Spatial and Temporal Variability of Dust on Snow Impacts in the Great Salt Lake Basin

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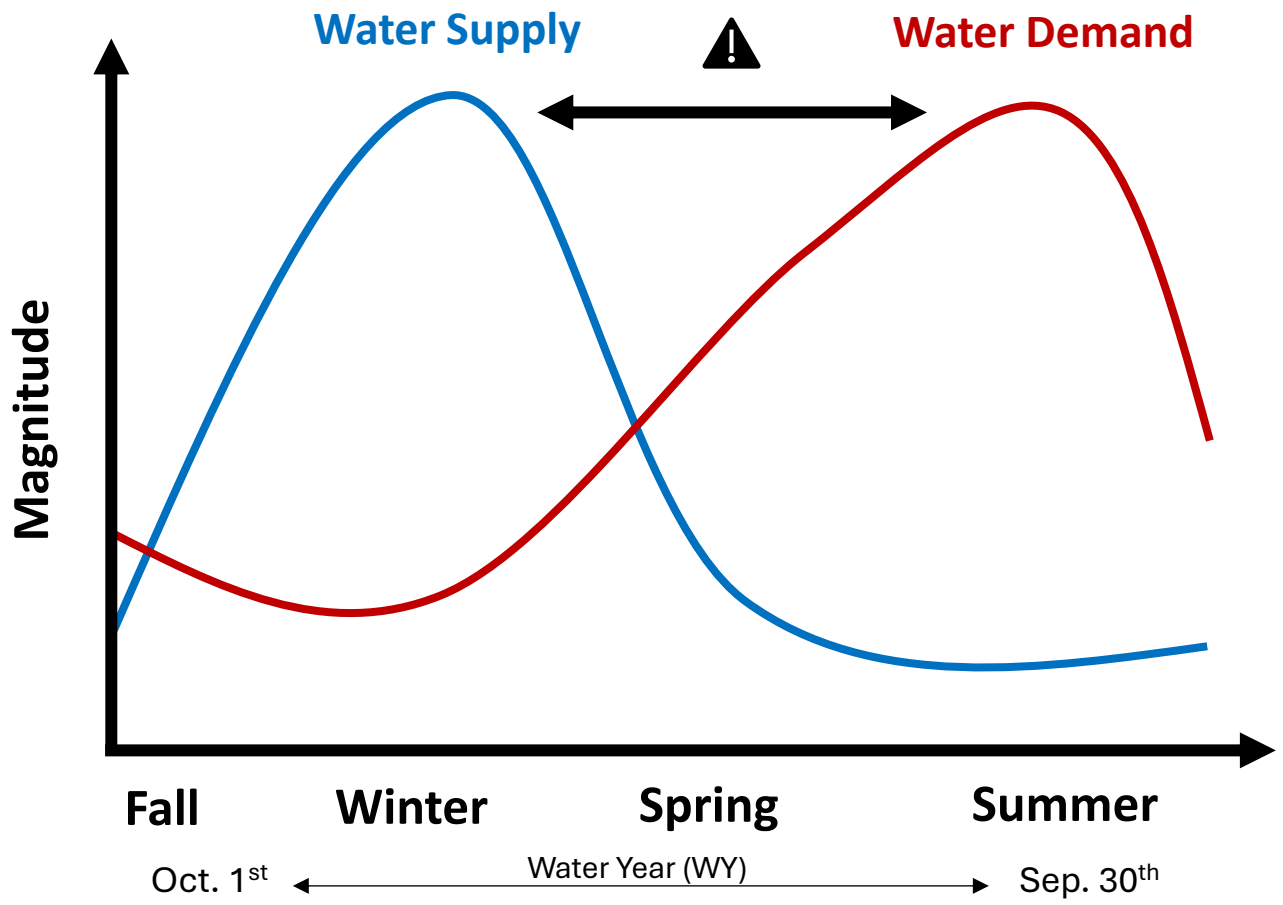
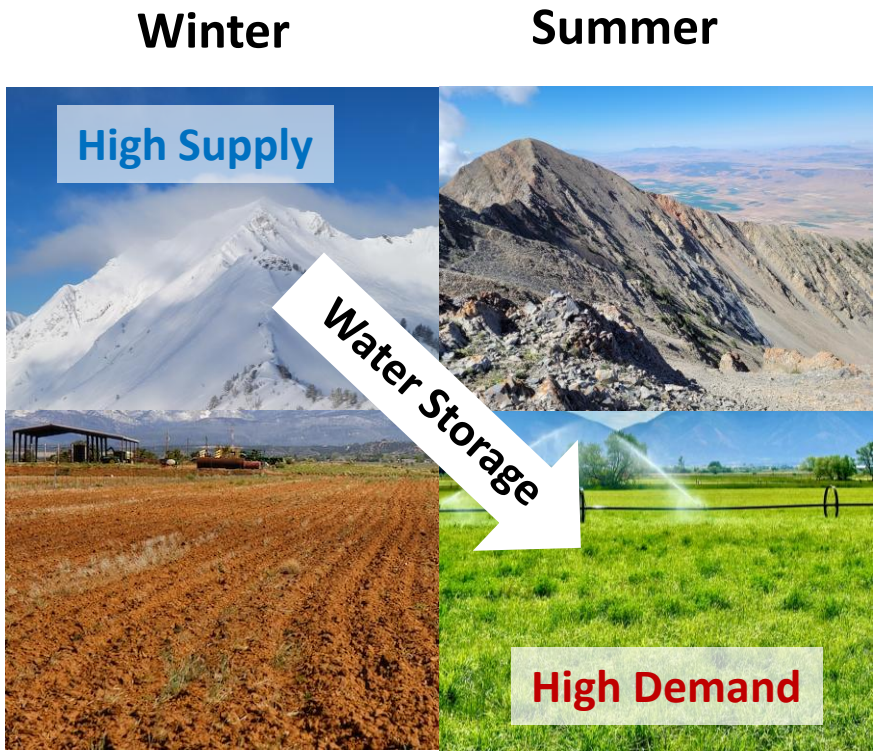
5) Department of Geosciences, BYU

SNOW HYDRO
Research to Operations Lab

Water in the West

~2/3 of water originates as snow





⚠ **Storage of cold season water supply is critical to meet warm season water demand. Storage is manmade (reservoirs) and natural (snowpack).**

Inspired by Hale et al. (2023); Li et al (2017); Mankin et al. (2015)

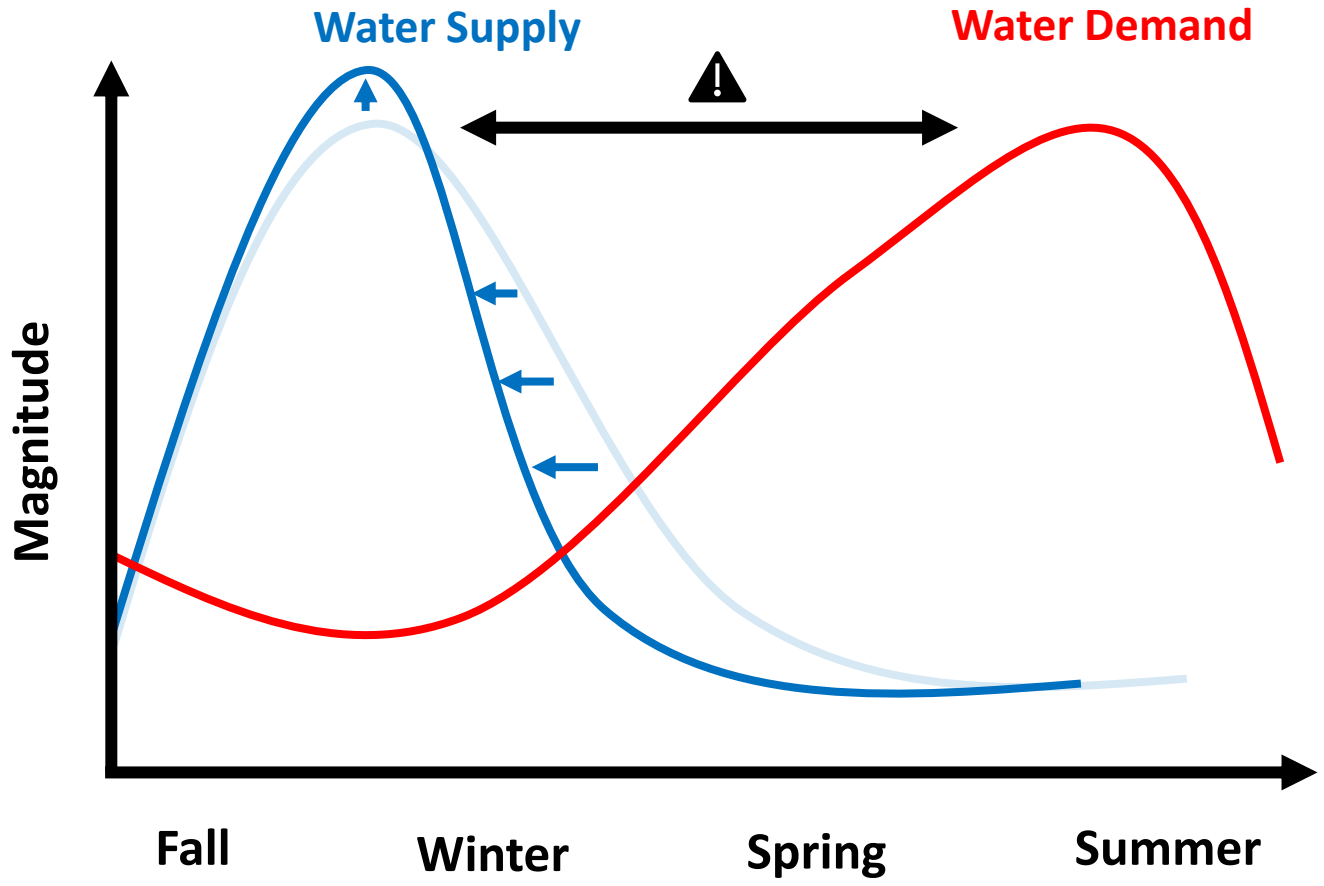
Clean snow reflects ~90% of visible solar radiation (albedo ~ 0.9)

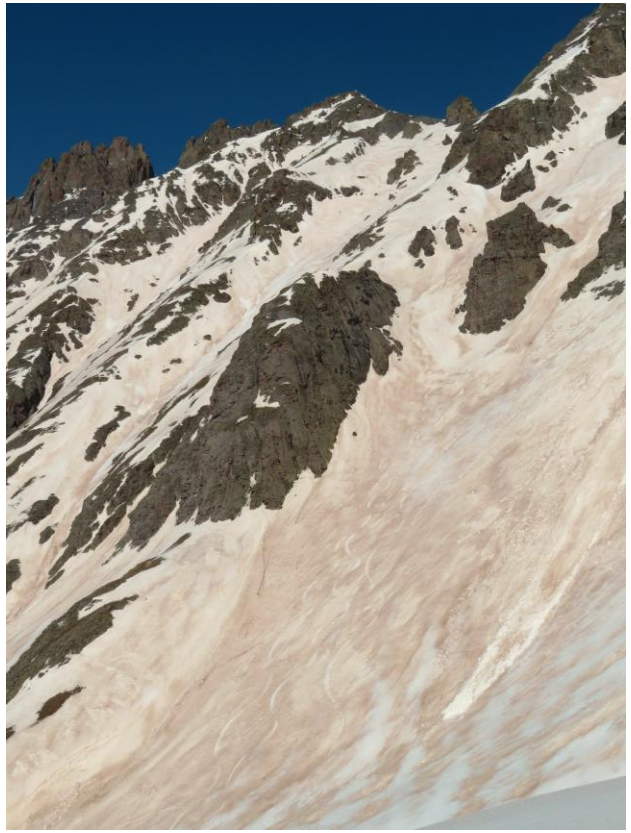
Brighter snowpack
Less melting

Snow darkened by dust absorbs more visible solar radiation, adding energy for melt

Darker snowpack
More melting

Water in the West



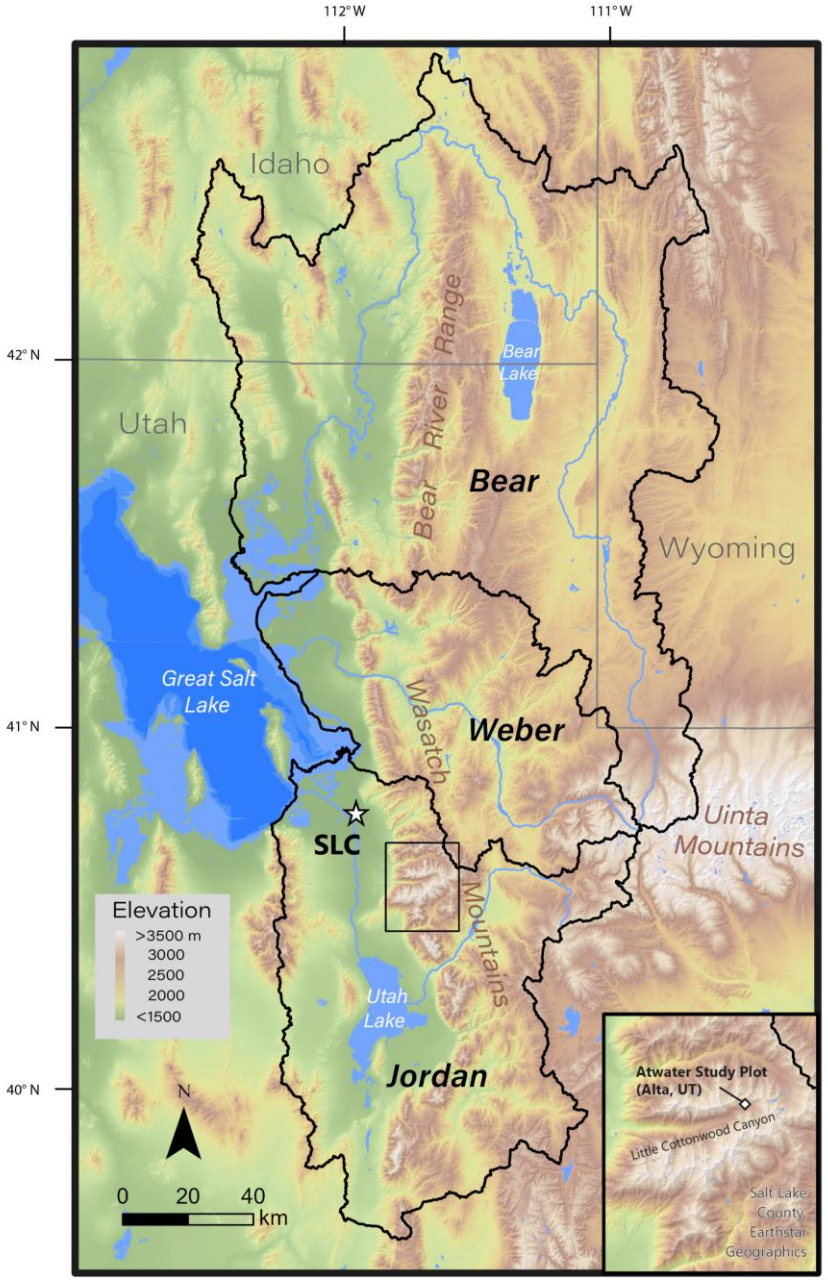


Dust on snow -> Earlier snowmelt -> Shorter snow season

- Further offset between peak supply and peak demand
- Additional strain on reservoirs and ecosystems

The Impacts of dust on snow are not well constrained, spatially or historically

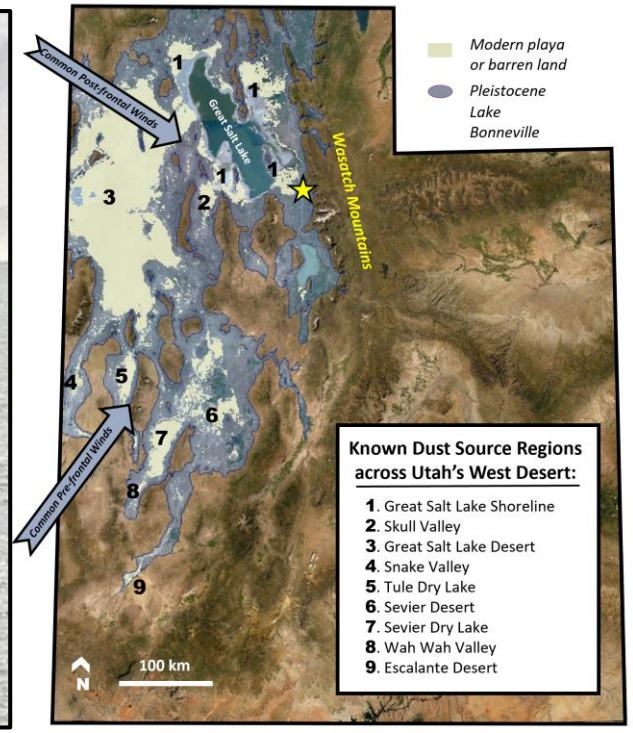
Skiles et al. (2012; 2015); Painter et al. (2010); Deems et al. (2013); Bryant et al. (2013)



The Great Salt Lake Basin (GSLB)

- Home to ~2.7 million, 80% of Utahns
- Water from snow
  - Economic driver of agriculture and rangeland
  - Primary inflow to the GSL
- Seasonal dust deposition from upwind West Desert playas

Dust Blowing off source regions in the Great Salt Lake Desert on April 18th 2023.



Lang et al. (2025); Hahnenberger and Nicoll (2014); Bardsley et al. (2013); Salt Lake County; Mesowest

Research Question:

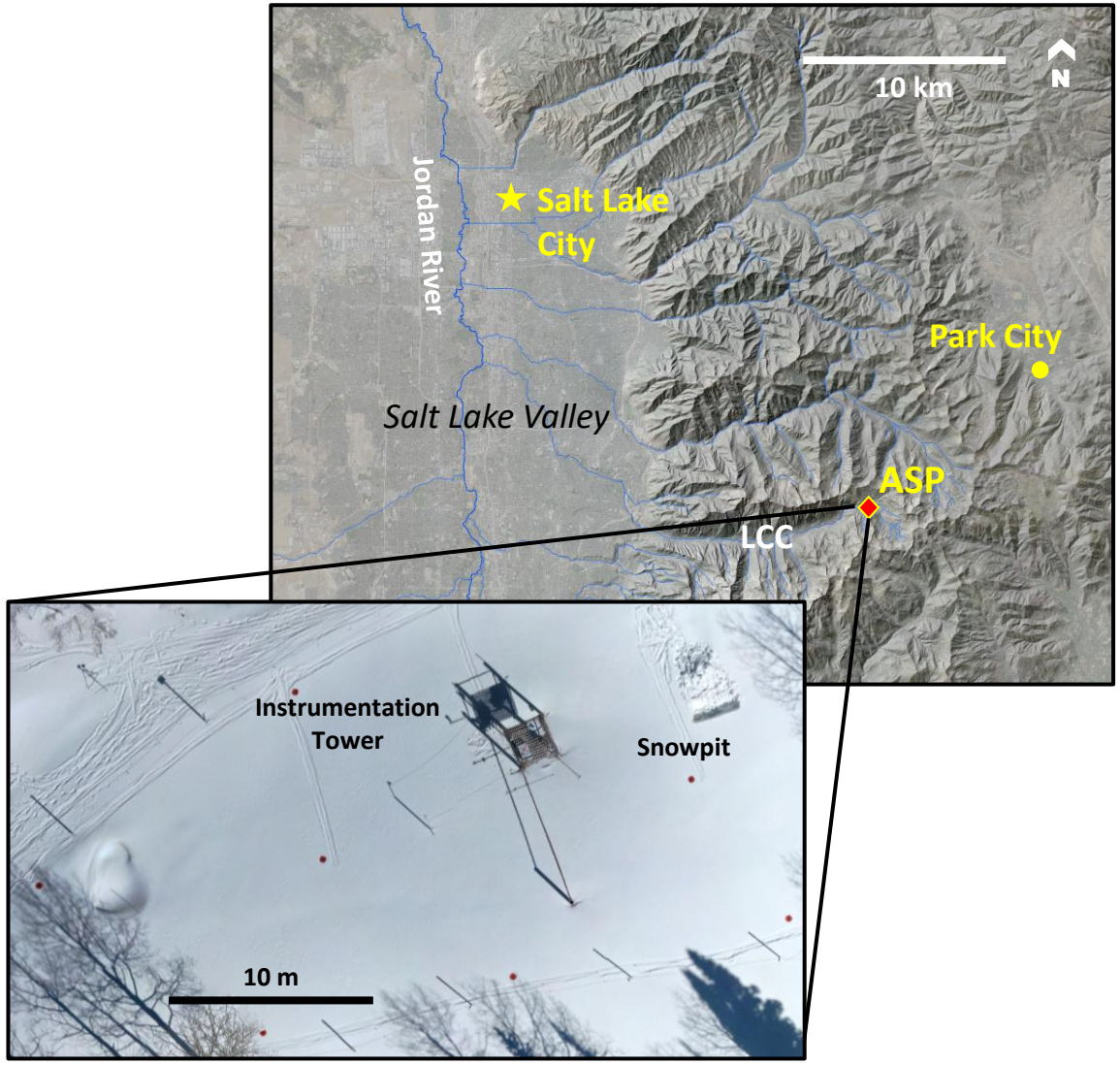
How does dust impact snowmelt timing in the Great Salt Lake Basin?

Approach	Primary Method
1 One year field campaign to quantify dust on snow processes	*Field Observation*
2 Use satellite observations to detect changes in snow darkening over two decades	*Remote Sensing*
3 Quantify the spatial variability of snow darkening effects on snowmelt	*Process-based Modeling*

Field campaign to track dust on snow events over 2022 snow season

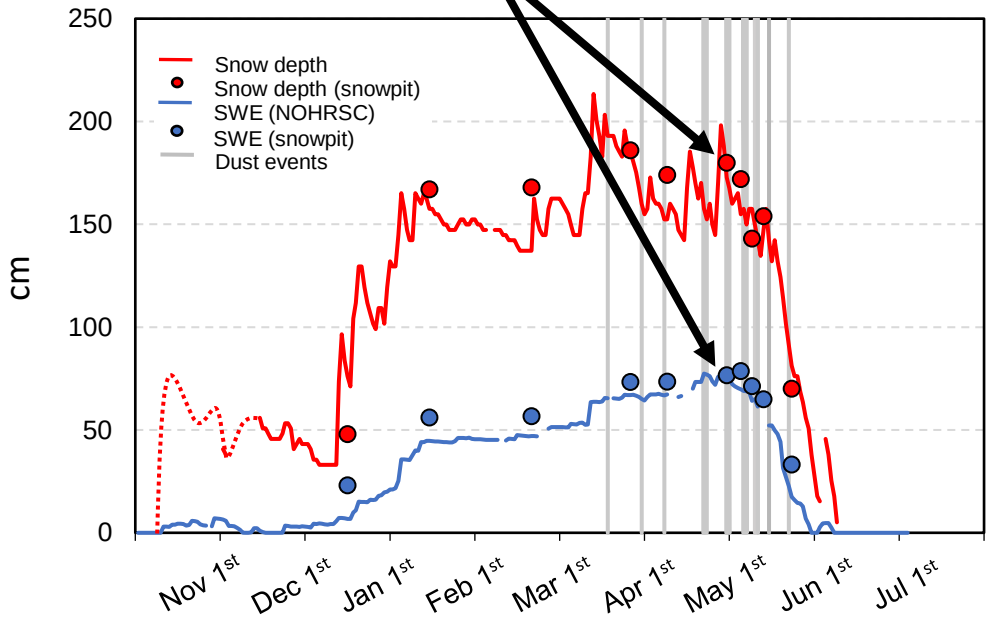
- How much dust?
- How did it impact snowmelt?

Atwater Study Plot (ASP) Alta, UT



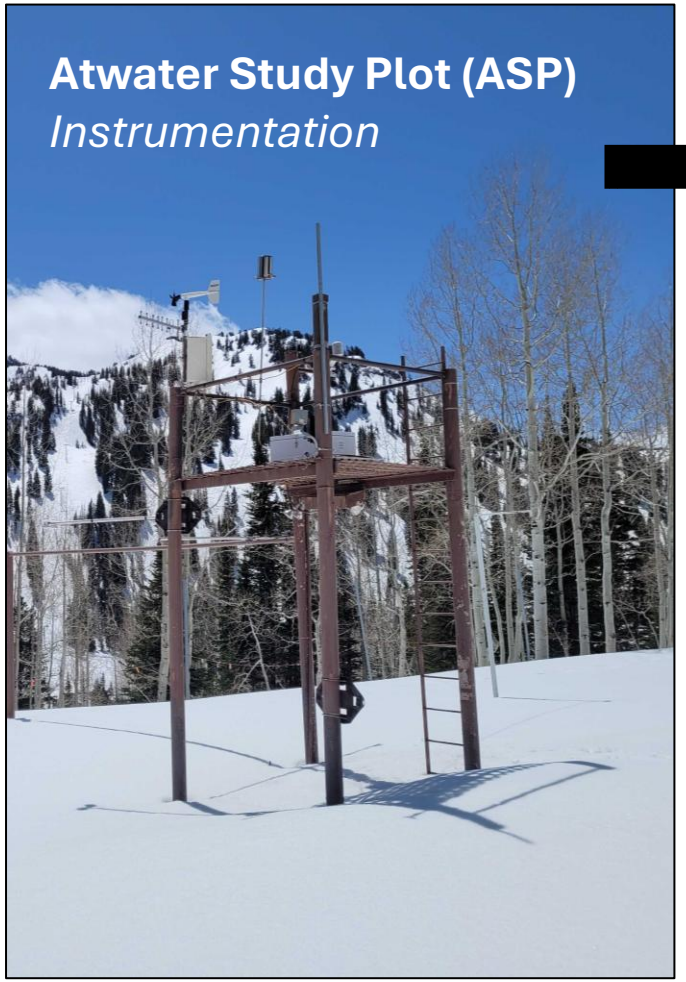
2022 Field Observations

- **Times series of snow hydrology field measurements**
  - Monthly-weekly snowpits
- **Meteorology and radiation data**
  - Temperature, wind, humidity
  - Snow albedo, energetic components of snowmelt



Lang et al. (2023)

How did dust affect snowmelt timing?



Snobal *Marks et al. (1998)*

1D Snow mass and energy balance model

Darkened Snow Run

- Observed conditions

Compared to:

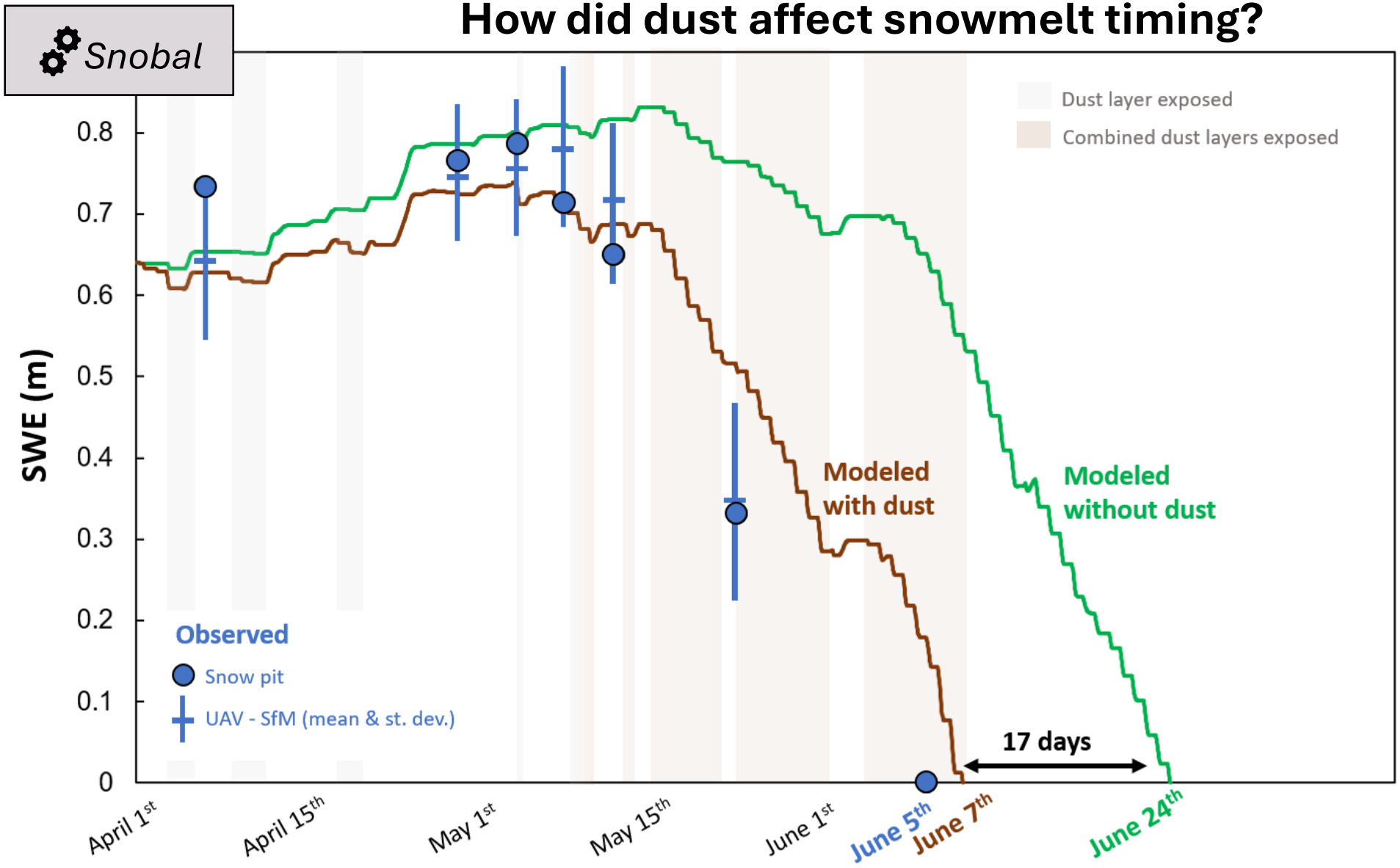
Clean Snow Scenario

- Snow albedo changed to represent snow without impurities
- Hypothetical "dust free" scenario

Following Painter et al. (2007), Skiles et al. (2012)

Lang et al. (2023)

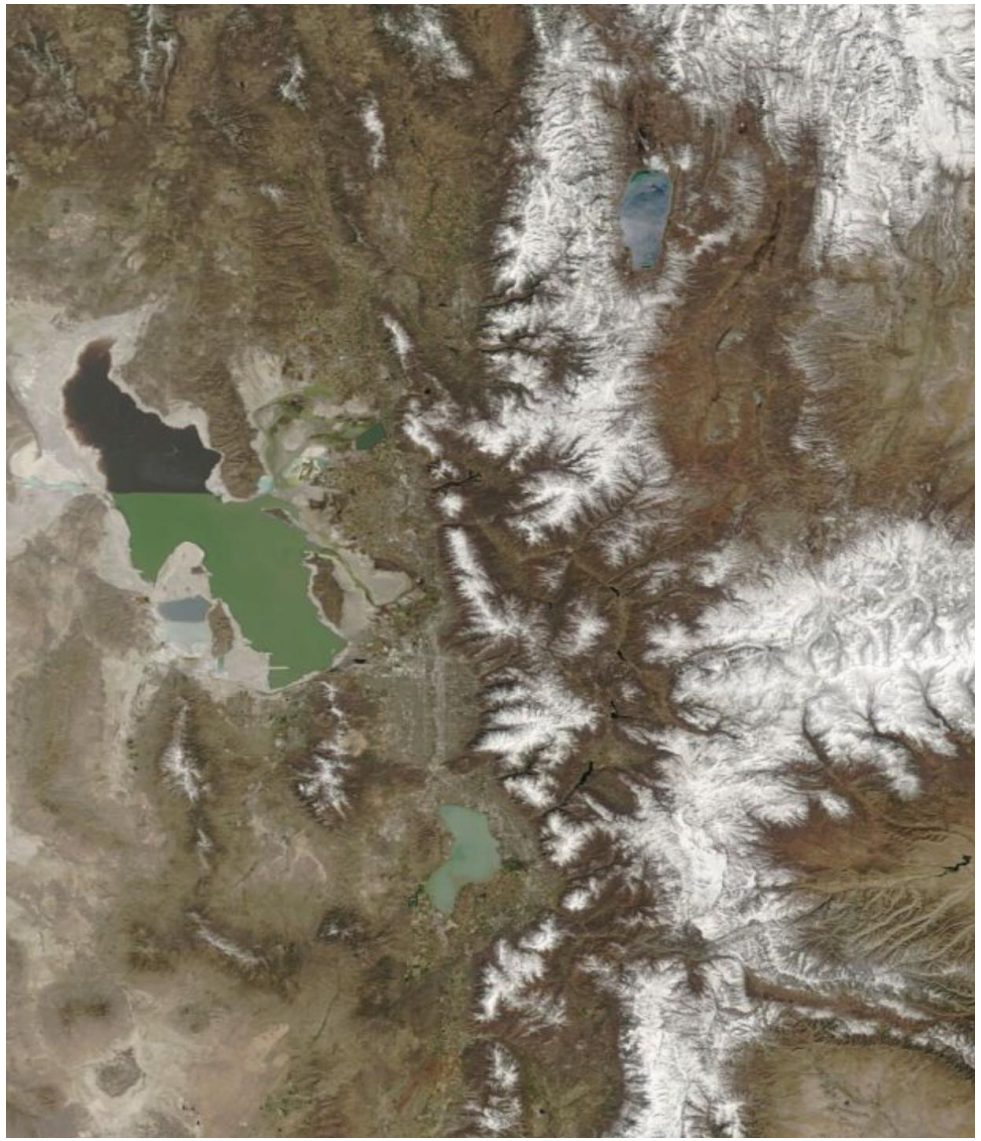
How did dust affect snowmelt timing?

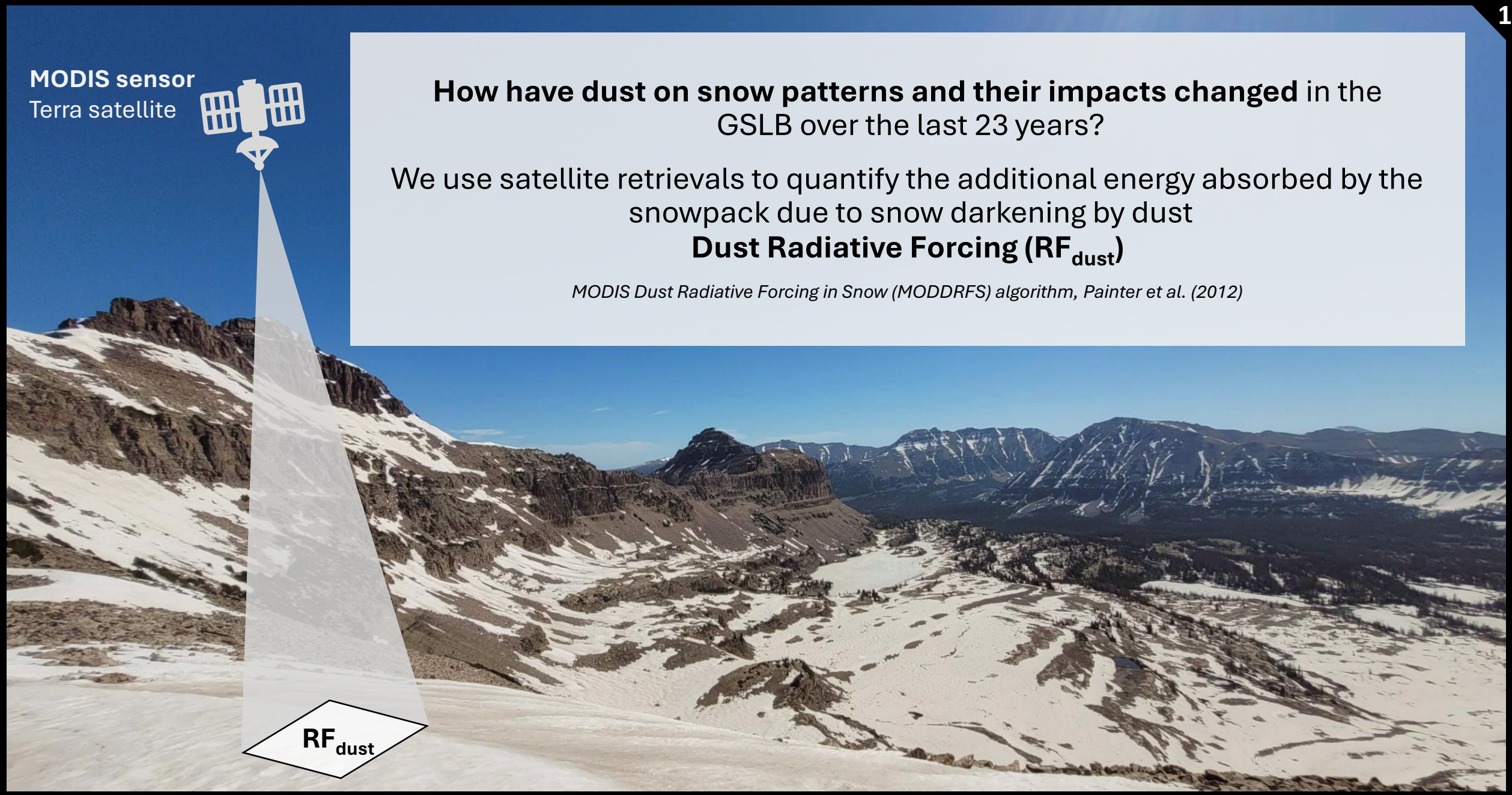


Darkened Snow Run

Clean Snow Run

Lang et al. (2023)





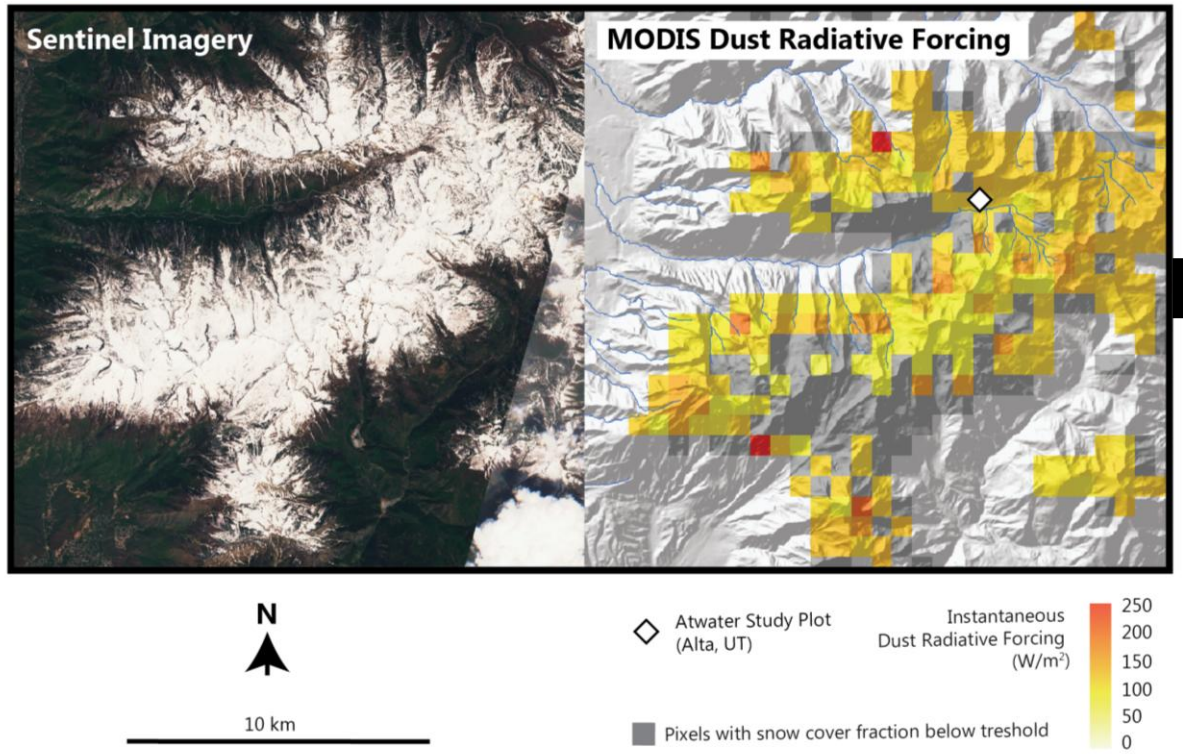
How have dust on snow patterns and their impacts changed in the GSLB over the last 23 years?

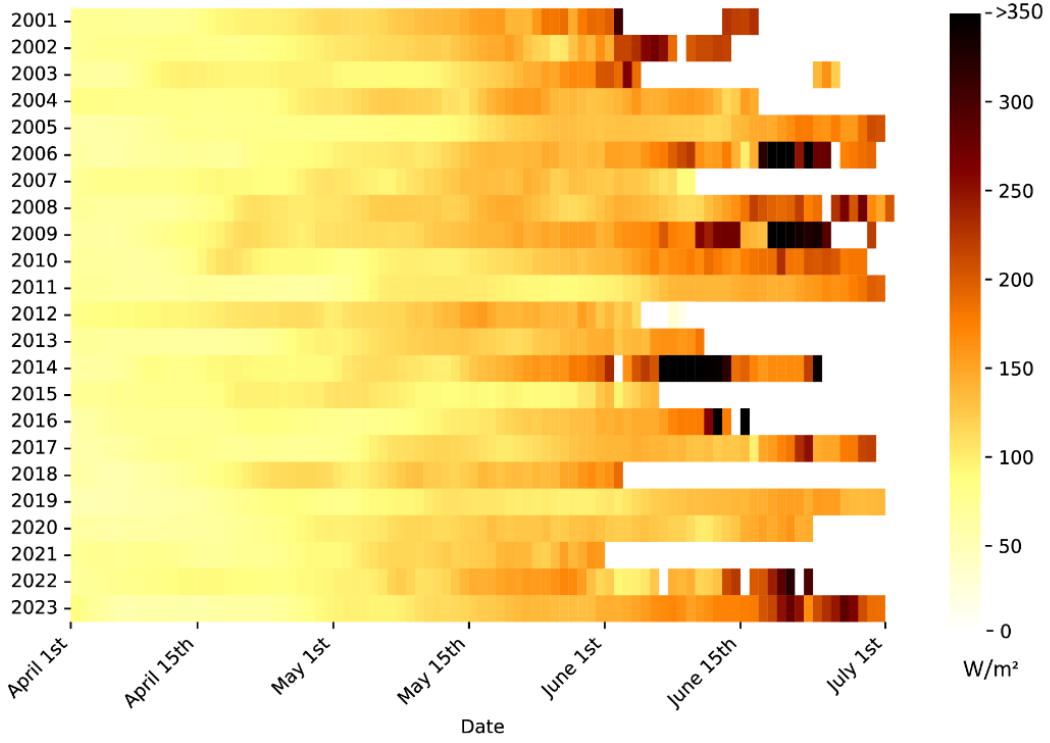
We use satellite retrievals to quantify the additional energy absorbed by the snowpack due to snow darkening by dust

Dust Radiative Forcing (RF_{dust})

MODIS Dust Radiative Forcing in Snow (MODDRFS) algorithm, Painter et al. (2012)

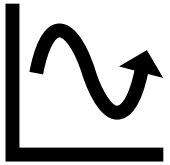
Dust Radiative Forcing Retrievals





- **Daily ~500 x 500 m retrievals** from 2001-2023
- ~344 million pixels!

- **Spatiotemporal patterns** in RF over the entire **Great Salt Lake Basin**

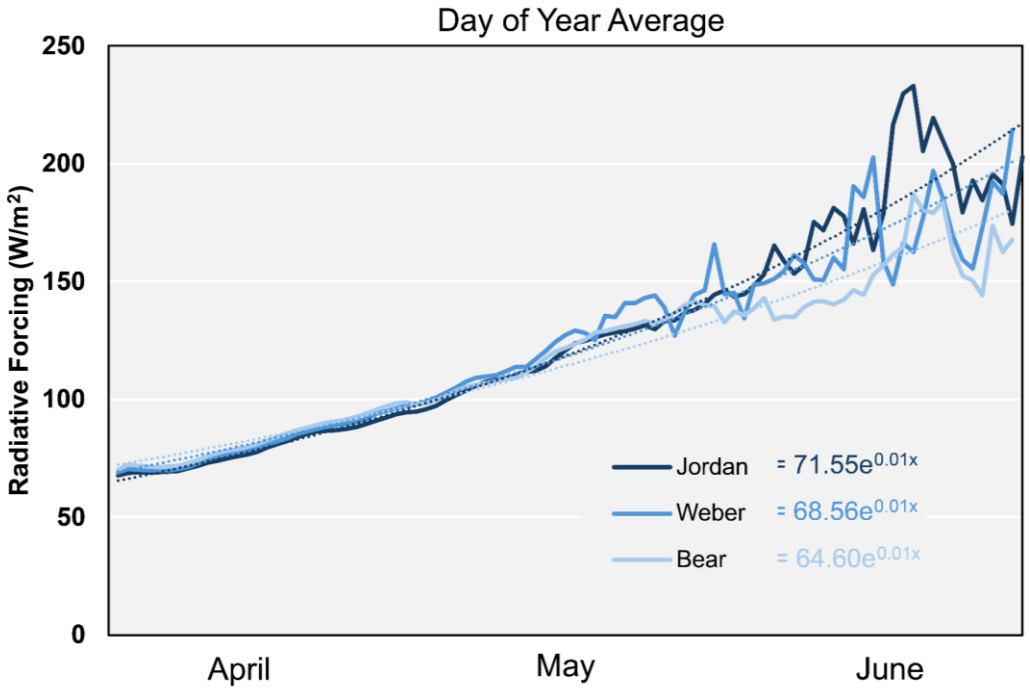


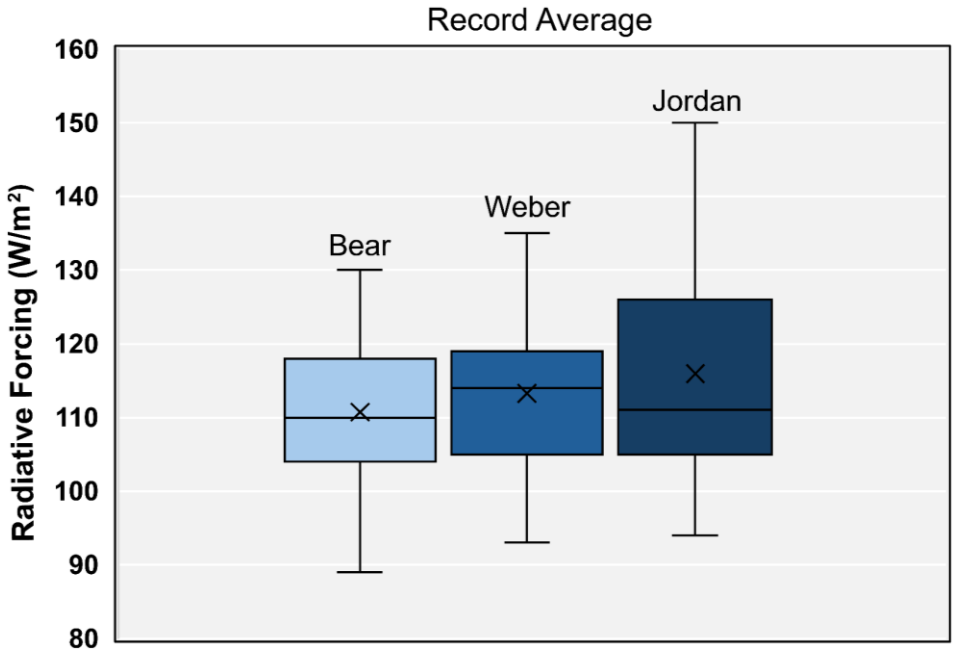
Lang et al. (2025)

Record-averaged patterns in Radiative Forcing

April – June, 2001-2023

Greater Snowmelt Impact



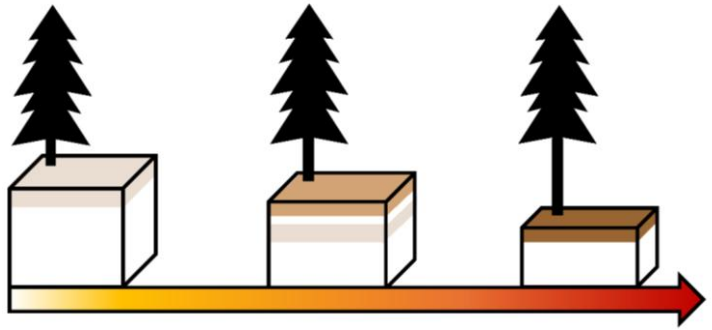


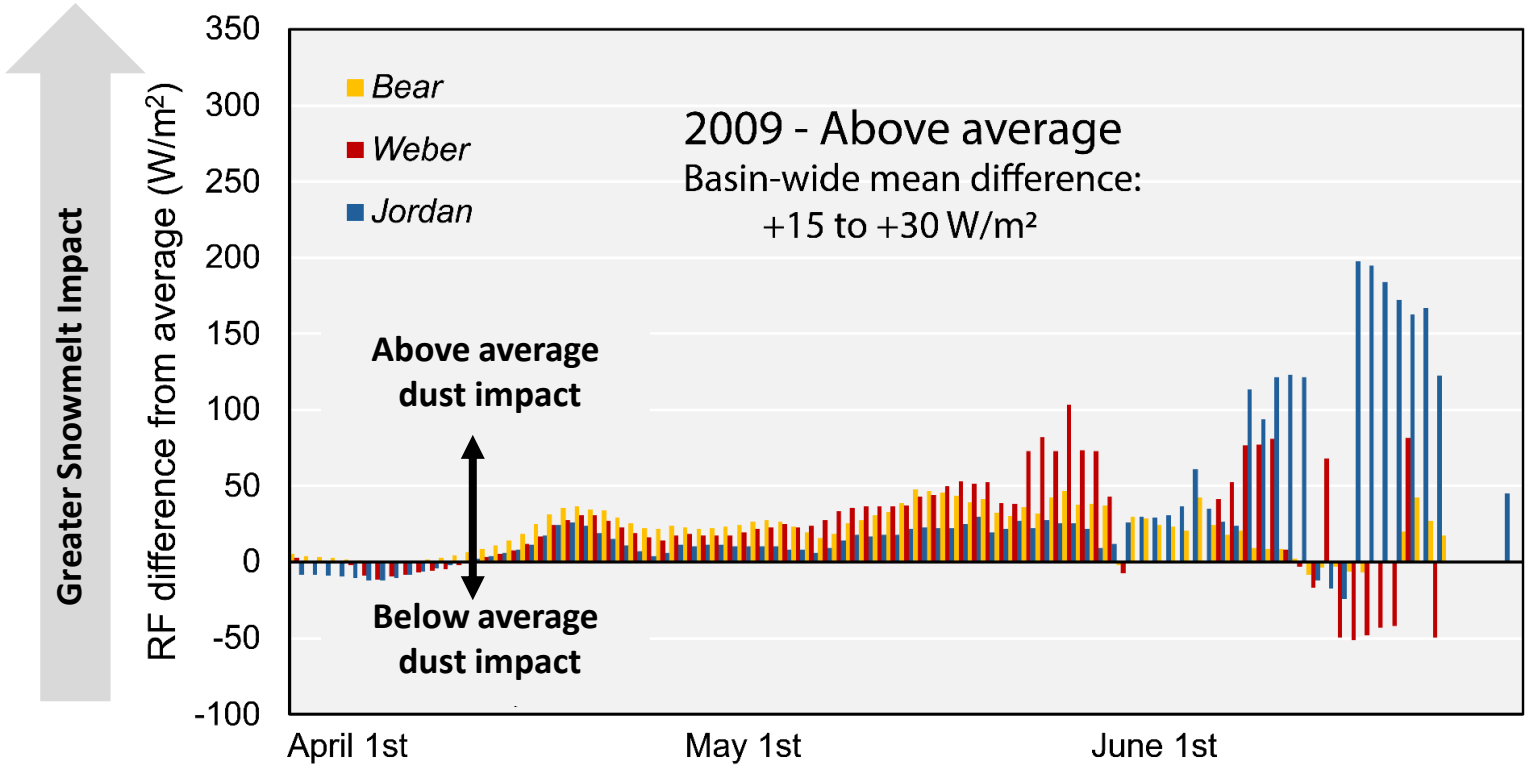
- The impact of dust increases exponentially over the snowmelt season
- The impact of dust is similar between GSLB watersheds

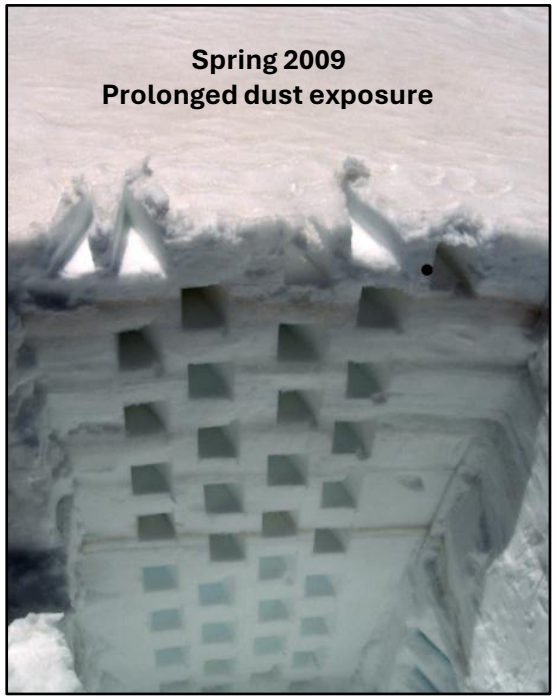
Lang et al. (2025)

Above average dust impact year: 2009

- Combination of **high dust** deposition and **long exposure**







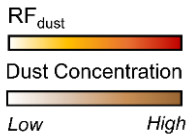


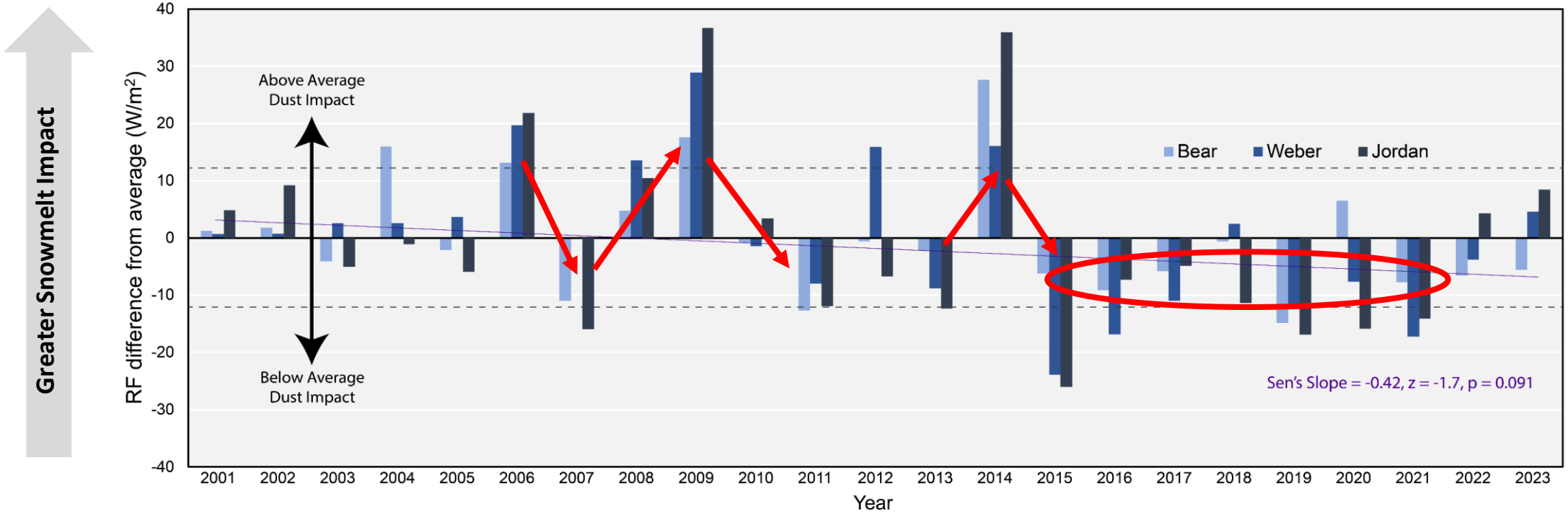
Image modified from Steenburgh et al. (2012)

Lang et al. (2025)

Spatiotemporal Patterns in Dust Radiative Forcing

April – June, 2001-2023

Radiative Forcing Anomalies for Watersheds in the Great Salt Lake Basin



- No definite cyclical pattern
- High interannual variability
- Below average RF common in last decade

Even in below average years – The impact of darkened snow is substantial (~80 W/m^2)

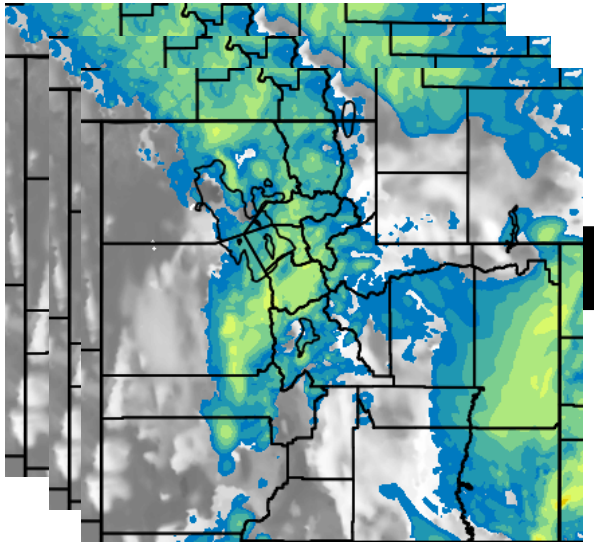
Lang et al. (2025)

How does the impact of dust darkened snow translate to snowmelt timing?

We use a **modeling approach** to
Simulate snowmelt **with and without snow darkening**

Hourly inputs from numerical **weather prediction model** – HRRR

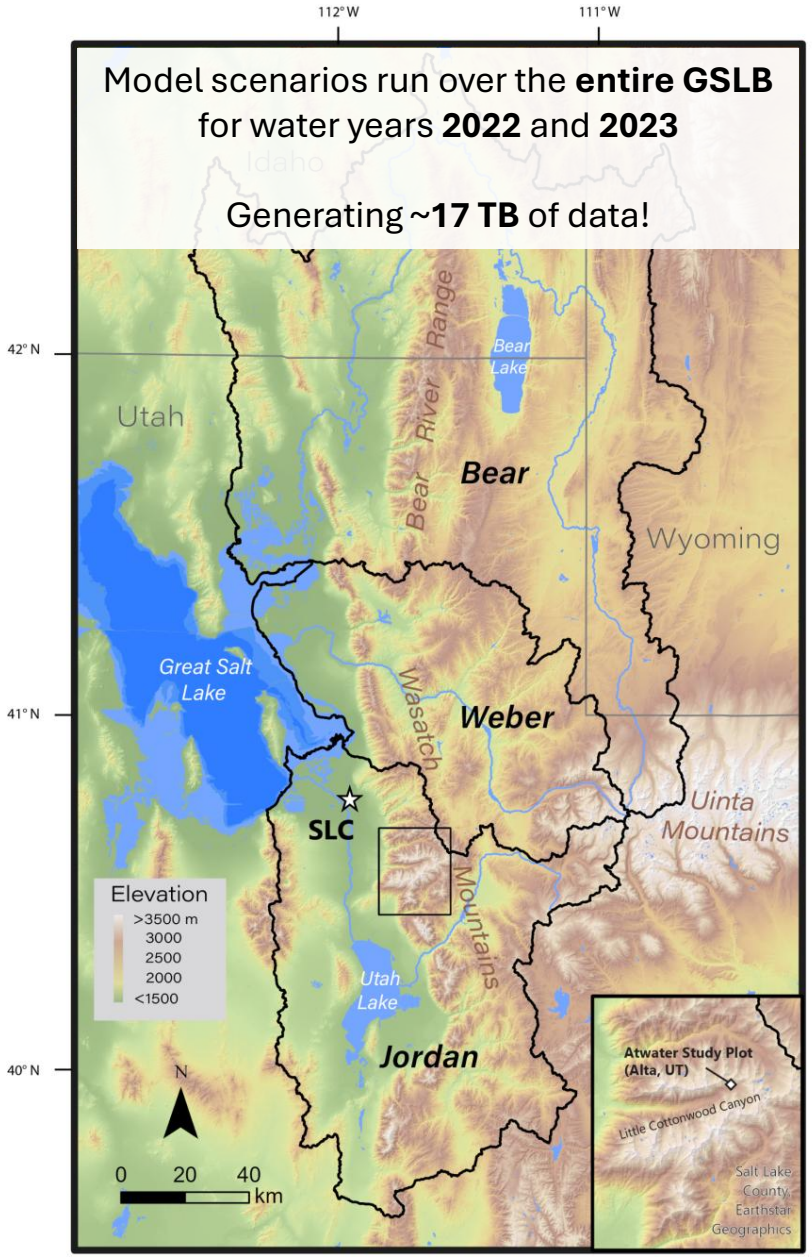
- *Precip, temp, radiation, wind, etc.*



High Resolution Rapid Refresh (HRRR)
Benjamin et al. (2016)

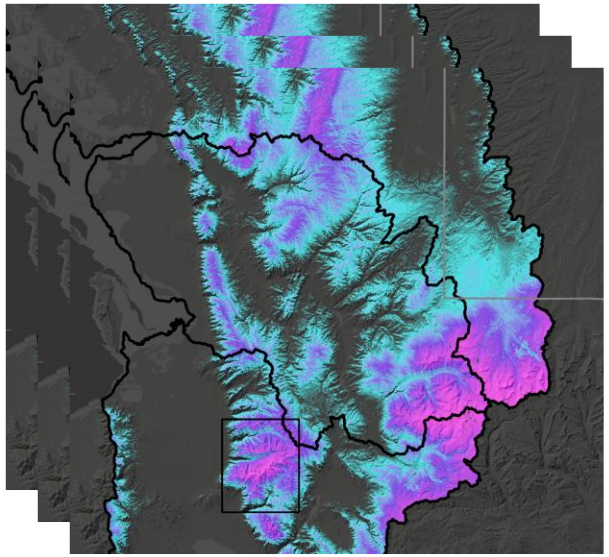
Model scenarios run over the **entire GSLB** for water years **2022** and **2023**

Generating ~**17 TB** of data!

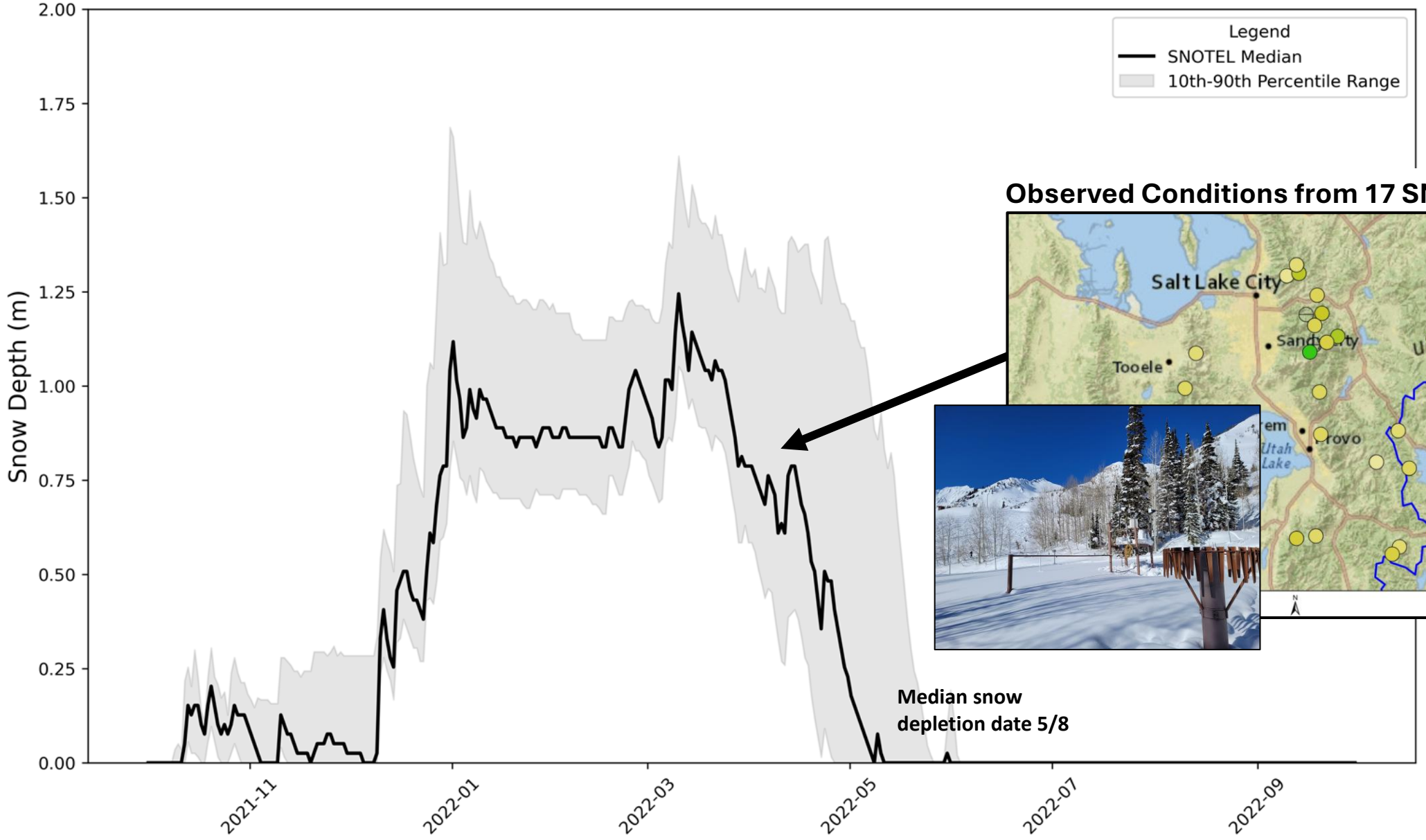


Daily outputs of Snow parameters
at 100m x 100m resolution

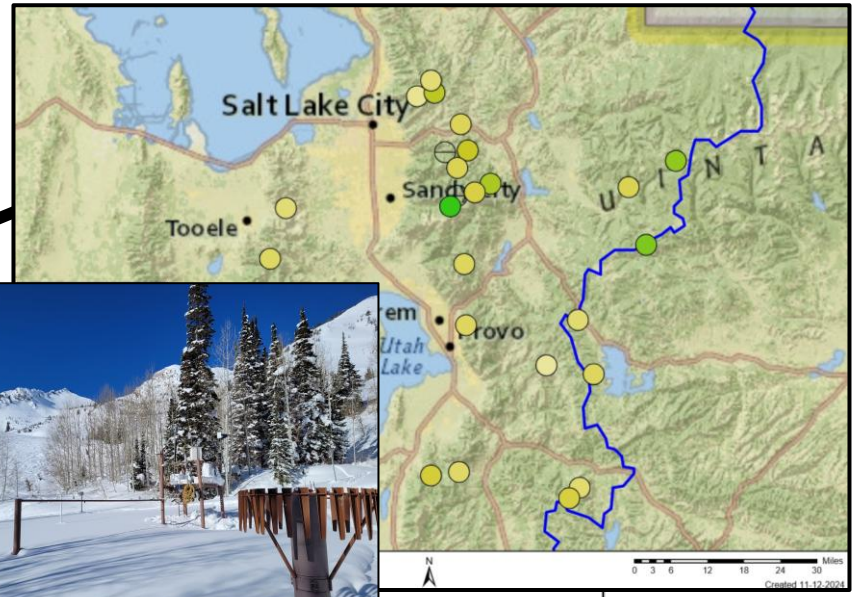
- *Snow depth, SWE, snowpack temp, liquid water content, etc.*



Ground-truthing modeled results: Jordan watershed WY 2022



Observed Conditions from 17 SNOTEL Sites



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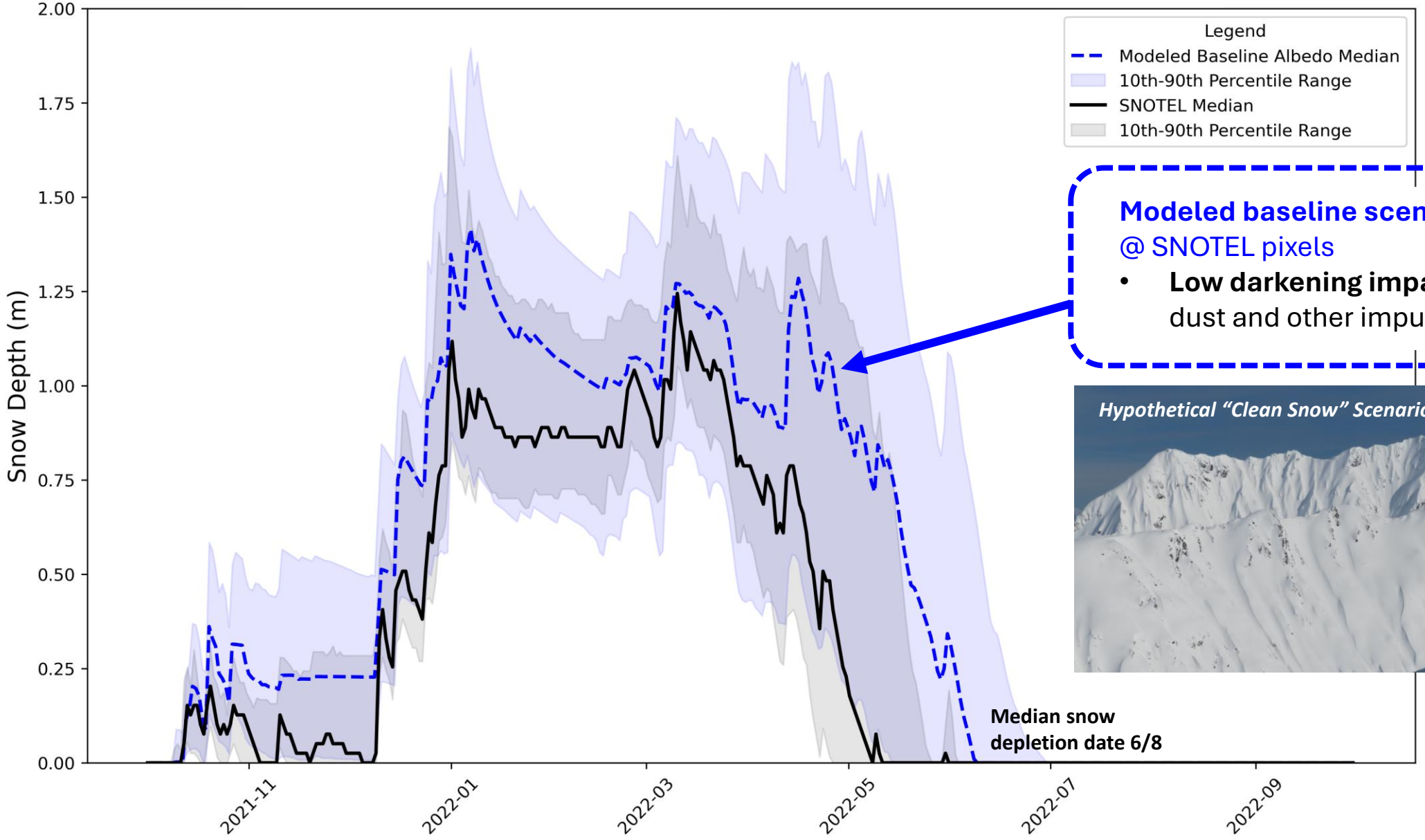
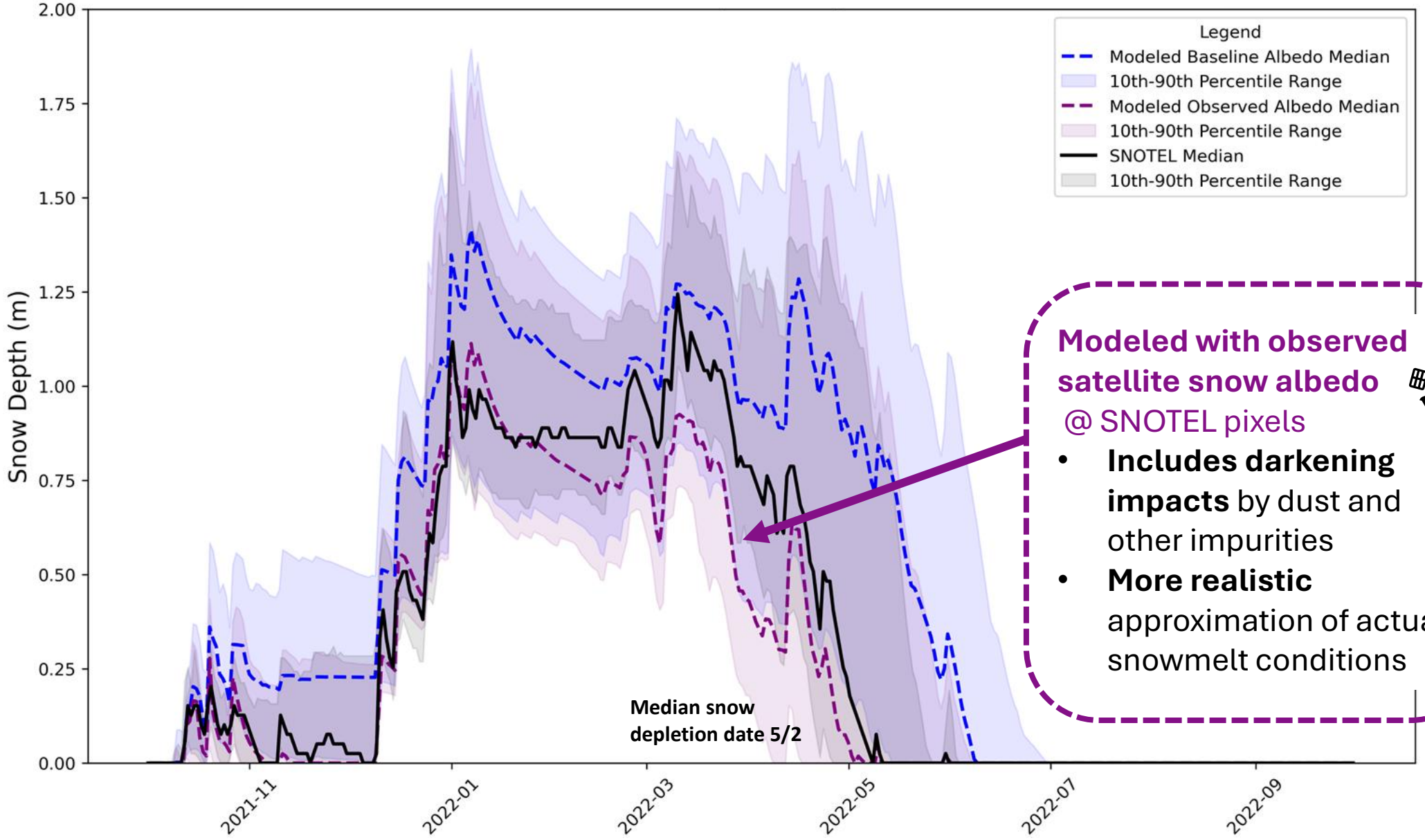


Modeled baseline scenario
@ SNOTEL pixels

- **Low darkening impacts** by dust and other impurities

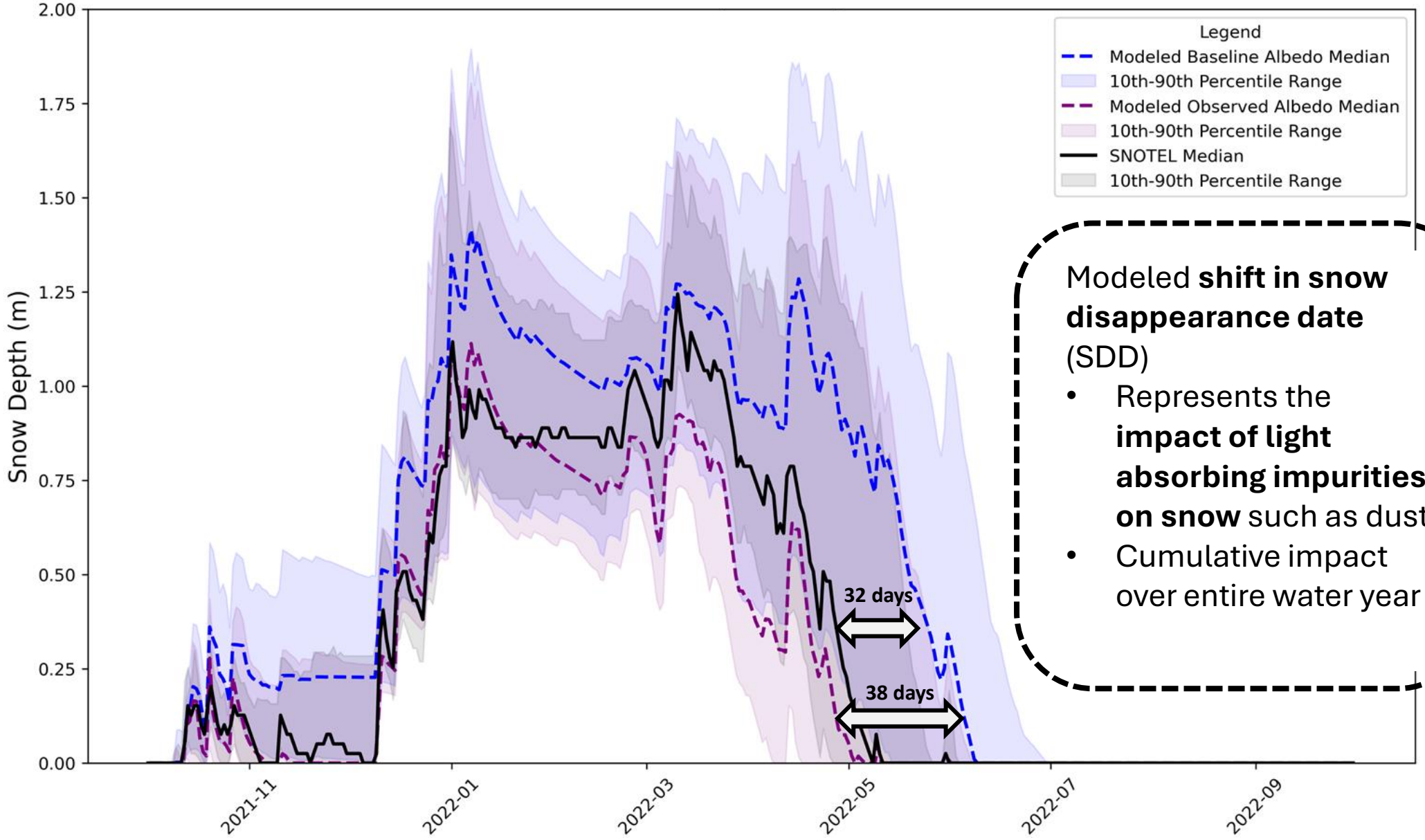
Ground-truthing modeled results: Jordan watershed WY 2022



Modeled with observed satellite snow albedo @ SNOTEL pixels

- **Includes darkening impacts** by dust and other impurities
- **More realistic** approximation of actual snowmelt conditions

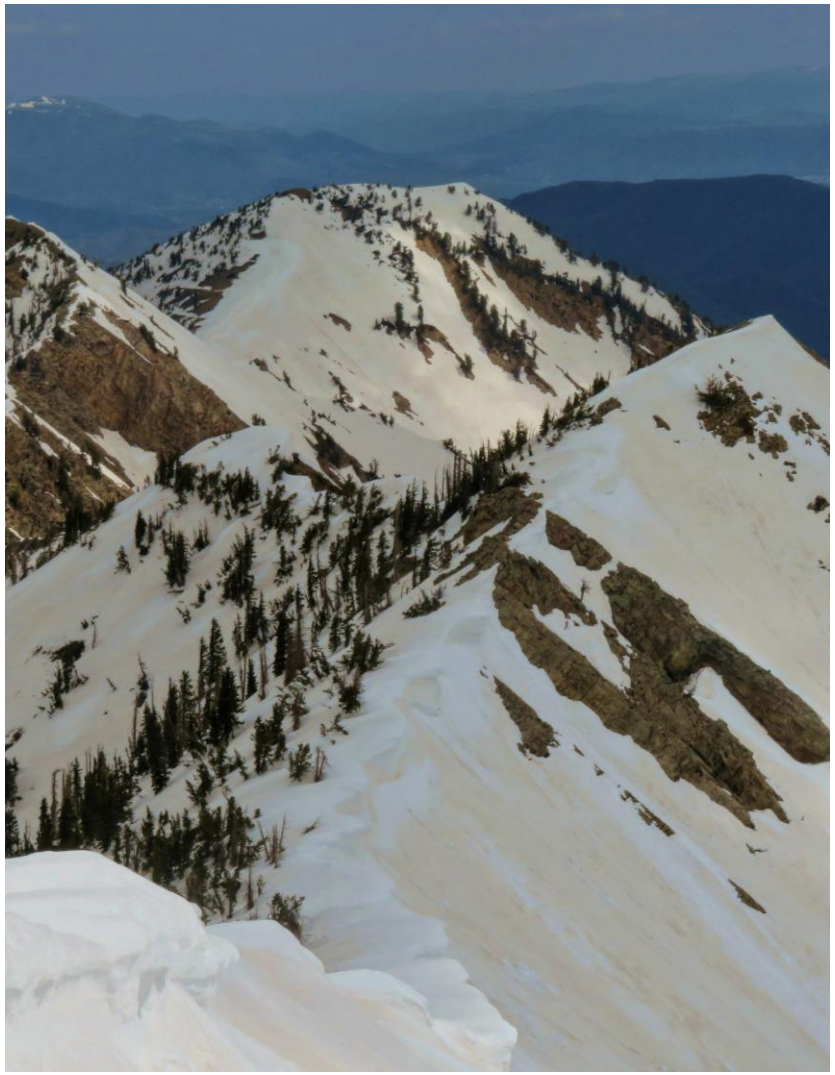
Ground-truthing modeled results: Jordan watershed WY 2022



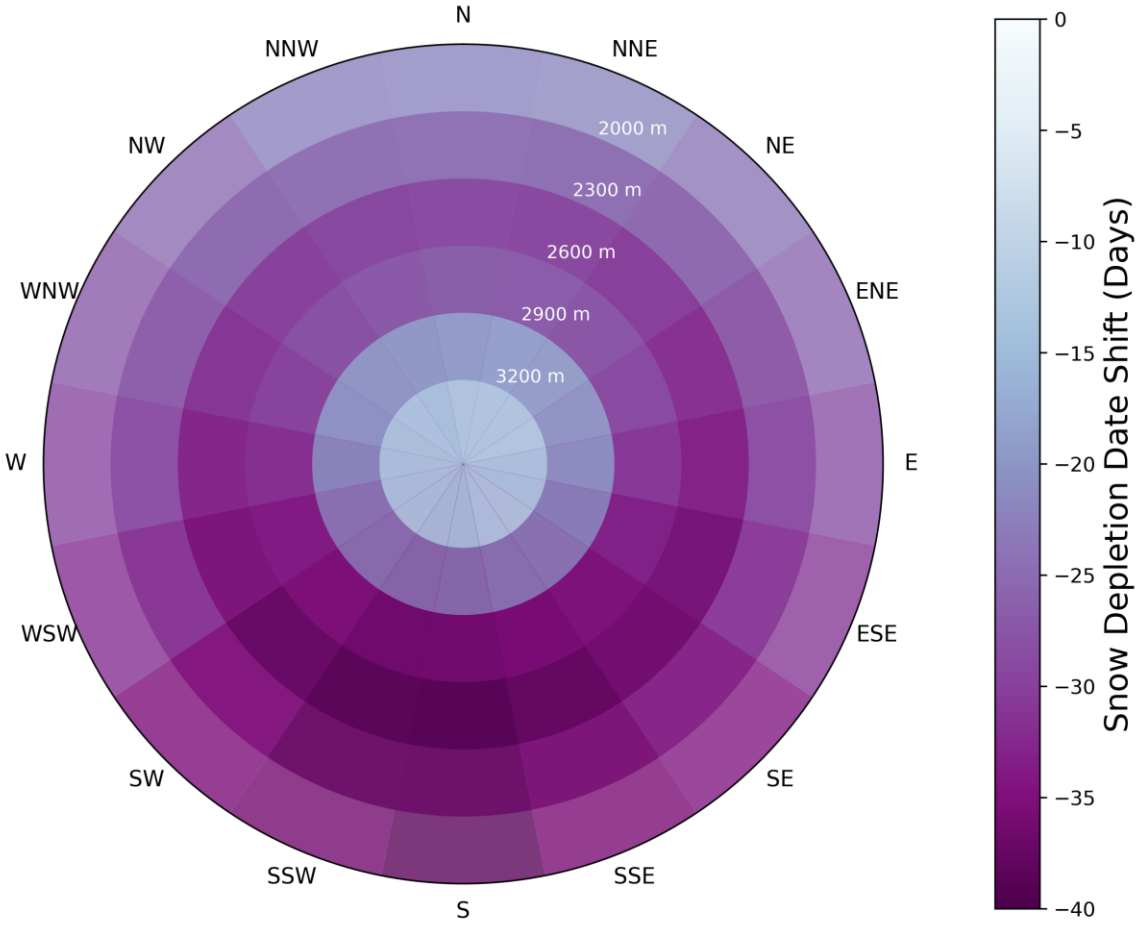
Modeled **shift in snow disappearance date** (SDD)

- Represents the **impact of light absorbing impurities on snow** such as dust
- Cumulative impact over entire water year

Spatial variability in snowmelt impact by dust



Data for Jordan Watershed WY 2022



Average shift over basin = 29 days

Darkened snow has greater impact

Spatial variability in snowmelt impact by dust

Potential dust on snow influences:

- *Alpine* – Frequent snow buries dust layers resulting in minimal dust exposure and melt impact
- *Subalpine* – Snow begins to melt earlier, less snowfall than alpine, dust is exposed longer
- *Southerly aspects* – more sun, greater energy absorption by darkened snow

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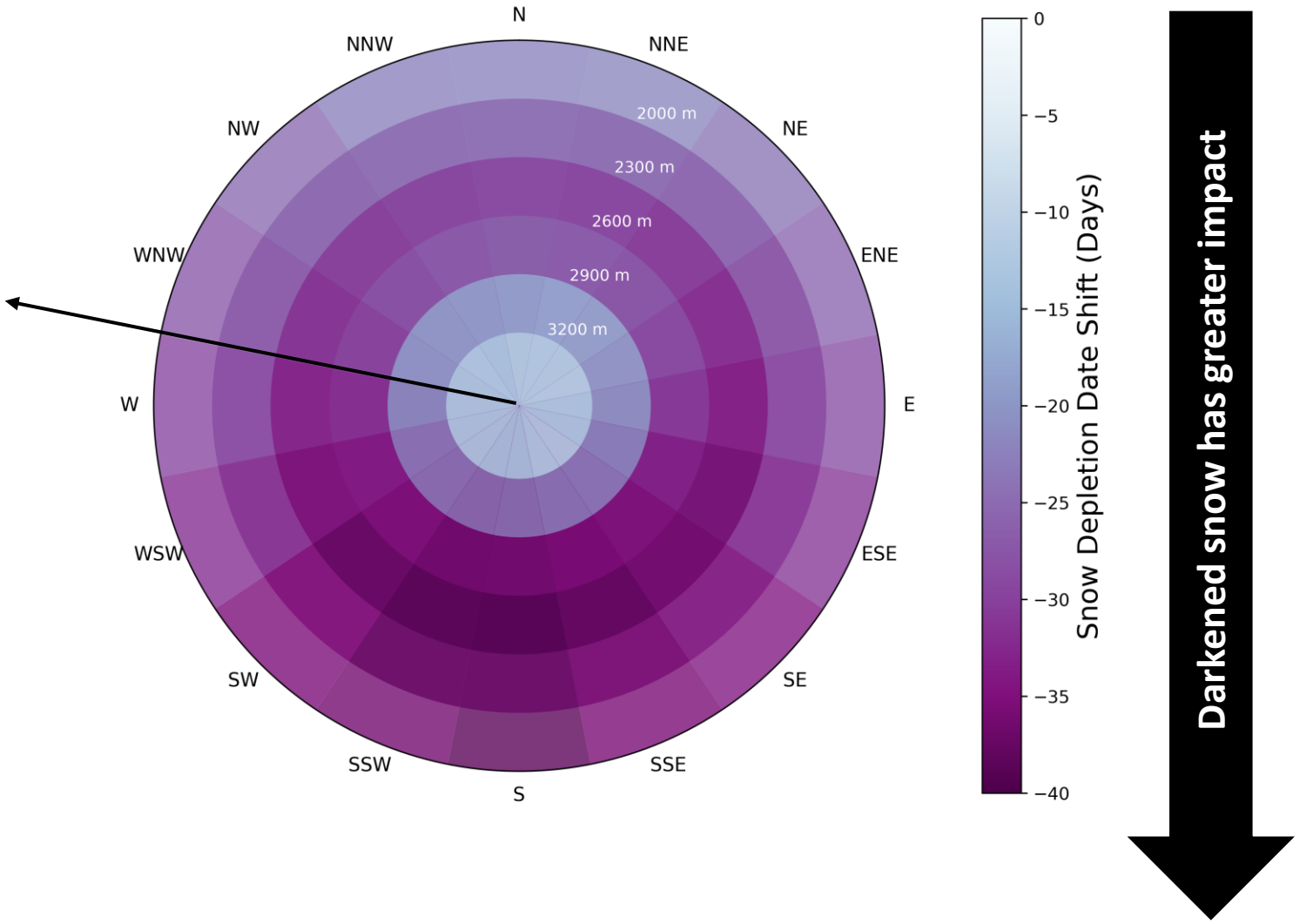

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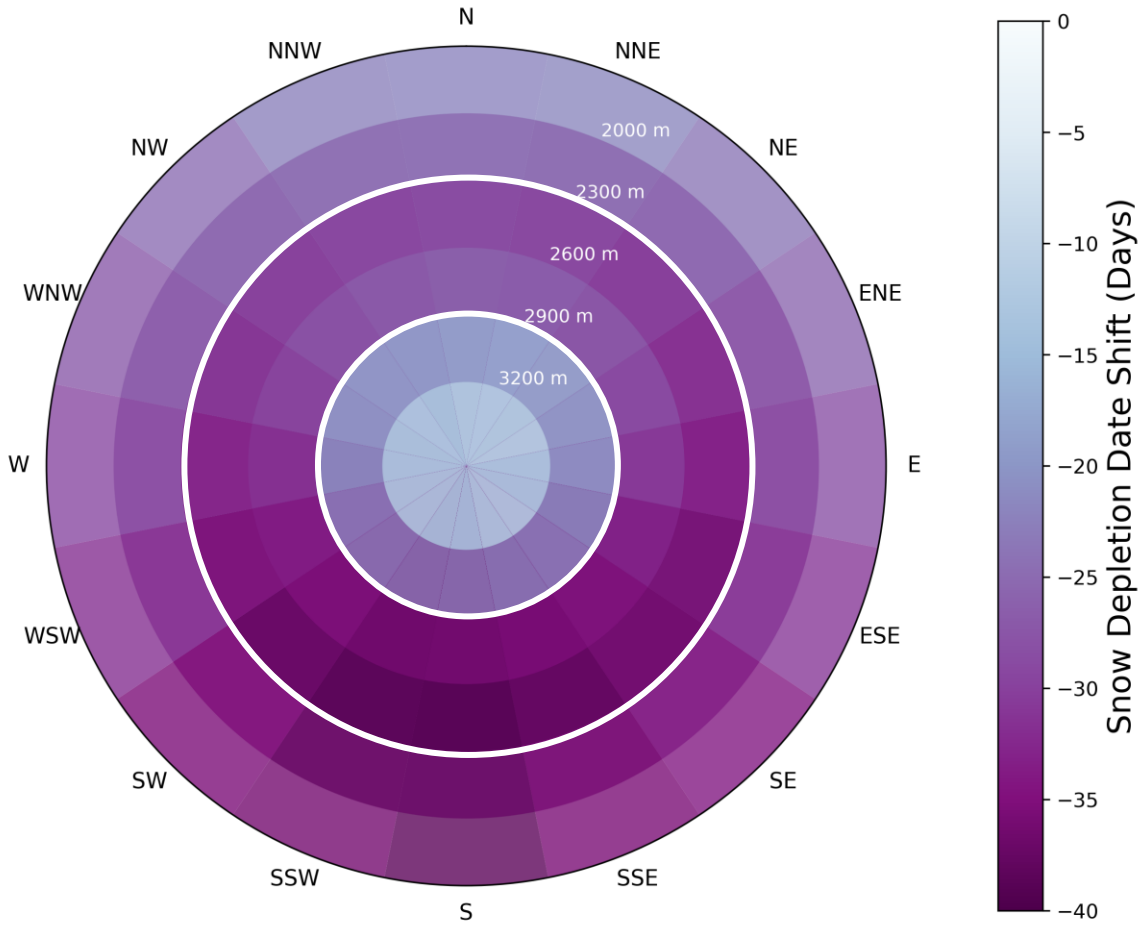

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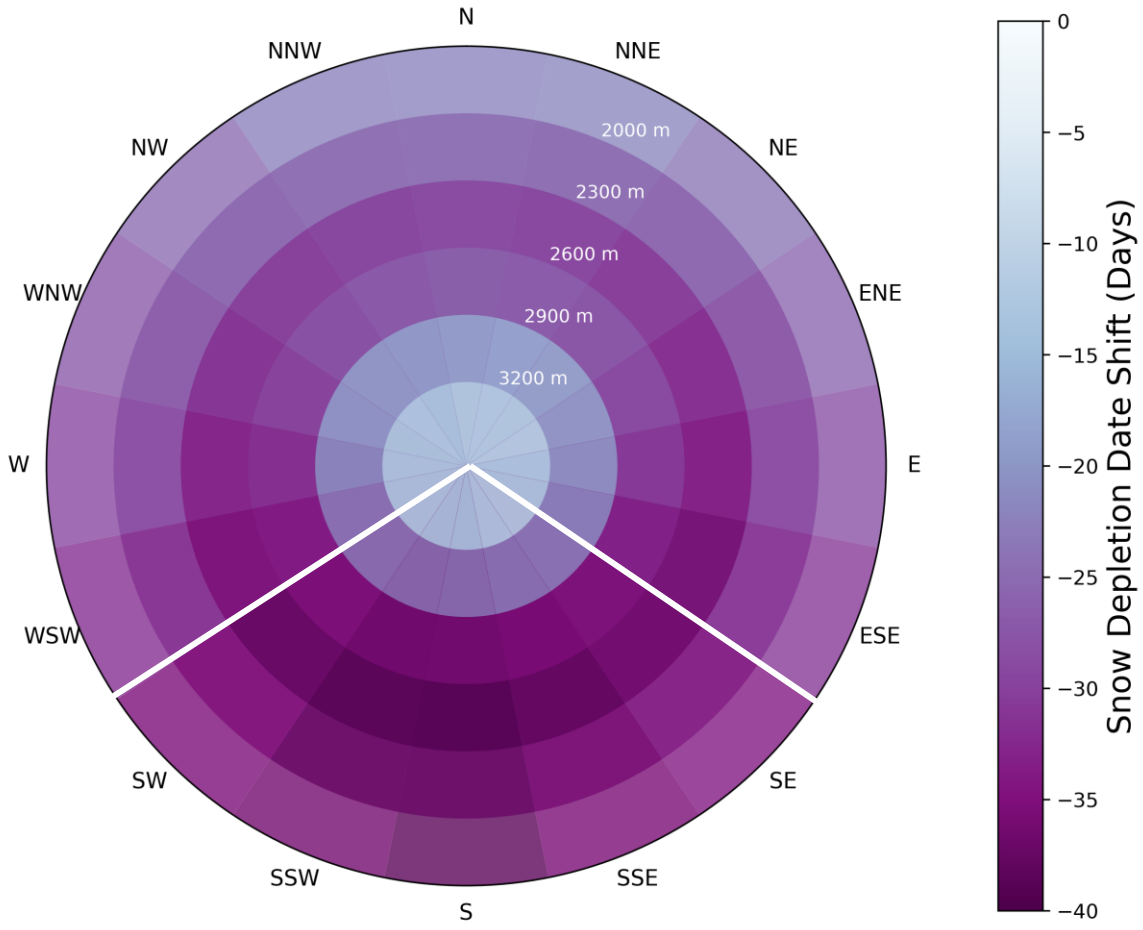

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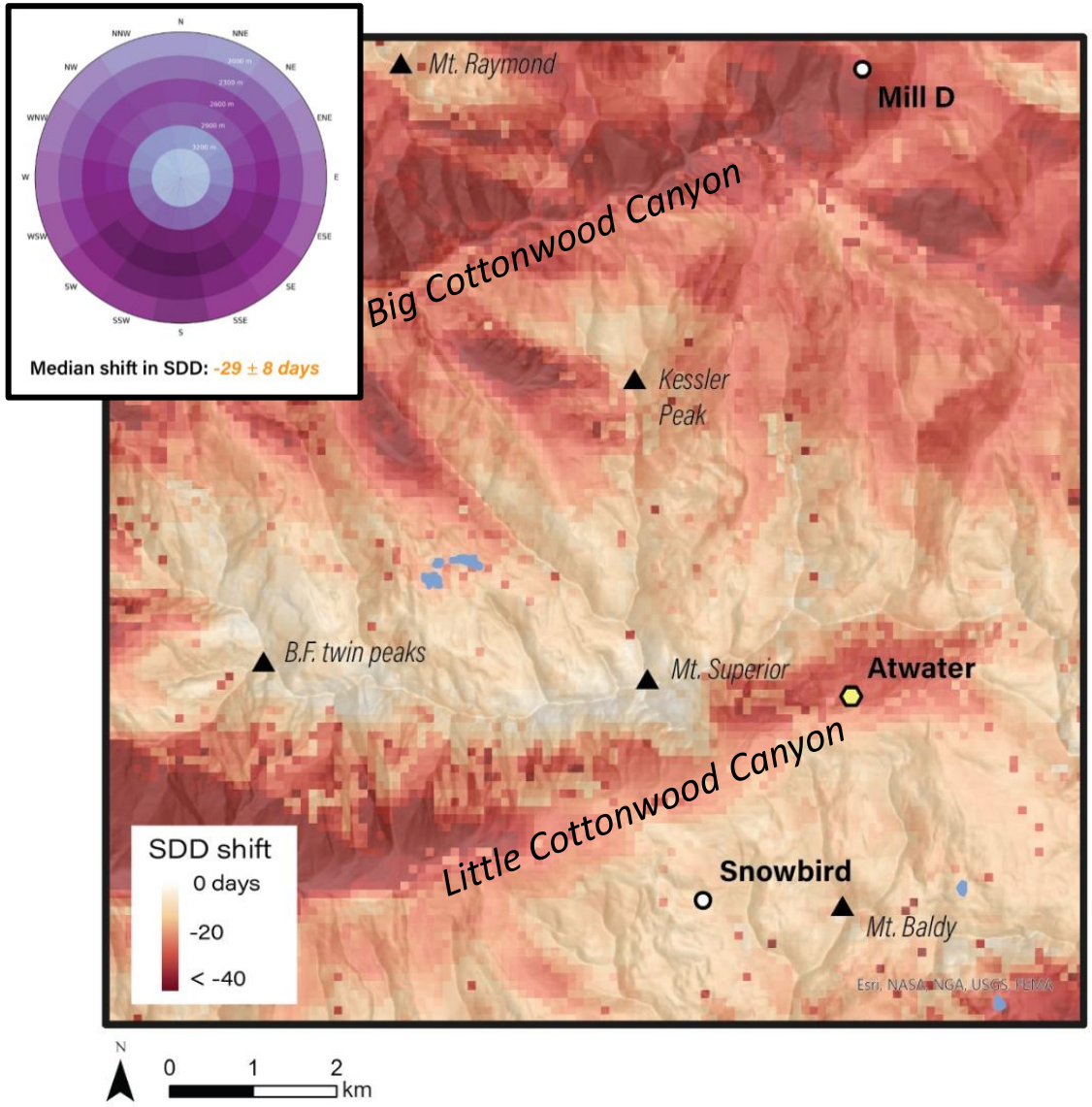
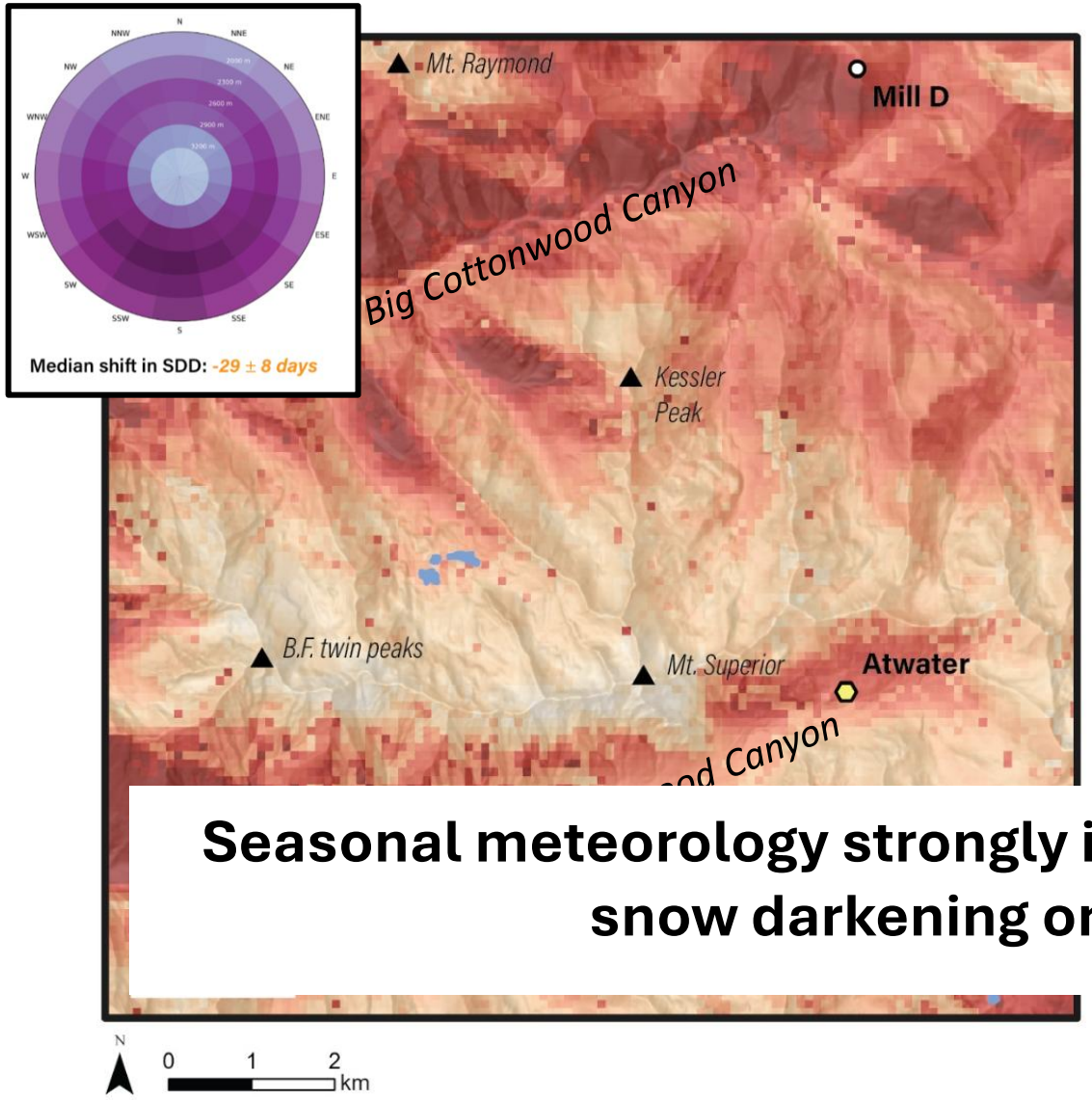
Snow Disappearance Date Shift: WY2022

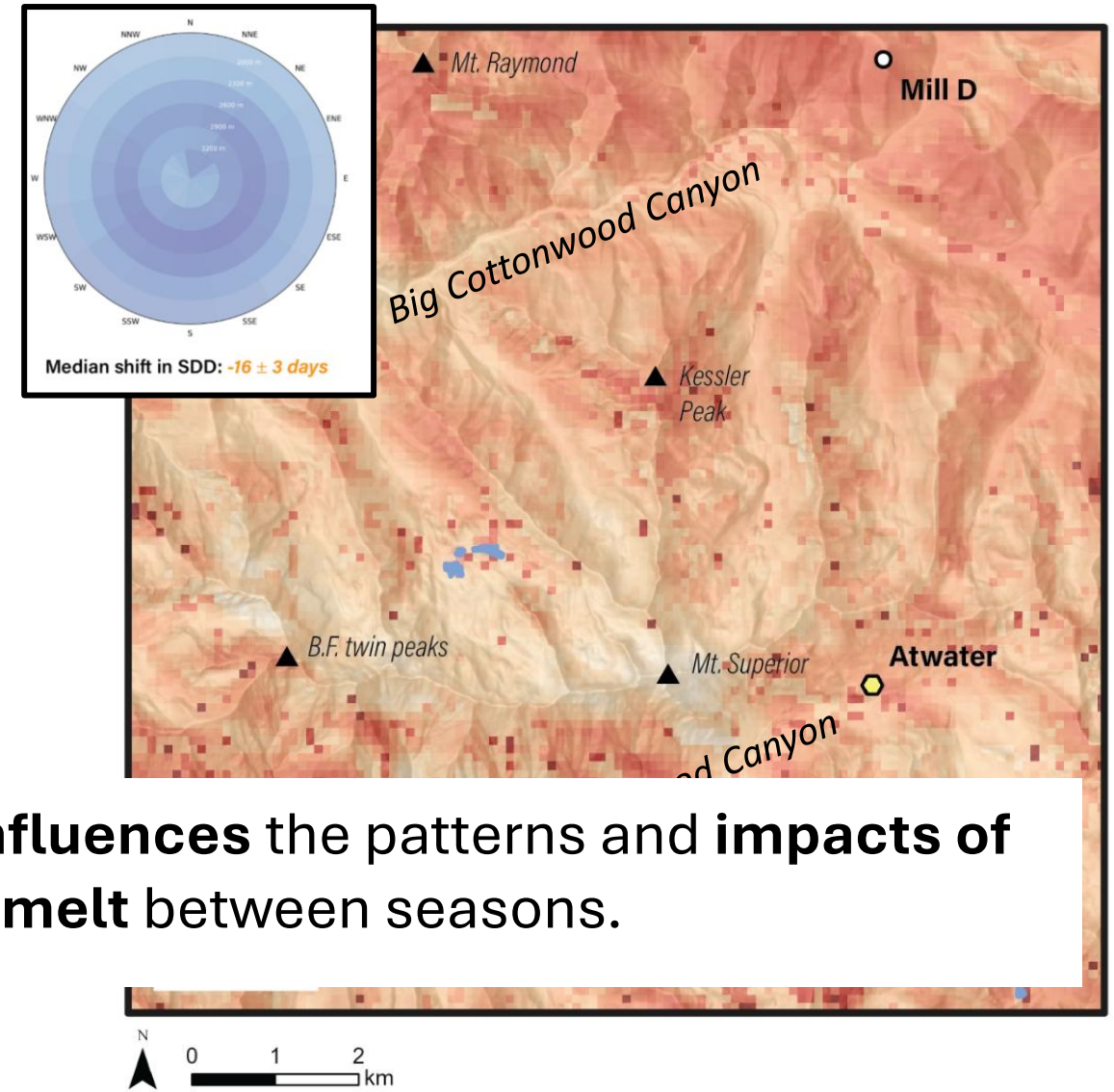


Spatial impacts are highly variable (days-months) **by terrain**

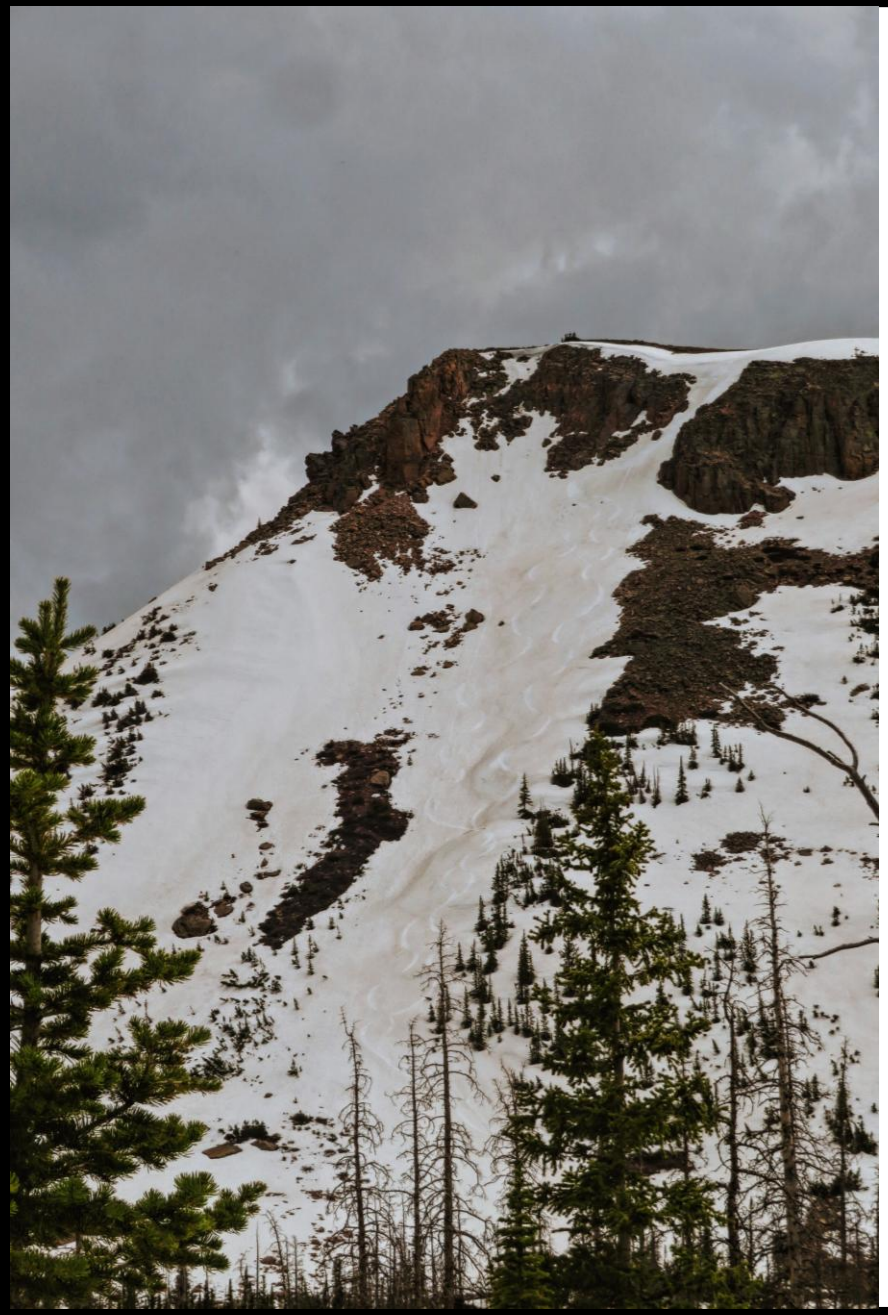
Snow Disappearance Date Shift: WY2022



Snow Disappearance Date Shift: WY2023



Seasonal meteorology strongly influences the patterns and **impacts of snow darkening on melt** between seasons.



Dust on snow is a "modern normal" in the Great Salt Lake basin

- Remote sensing shows snow darkening is present every year
  - The magnitude of impact is highly variable annually
  - No robust multi-decade trend

It's not just the amount of dust that matters

- Dust layers must also be exposed near the surface to impact snowmelt
  - Snowfall patterns are important

Snowmelt impacts vary by terrain

- The impact is greatest where dust is exposed to sunlight the longest
  - Subalpine mid-elevations (~2300-2900 m) are most sensitive to snow season declines

Accounting for snow darkening improves snowmelt modeling accuracy

- Allows for prediction of snowmelt using observed conditions
  - Useful tool in a changing climate

Thanks for listening!

Questions?

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