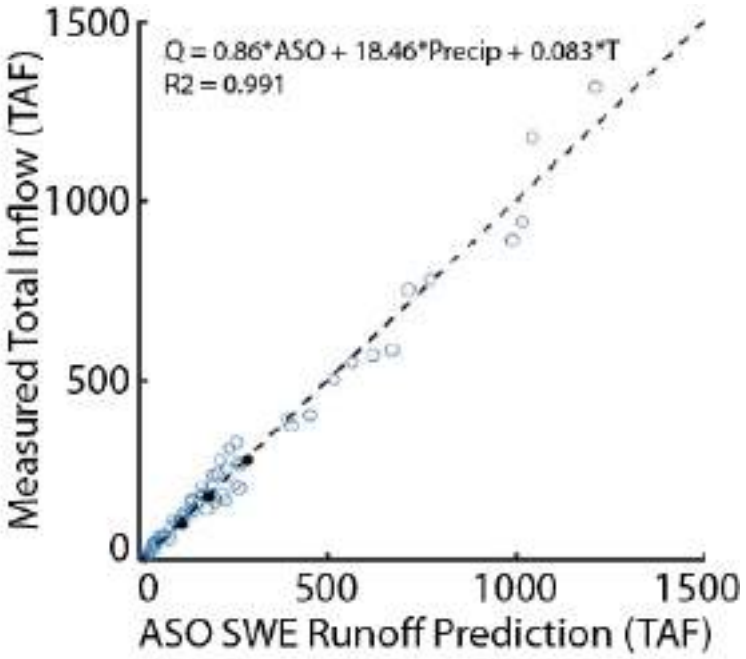
	Item #	Category Name	AF	MWh	$/MW	Total			
Each Year	1	Planning Resources ahead of time	200,000	70,000	10	$ 700,000.00	Per year		Very Conservative!!
Average over 87 yrs	2	Amount of water up there that is not known	91,954	32,184	10	$ 321,839.08	Per year		Very Conservative!!
Average over 87 yrs	3	Amount that was not known	70,713	24,749	5	$ 123,747.13	Per year		Very Conservative!!
Average over 87 yrs	4	Operational Dymanics, planning for the unforseen	13,000	4,550	20	$ 91,000.00	Per year		Very Conservative!!
Average over 87 yrs	5	Market Opportunity	20,000	7,000	40	$ 280,000.00	Per year		Very Conservative!!
						$ 1,516,586.21			
				542,000	30	$ 16,260,000.00			
						9%	Eff Gain.		Conservative



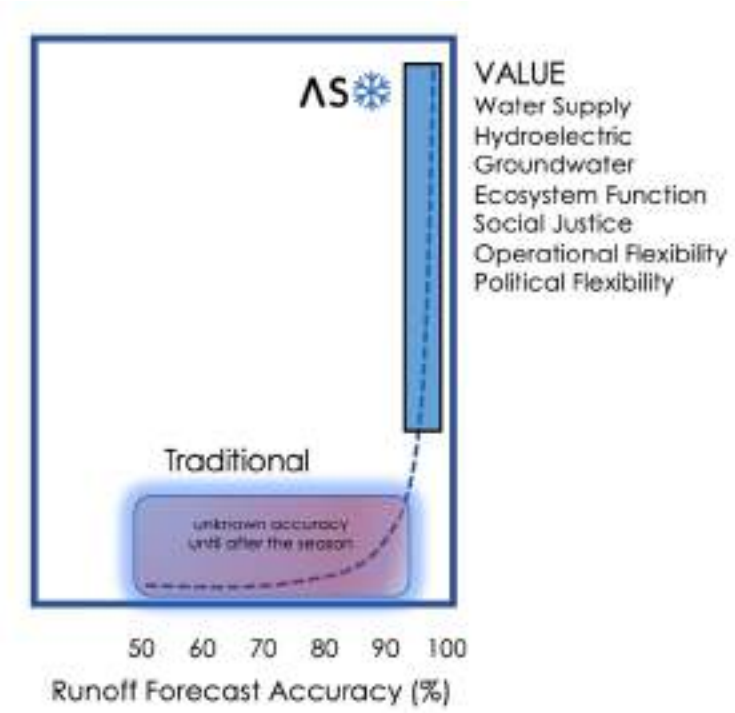
Accurate Snow Mapping Enables Unprecedented Value



NASA-legacy snow water equivalent **mapping** across entire watersheds



Unprecedented snowmelt runoff forecasting **accuracy**



Marked improvement in consistently high accuracy translates to customer **value**

ROI estimates: 40-100X

Federal Legislation

116TH CONGRESS
2D SESSION

H. R. 2

AN ACT

To authorize funds for Federal-aid highways, highway safety programs, and transit programs, and for other purposes.

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,

SECTION 1. SHORT TITLE.

This Act may be cited as the "Moving Forward Act".

SEC. 81236. DETERMINATION OF WATER SUPPLY ALLOCATIONS.

(a) SNOWPACK MEASUREMENT DATA.—When determining water supply allocations, the Secretary, acting through the Commissioner of the Bureau of Reclamation, shall incorporate to the greatest extent practicable information from emerging technologies for snowpack measurement such as—

(1) synthetic aperture radar;

(2) laser altimetry; or

(3) any other emerging technologies that can provide more accurate or timely snowpack measurement data as determined by the Secretary.

(b) COORDINATION.—In carrying out subsection (a), the Secretary may coordinate data use and collection efforts with other Federal agencies and bureaus that currently use or may benefit from the use of emerging technologies for snowpack measurement.

(c) AUTHORIZATION OF APPROPRIATIONS.—There is authorized to be appropriated to the Secretary $5,000,000 to carry out this section.

(d) REPORT.—Not later than October 1, 2022, the Secretary shall submit to Congress a report summarizing the use of emerging technologies pursuant to this section and describe any benefits derived from the use of such

Federal Legislation

United States of America

Congressional Record

PROCEEDINGS AND DEBATES OF THE 116th CONGRESS, SECOND SESSION

Vol. 166 WASHINGTON, THURSDAY, AUGUST 13, 2020 No. 145

House of Representatives

The House was not in session today. Its next meeting will be held on Friday, August 14, 2020, at 2 p.m.

Senate

THURSDAY, AUGUST 13, 2020

By Mrs. FEINSTEIN (for herself and Ms. HARRIS):

S. 4530. A bill to establish a Snow Water Supply Forecasting Program within the Department of the Interior, and for other purposes; to the Committee on Energy and Natural Resources.

Mrs. FEINSTEIN. Mr. President, I rise to speak in support of the Snow Water Supply Forecasting Program Authorization Act, which I introduced today with Senator HARRIS. Representatives JOSH HARDER, JOHN GARAMENDI, JERRY MCNERNEY, GRACE NAPOLITANO, T.J. COX, and AMI BERA—all Democrats from California—and DIANA DEGETTE and JOE NEGUSE—both Democrats from Colorado—have introduced identical companion legislation in the House.

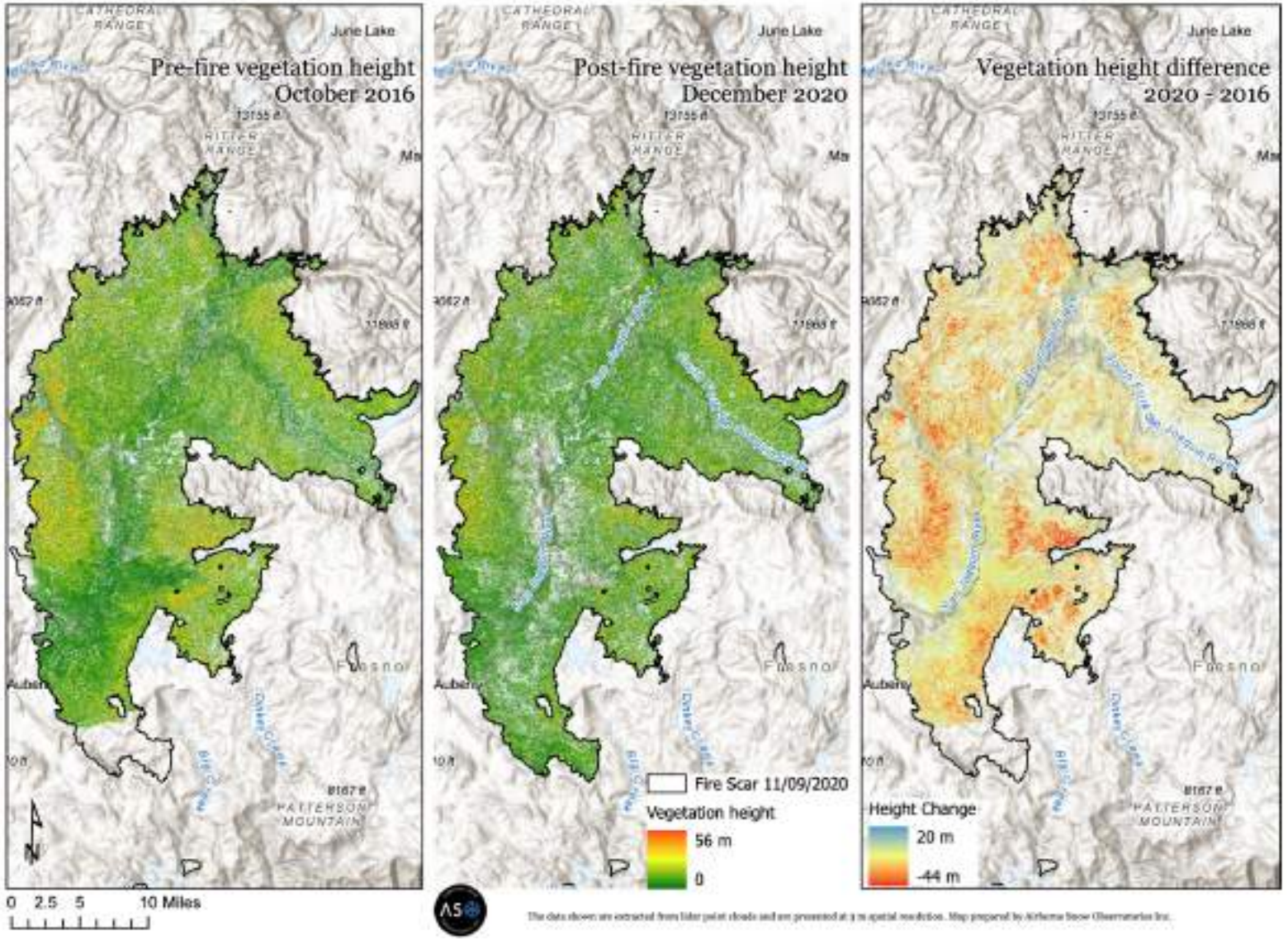
Airborne snow observatory, ASO, technology is a snow monitoring tool that provides precise measurement of depth and water content for every square meter of snow in a watershed. The technology measures snow depth and water content using an airplane-mounted light detection, LiDAR, instrument coupled with an imaging spectrometer.

When combined with conventional snow surveys, ASO provides a near-perfect picture of snow water content.

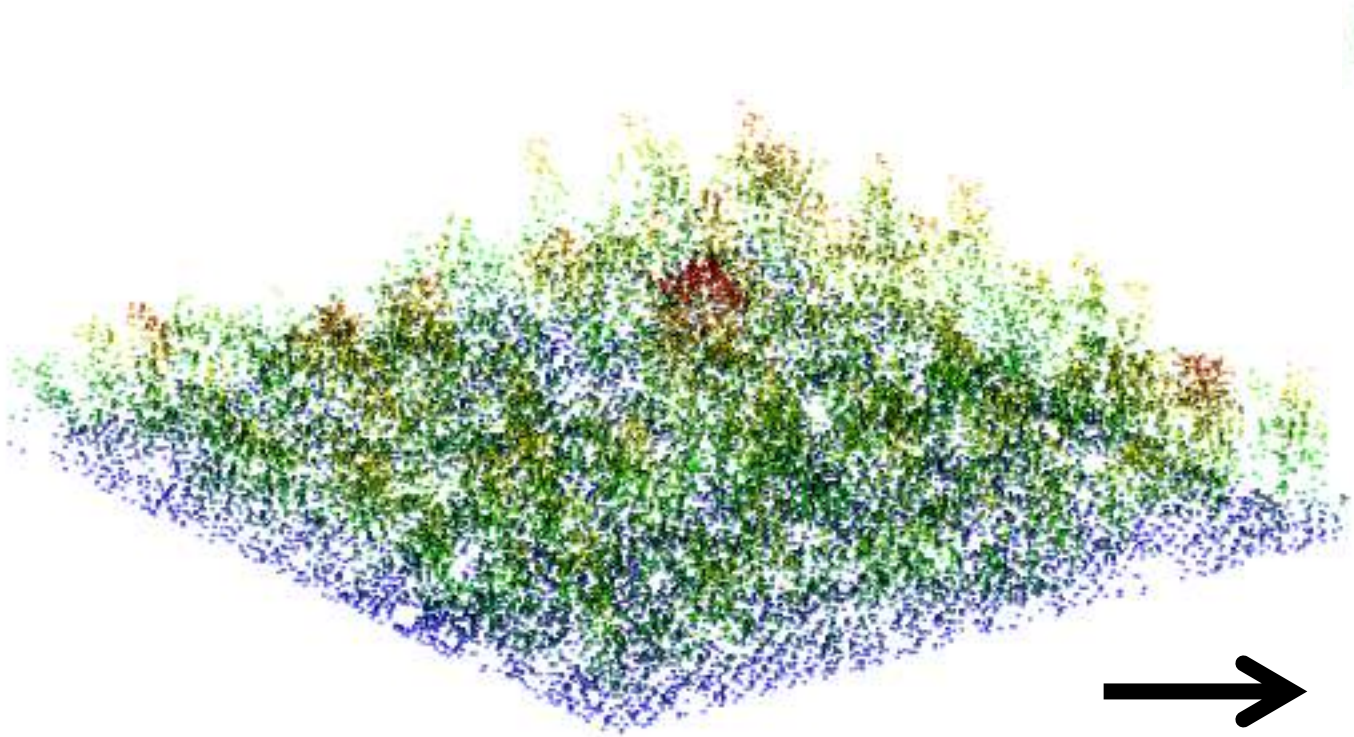
Broader Use of ASO data

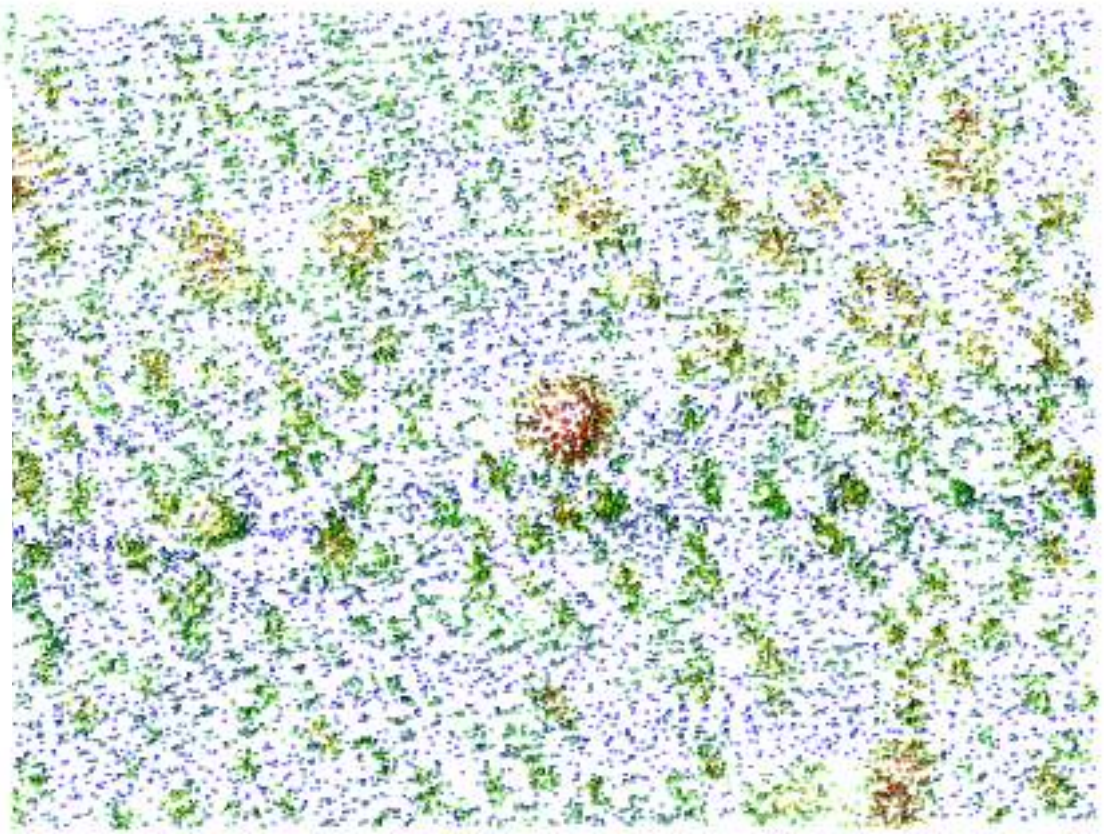
Airborne Snow Observatories, Inc.
A Public Benefit Corporation

Creek Fire 2020: impact on vegetation height

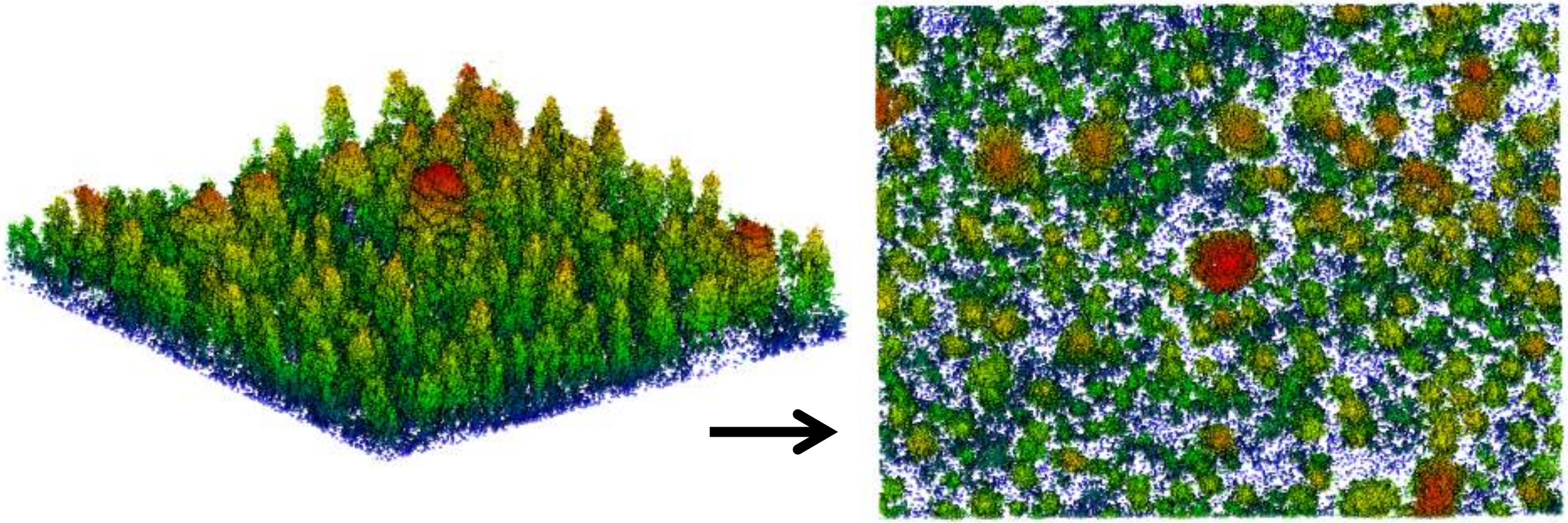


Merged point cloud: point density ~1 pt/m^2





Merged point cloud: point density ~15 pt/m^2



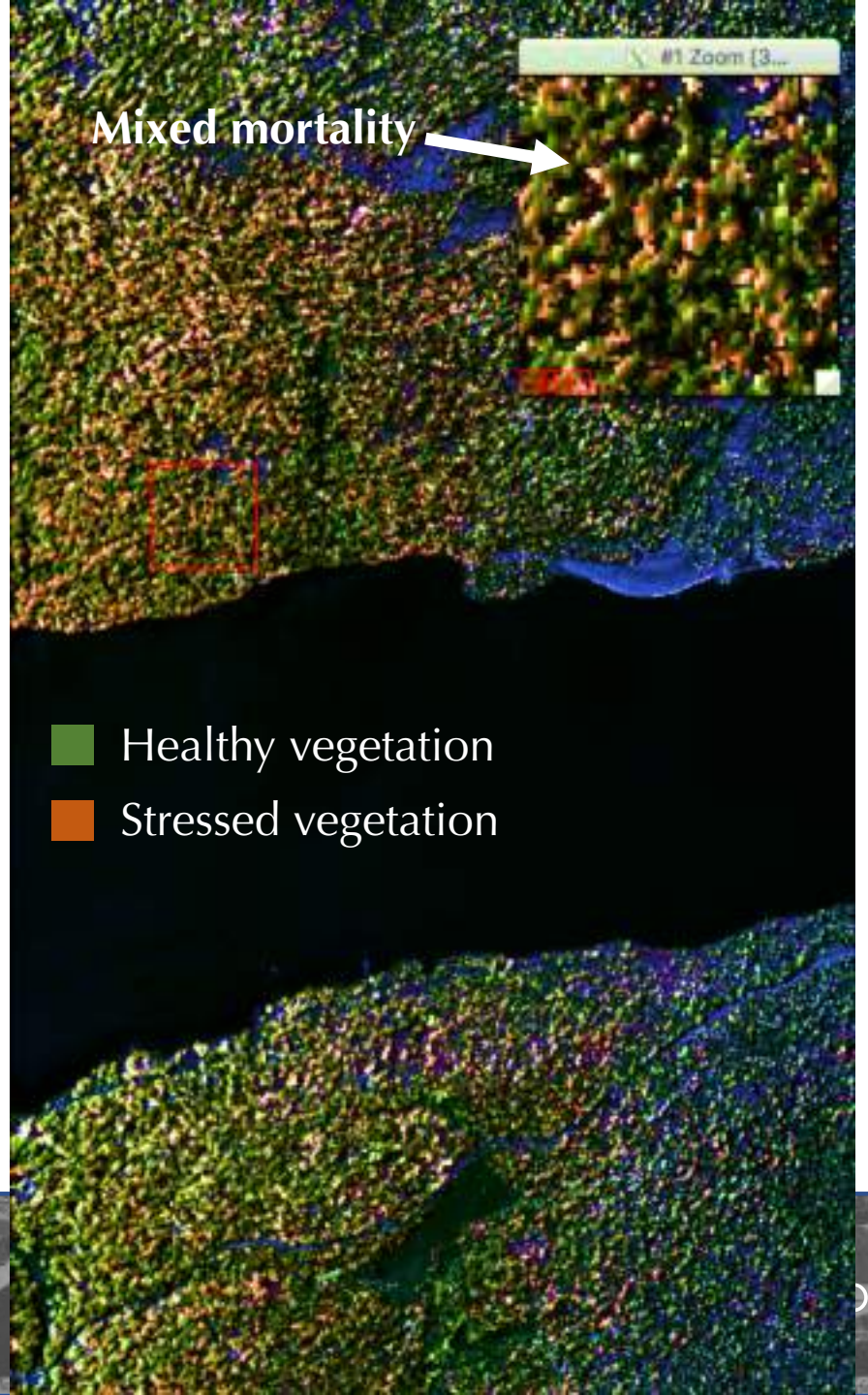
Ferraz, Saatchi, Bormann, and Painter,
in prep

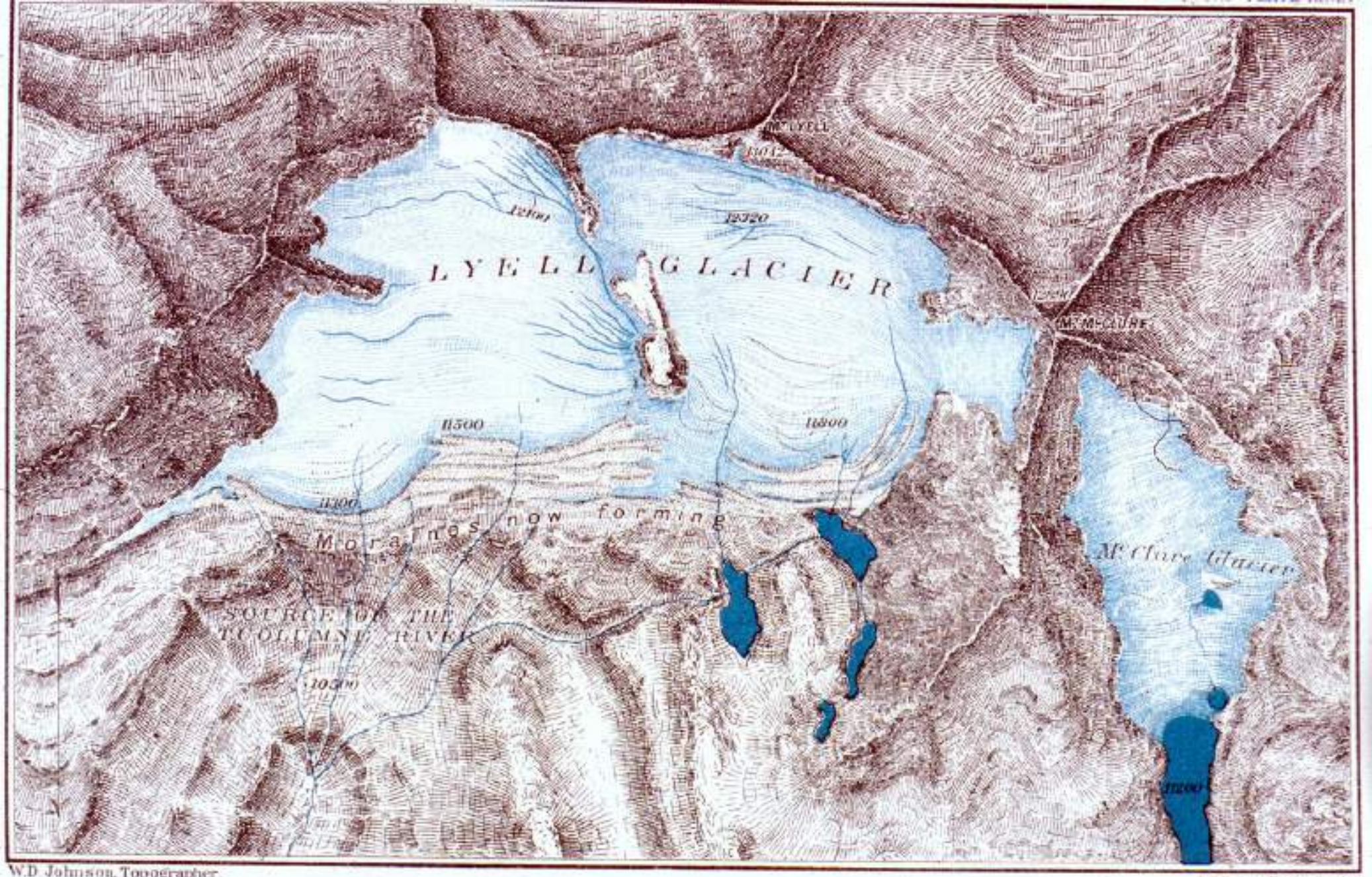
Tree Mortality from ASO

From ASO's spectrometer and lidar, dying trees can be identified individually and separated from those not stressed.

With these data, we can have spatially explicit representation of vegetation dynamics to understand their impacts on ecosystem function, drought sensitivity, and most importantly impacts on snowmelt runoff.

Lower San Joaquin Basin, June 2, 2019,
Airborne Snow Observatory





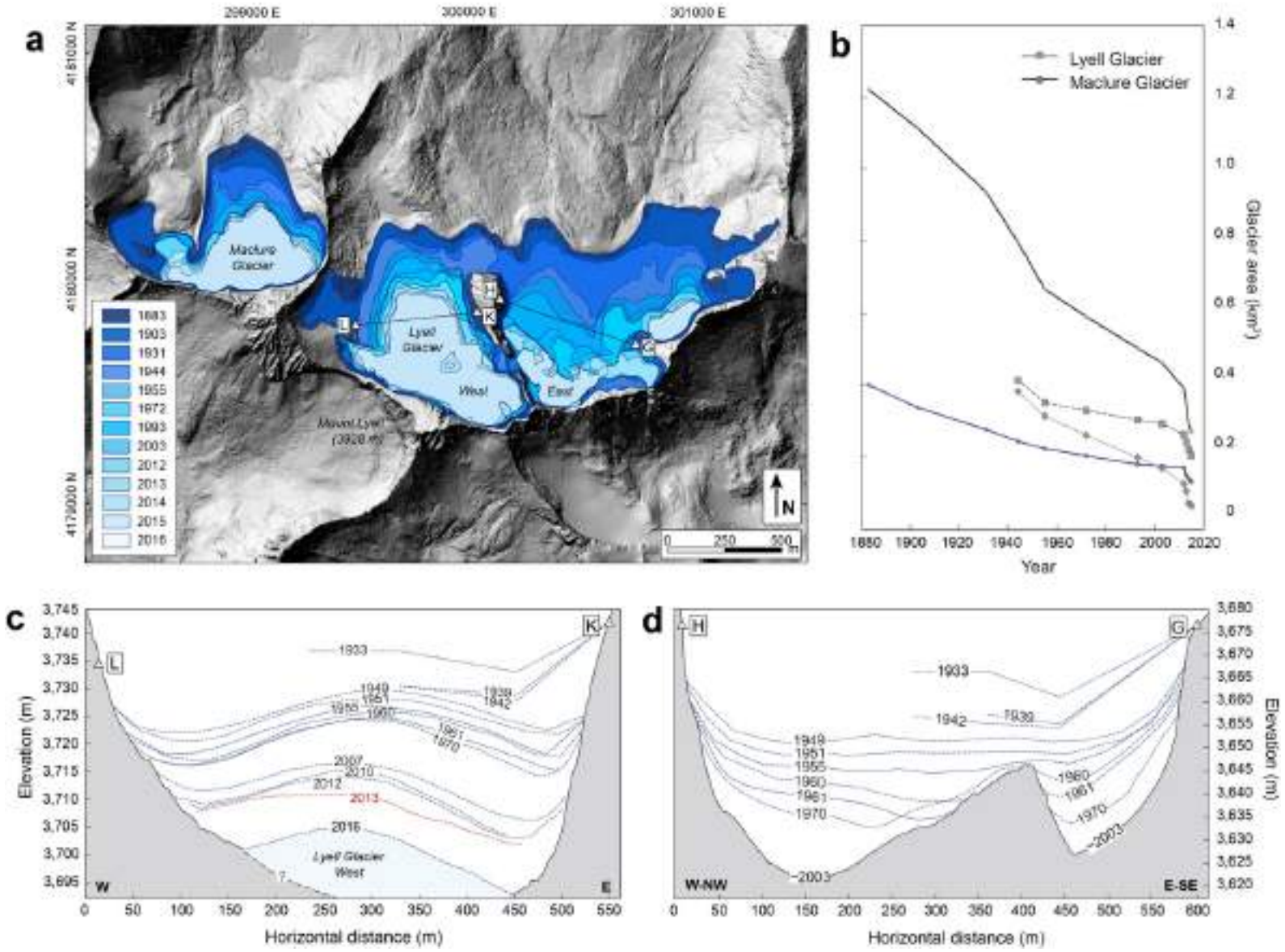
W.D Johnson, Topographer

I.C.Russell, Geologist

Mt LYELL GLACIER.

Scale 3¾ inches = 1 mile.

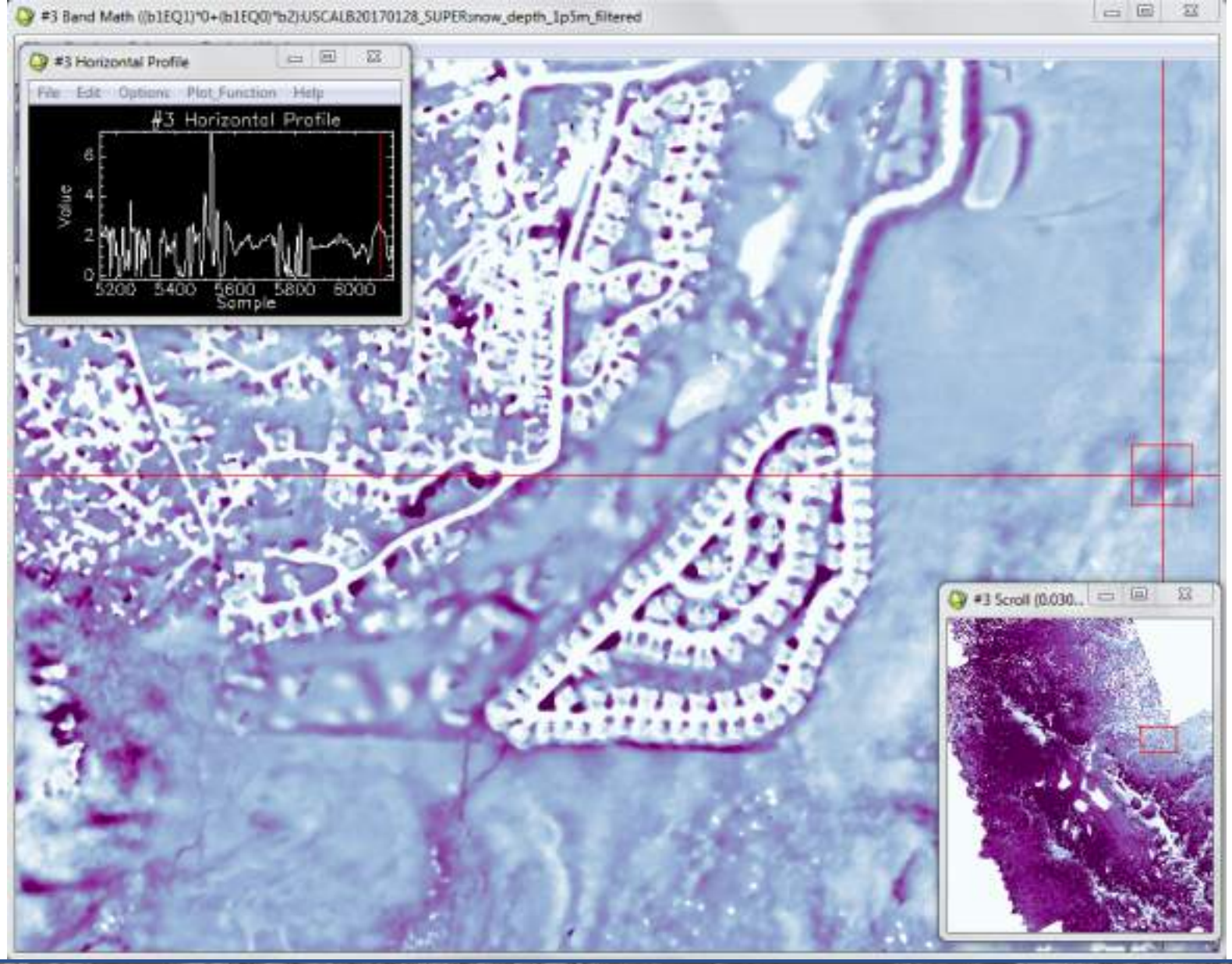
ories, Inc.
fit Corporation
jpl.nasa.gov
AIRBORNE SNOW OBSERVATORIES, INC



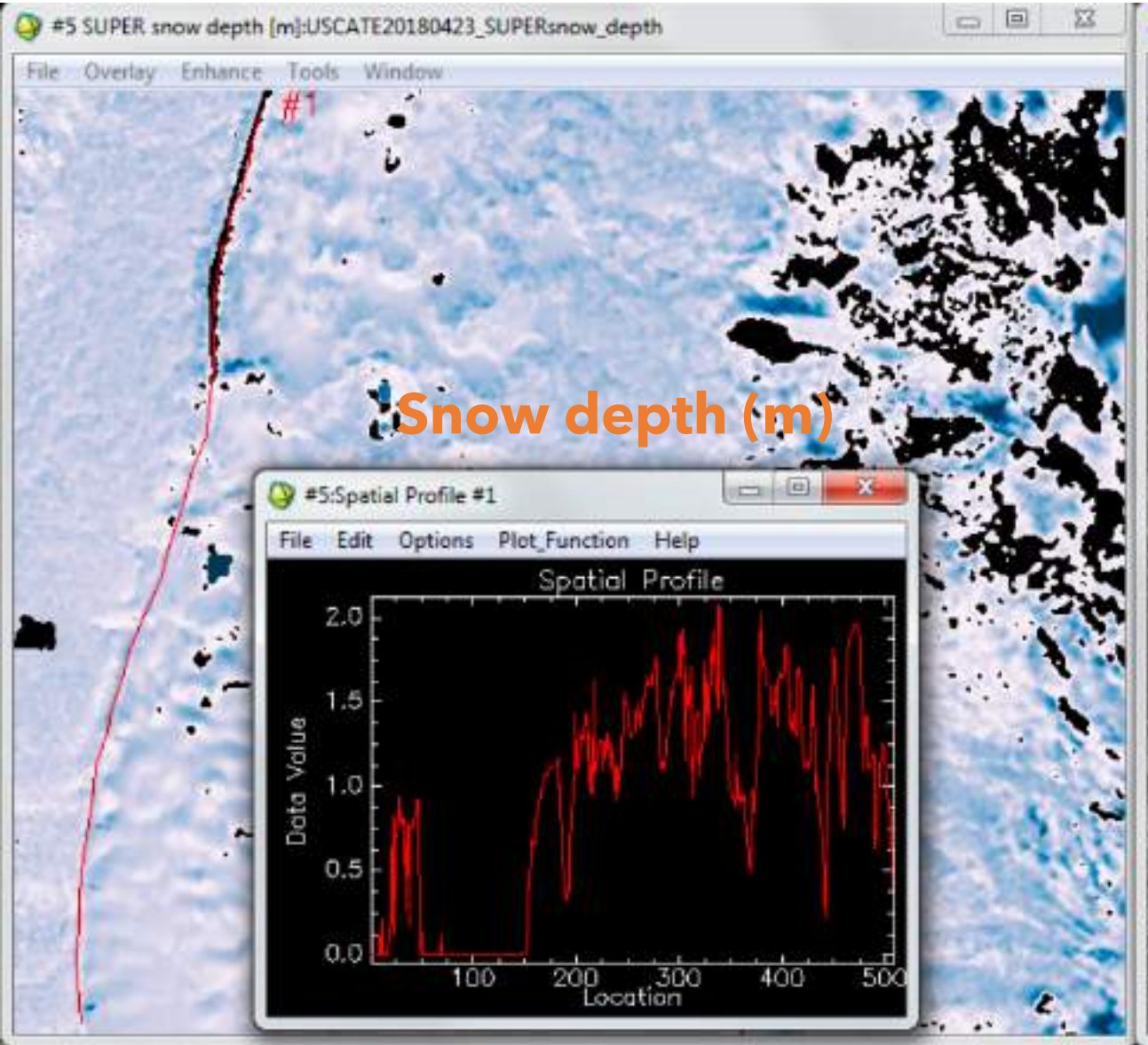
Stock et al, *in preparation*

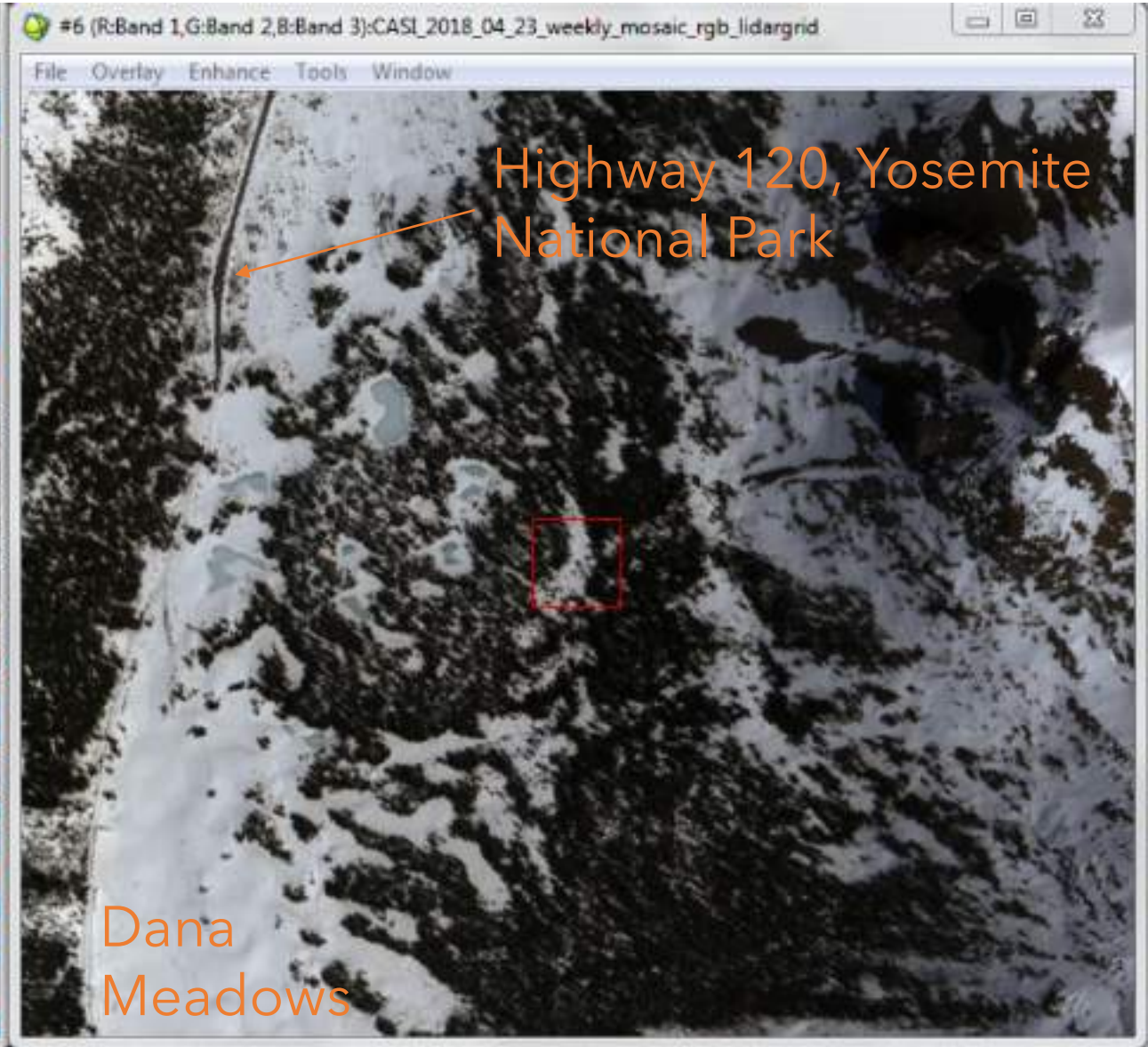
Sherwin Meadows
January 28, 2017

Snow Depth



Snow depth for Transportation, Recreation, etc.





ASO Data and Visualization System

Airborne Snow Observatories, Inc.
A Public Benefit Corporation

ASO is actively developing a dynamic data portal

Integrating:

- ASO data products
  Snow depth, SWE, albedo
- Snowmelt & hydrologic model outputs
  e.g. iSnobal, WRF-Hydro
- In-situ snow & streamflow data for validation
  e.g. CDEC, USGS

Enabling:

- public access
- subsetting & download
- data exploration / visualization / distillation
- temporal comparison
- client-driven customization & optimization

AIRBORNE SNOW OBSERVATORIES, INC.

Username

Password

LOGIN

SIGN UP

OUR MISSION

Provide highly accurate and reliable basin-wide distributed measurements of snow water equivalent and forecasts of snowmelt runoff with unique remote sensing and physical modeling

MEASUREMENT

Accurate snow depth, snow water equivalent, and snow albedo measurements across entire watersheds.

MODELING

Constraining physically based, distributed snow modeling for accurate daily representation of snow mass and energy states.

FORECASTING

Accurate snowmelt runoff forecasts at daily to seasonal time scales from physically based and empirically based model structures.

RAPID DELIVERY

Providing rapid turnaround of snow property measurements, snowpack modeling, and streamflow forecasts to support active, critical water management.

OUR DATA

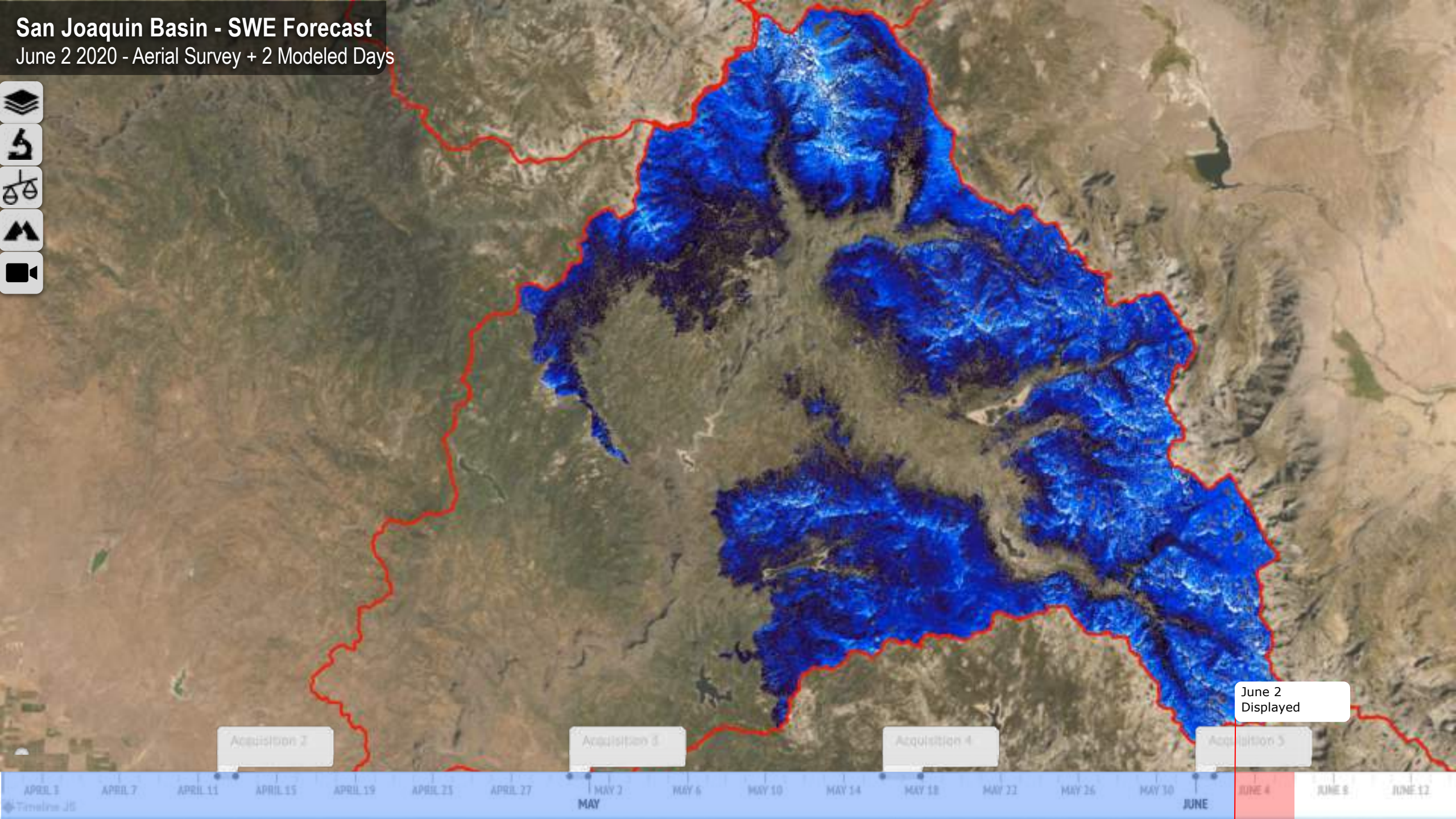
California | Colorado

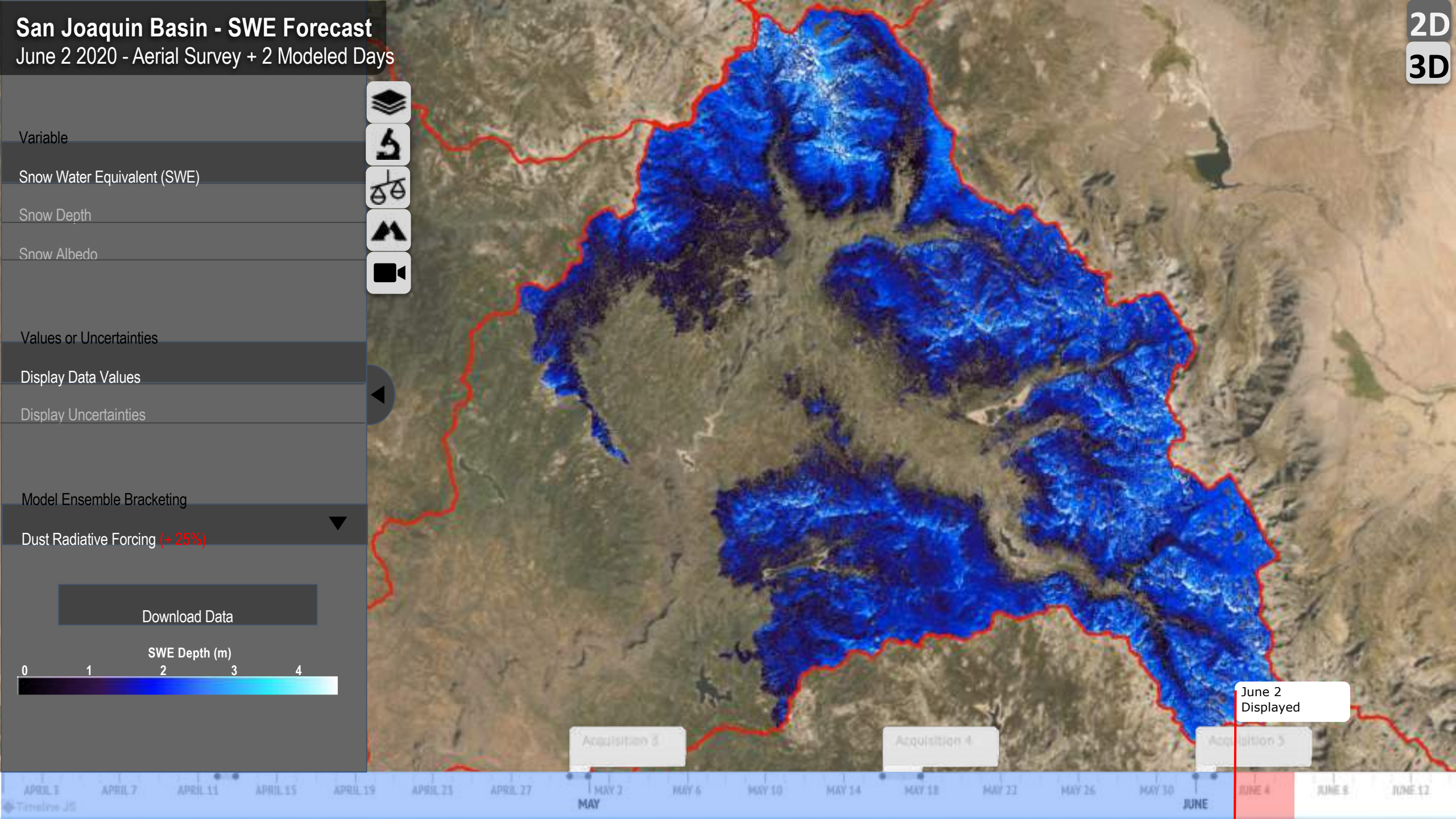
Airborne Snow Observatories, Inc.

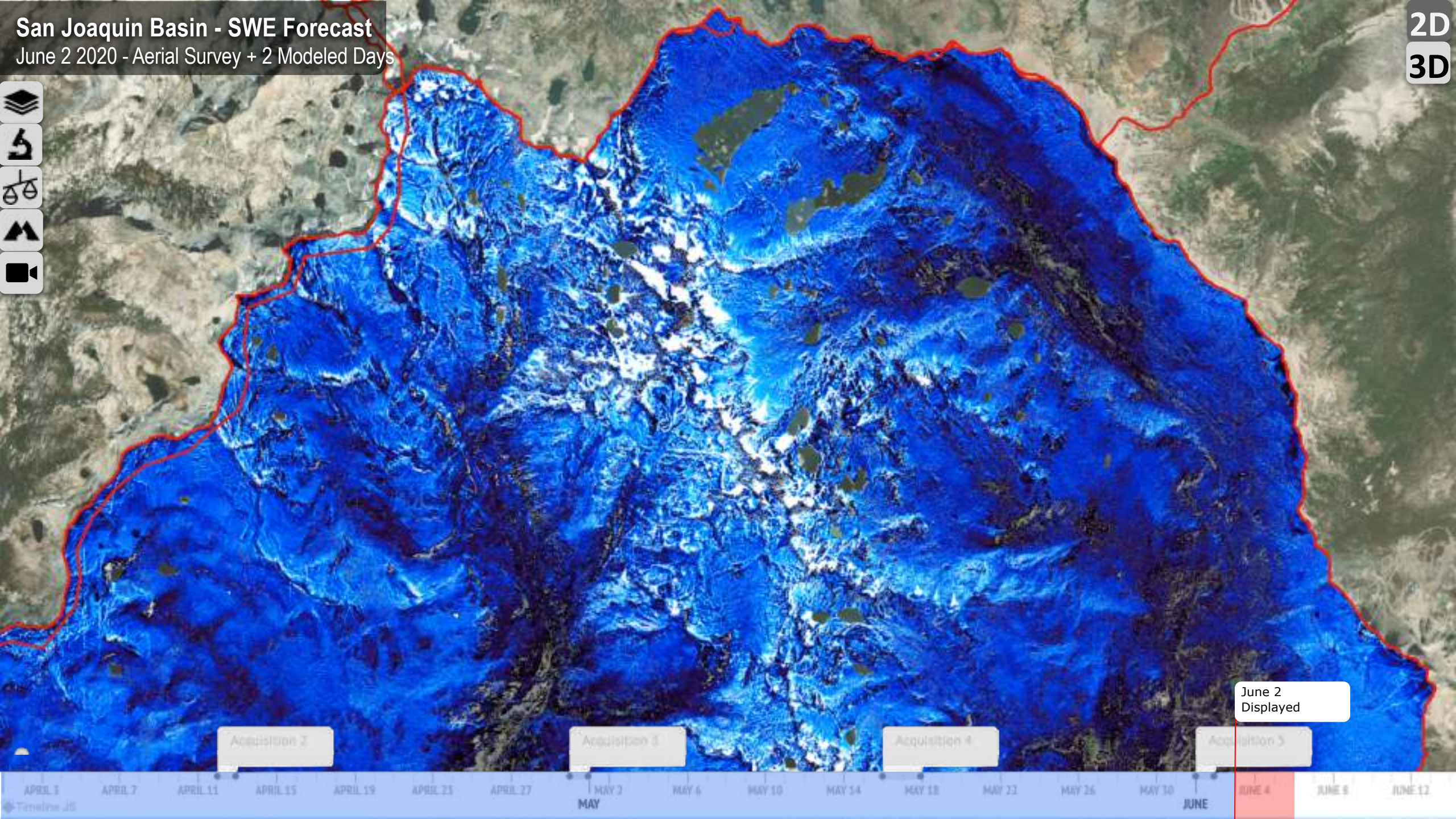
A Public Benefit Corporation

San Joaquin Basin - SWE Forecast

June 2 2020 - Aerial Survey + 2 Modeled Days

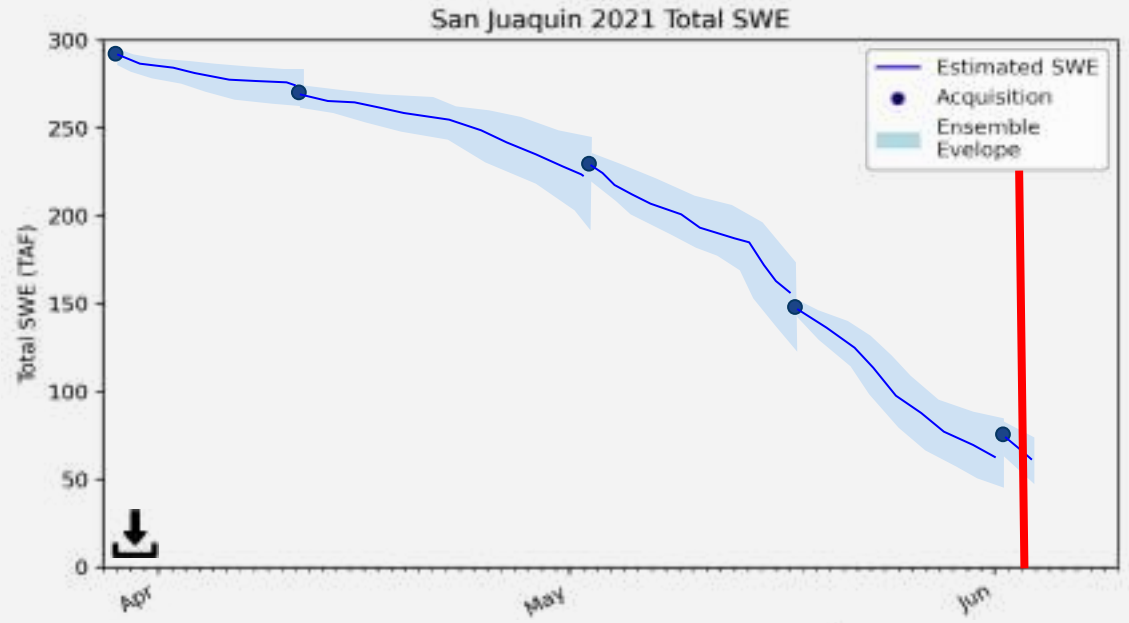


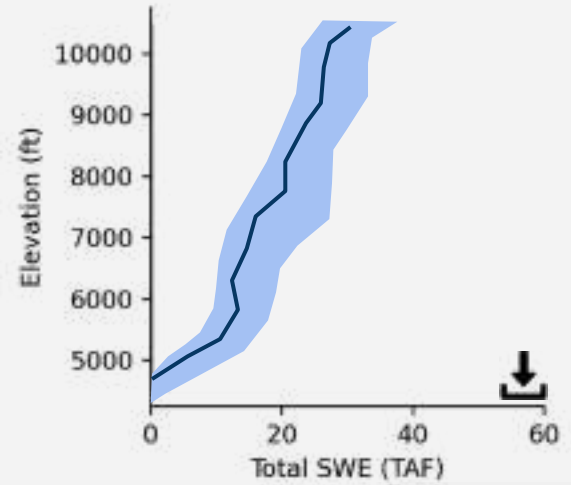

San Joaquin Basin - SWE Forecast
June 2 2020 - Aerial Survey + 2 Modeled Days
2D
3D
Variable
Snow Water Equivalent (SWE)
Snow Depth
Snow Albedo
Values or Uncertainties
Display Data Values
Display Uncertainties
Model Ensemble Bracketing
Dust Radiative Forcing (+ 25%)
Download Data
SWE Depth (m)
0
1
2
3
4
June 2
Displayed
Acquisition 3
Acquisition 4
Acquisition 5
APRIL 3
APRIL 7
APRIL 11
APRIL 15
APRIL 19
APRIL 23
APRIL 27
MAY 2
MAY 6
MAY 10
MAY 14
MAY 18
MAY 22
MAY 26
MAY 30
JUNE 4
JUNE 8
JUNE 12
MAY
JUNE

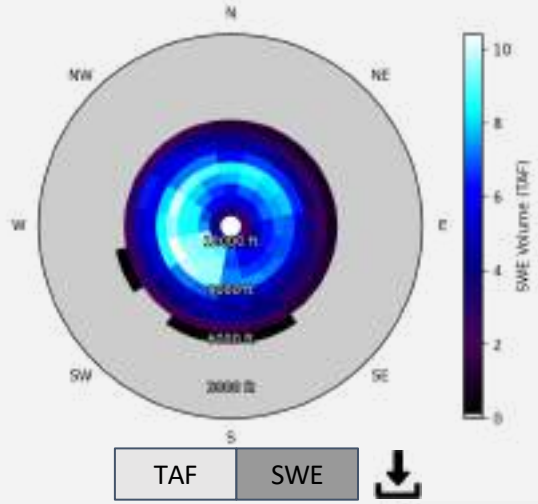

San Joaquin Basin - SWE Forecast
June 2 2020 - Aerial Survey + 2 Modeled Days
2D
3D
June 2
Displayed
Acquisition 2
Acquisition 3
Acquisition 4
Acquisition 5
APRIL 3
APRIL 7
APRIL 11
APRIL 15
APRIL 19
APRIL 23
APRIL 27
MAY 2
MAY 6
MAY 10
MAY 14
MAY 18
MAY 22
MAY 26
MAY 30
JUNE 4
JUNE 8
JUNE 12
MAY
JUNE

San Joaquin Basin - SWE Forecast

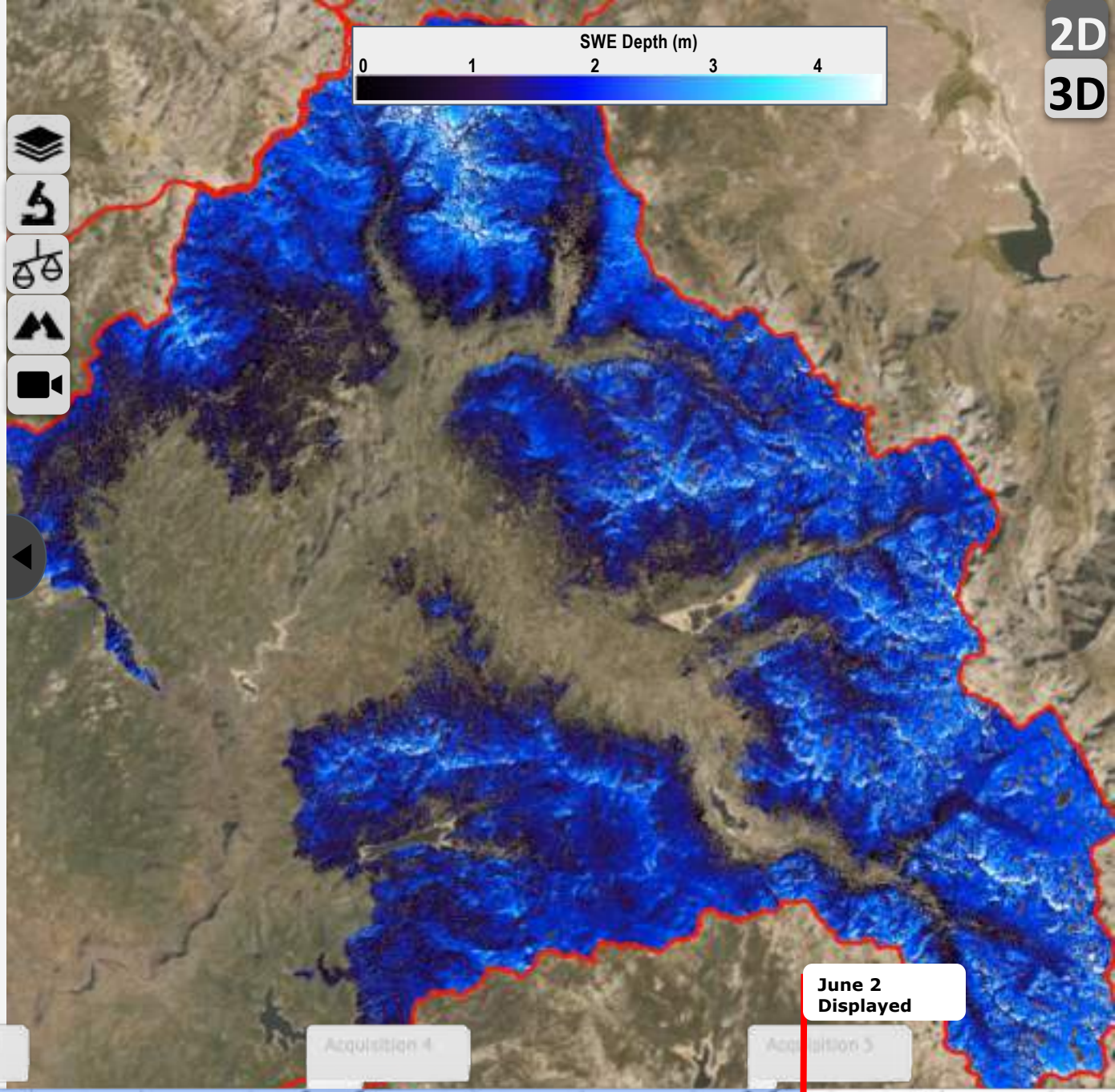
June 2 2020 - Aerial Survey + 2 Modeled Days





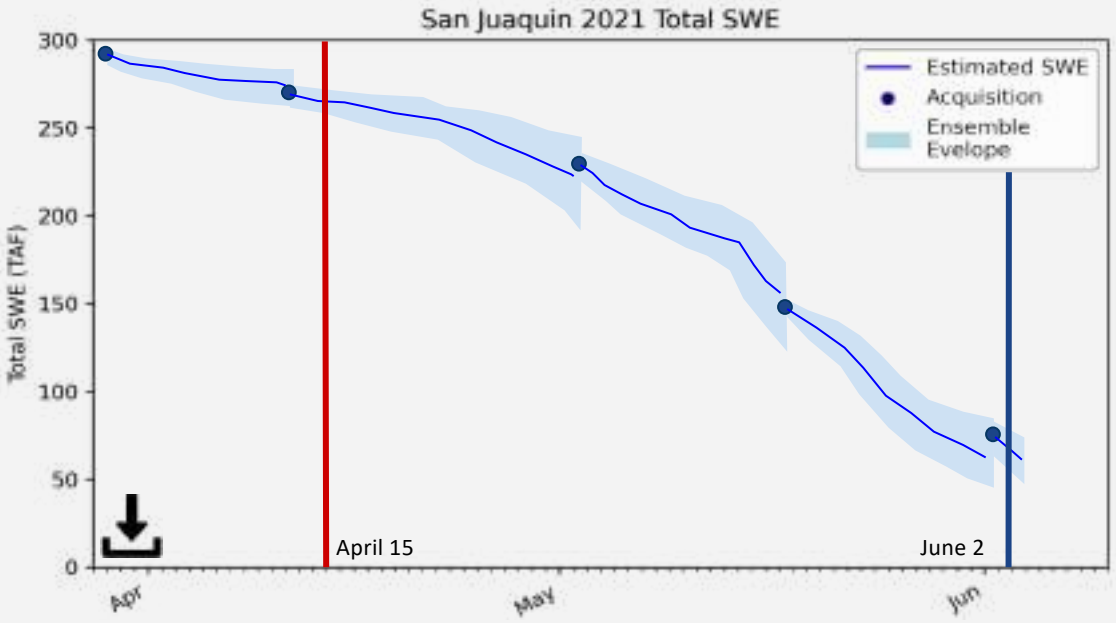


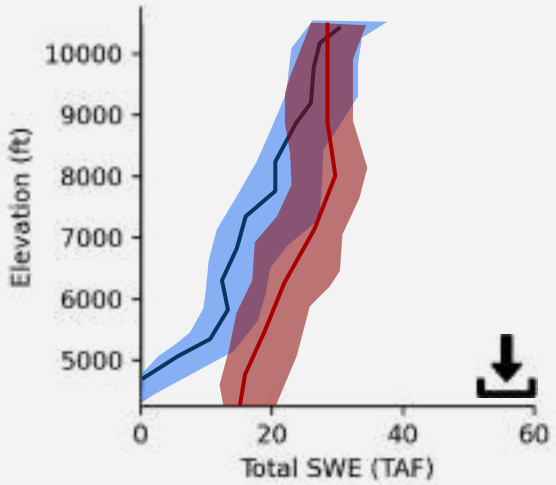
TAF | SWE

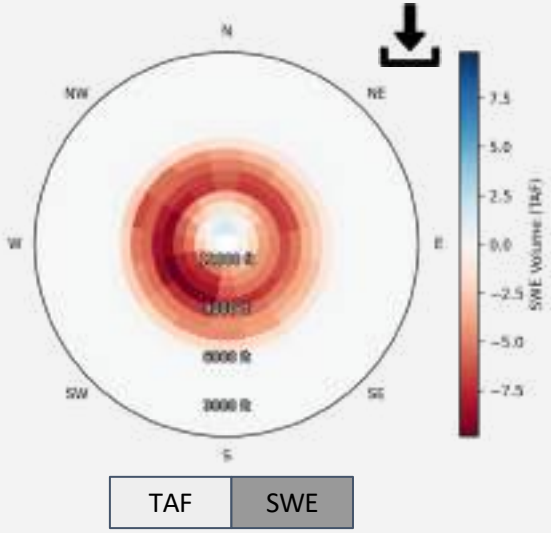


San Joaquin Basin - SWE Forecast

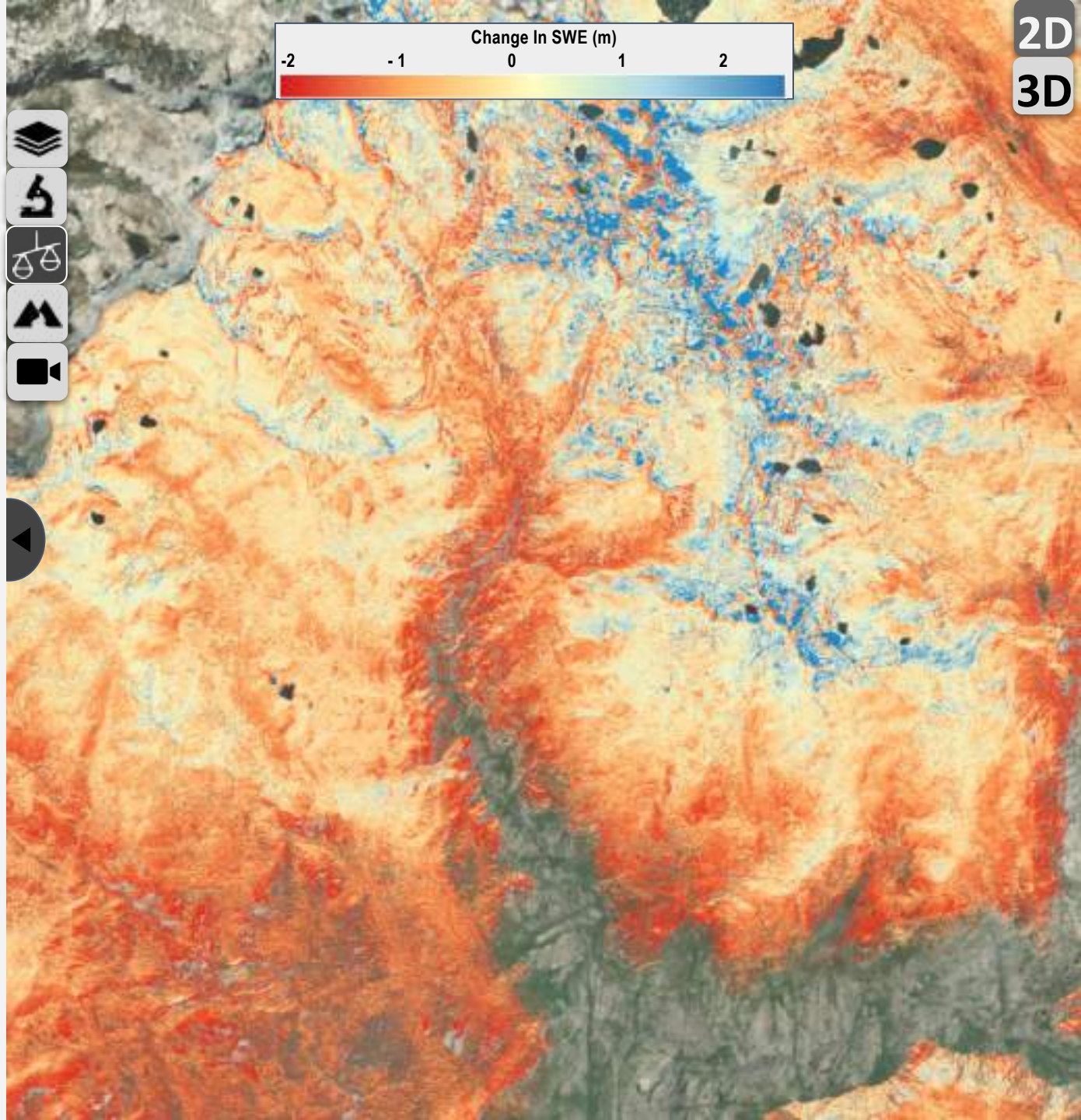
June 2 2020 - Aerial Survey + 2 Modeled Days

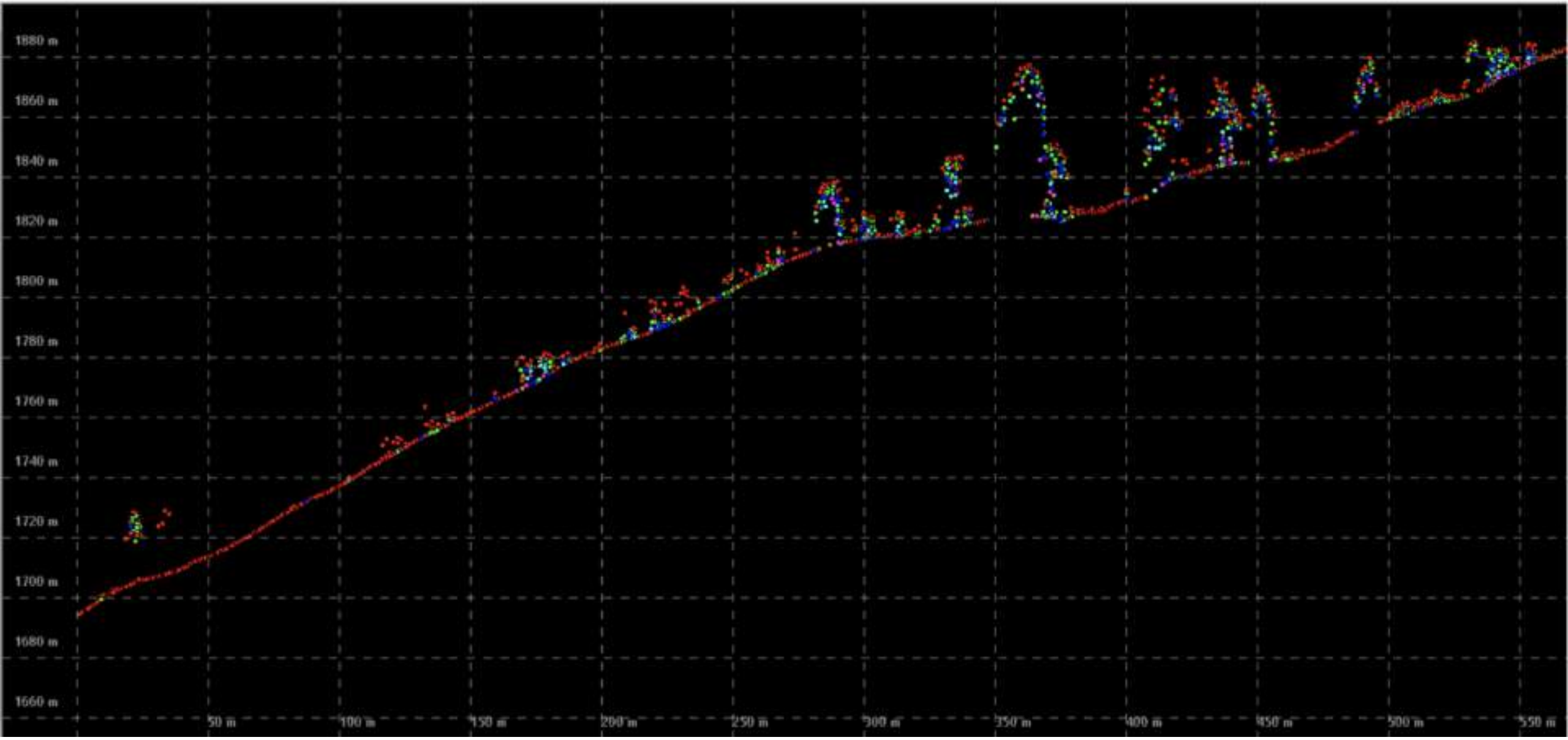






TAF | SWE




1880 m
1860 m
1840 m
1820 m
1800 m
1780 m
1760 m
1740 m
1720 m
1700 m
1680 m
1660 m
50 m
100 m
150 m
200 m
250 m
300 m
350 m
400 m
450 m
500 m
550 m

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