# Strategies for Measuring Snow: When Do you have Enough Data?


**Steven R. Fassnacht**

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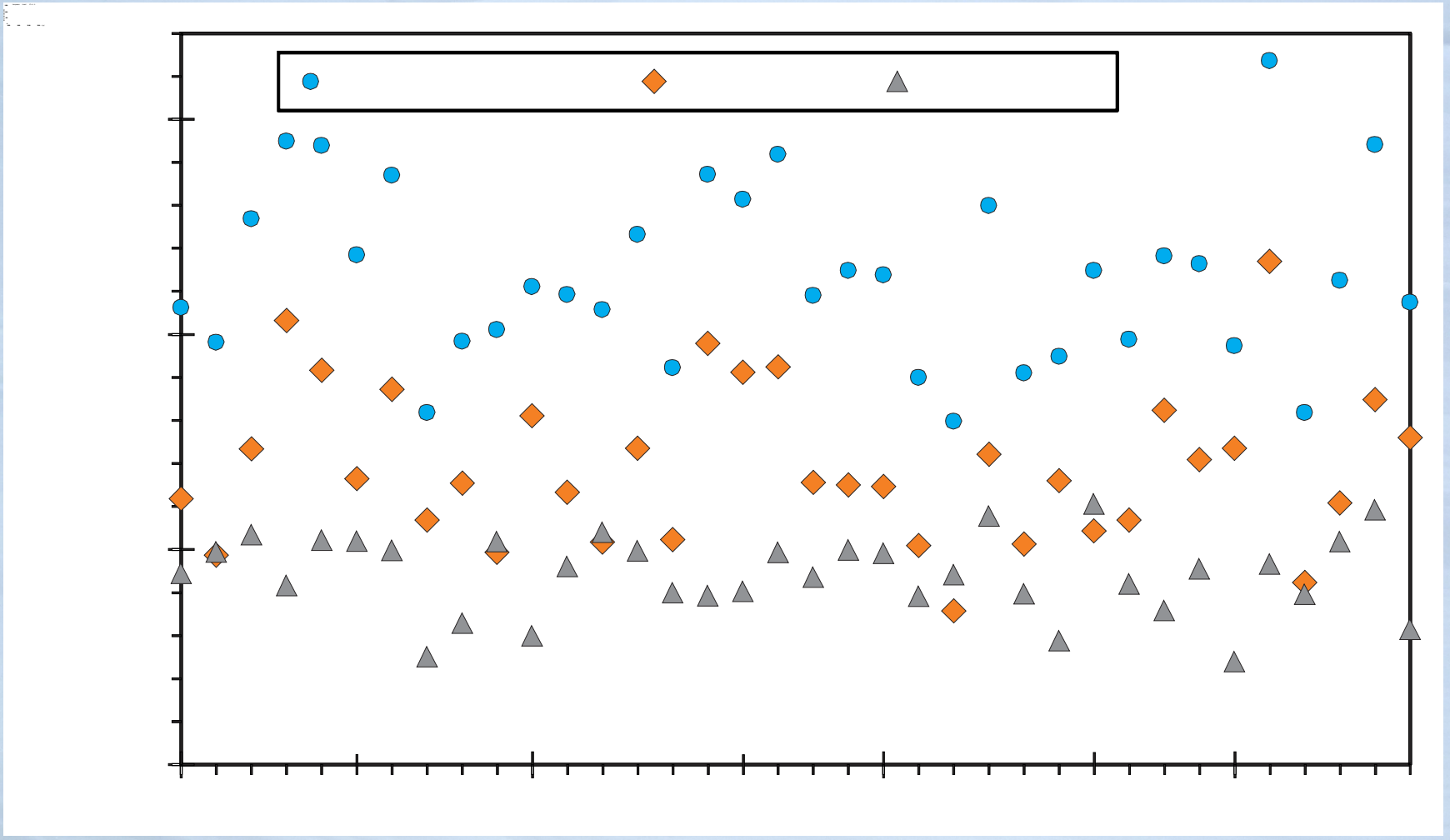
# Water and Snow

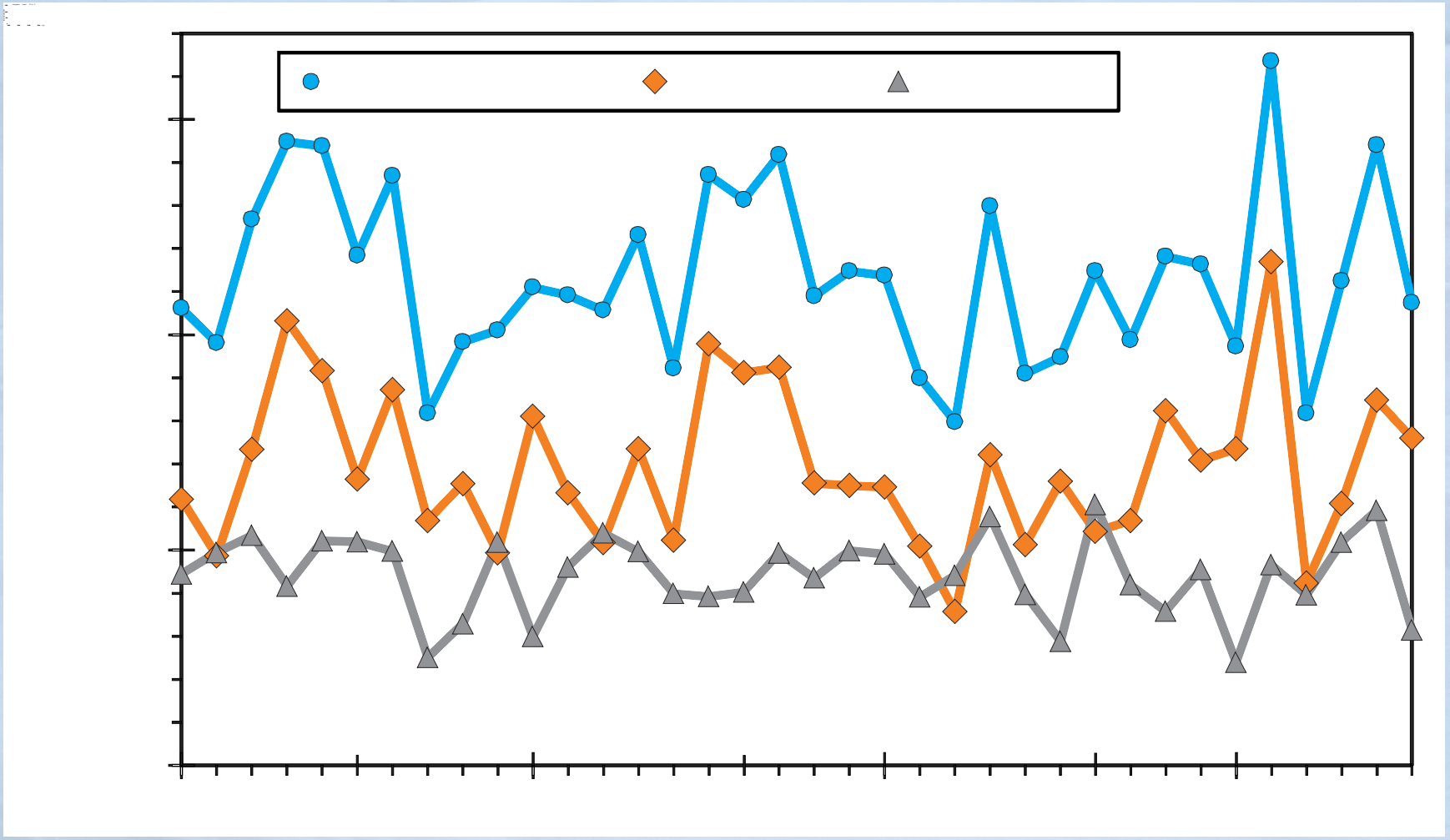
- Water: Flood or Drought
- Headwaters in mid-latitude regions
  - Often snow dominated

- How much water is stored?
- How much runoff will this be?
- How does this convert to streamflow?

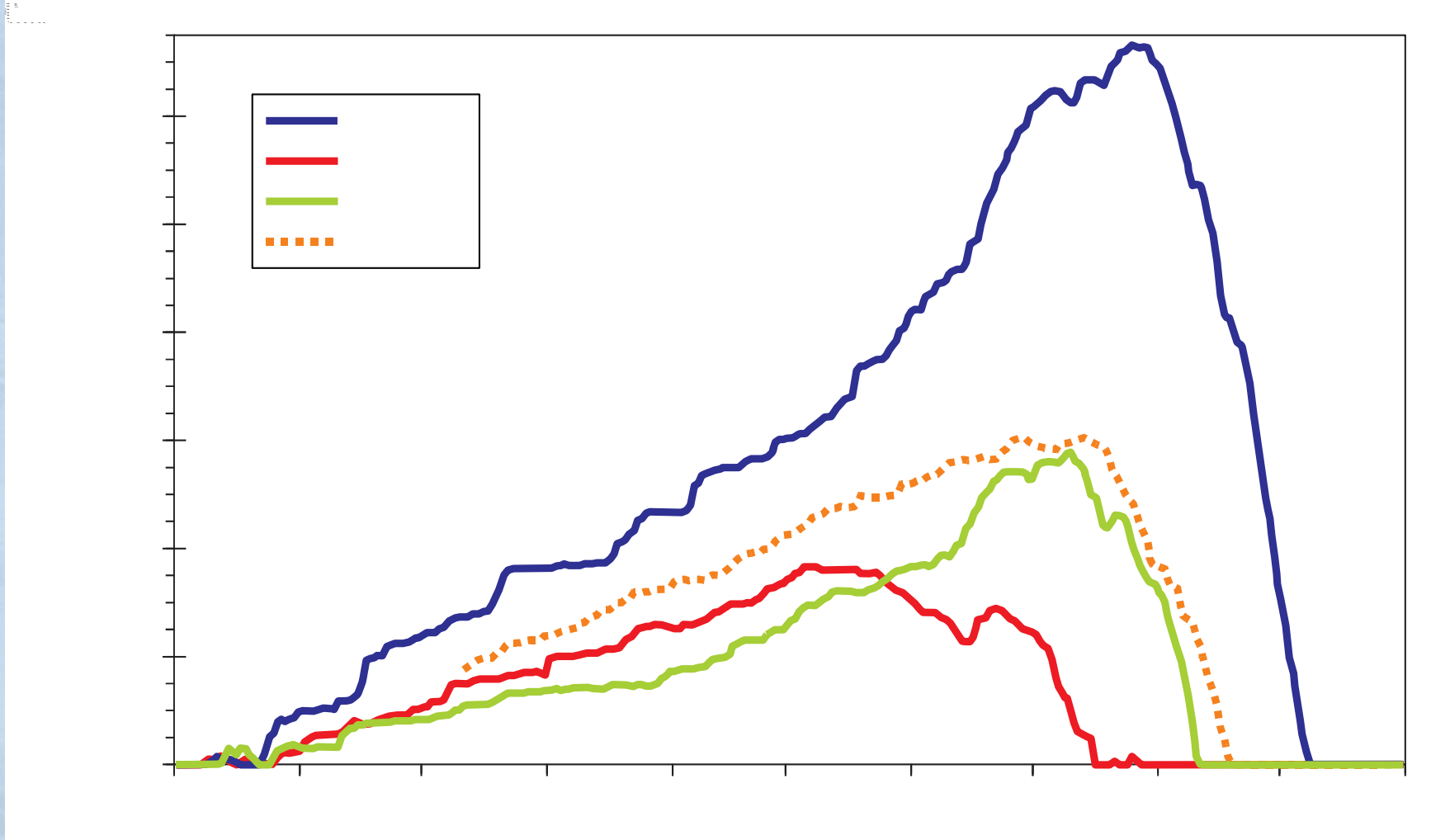
# Water Balance Components



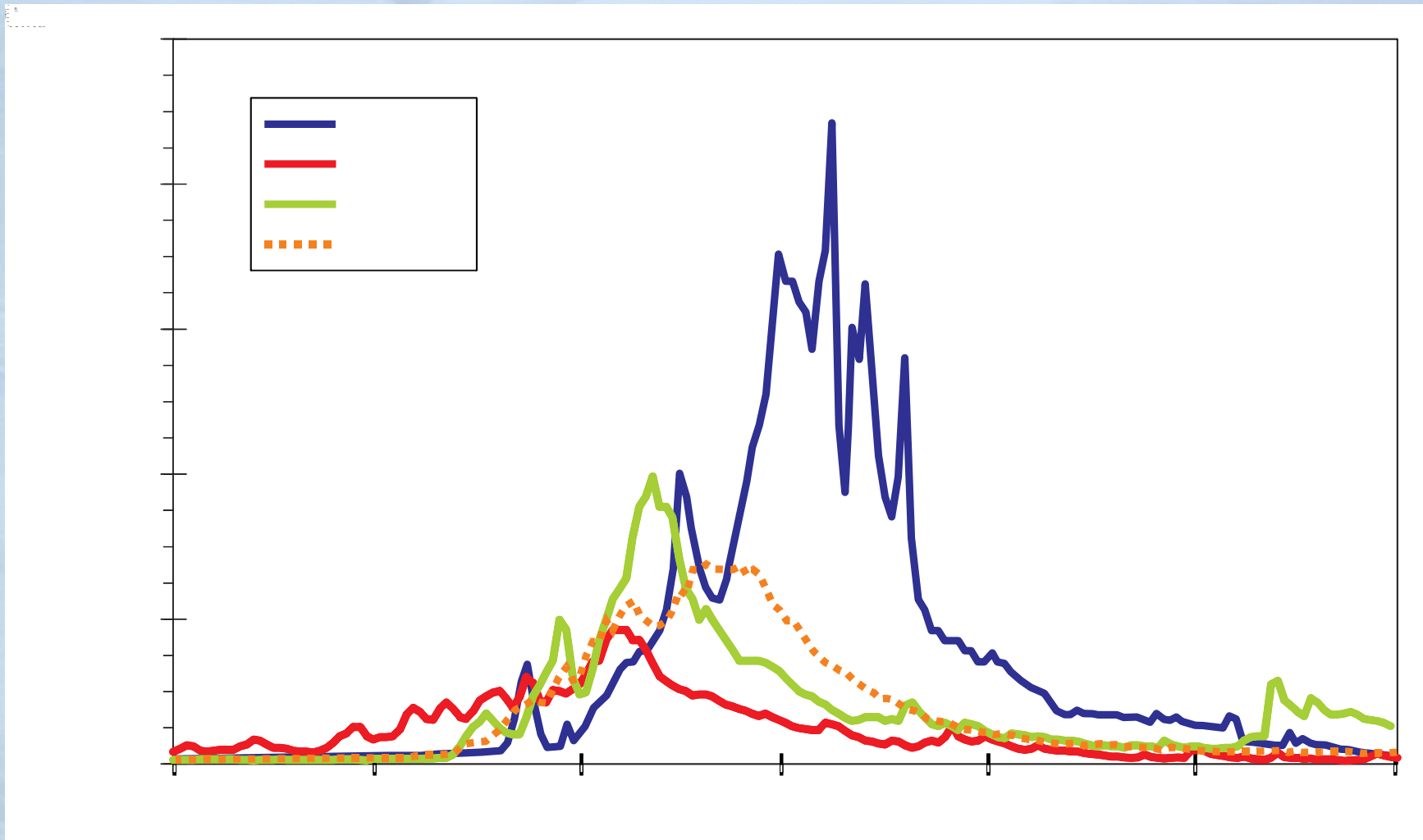
# Water Balance Components



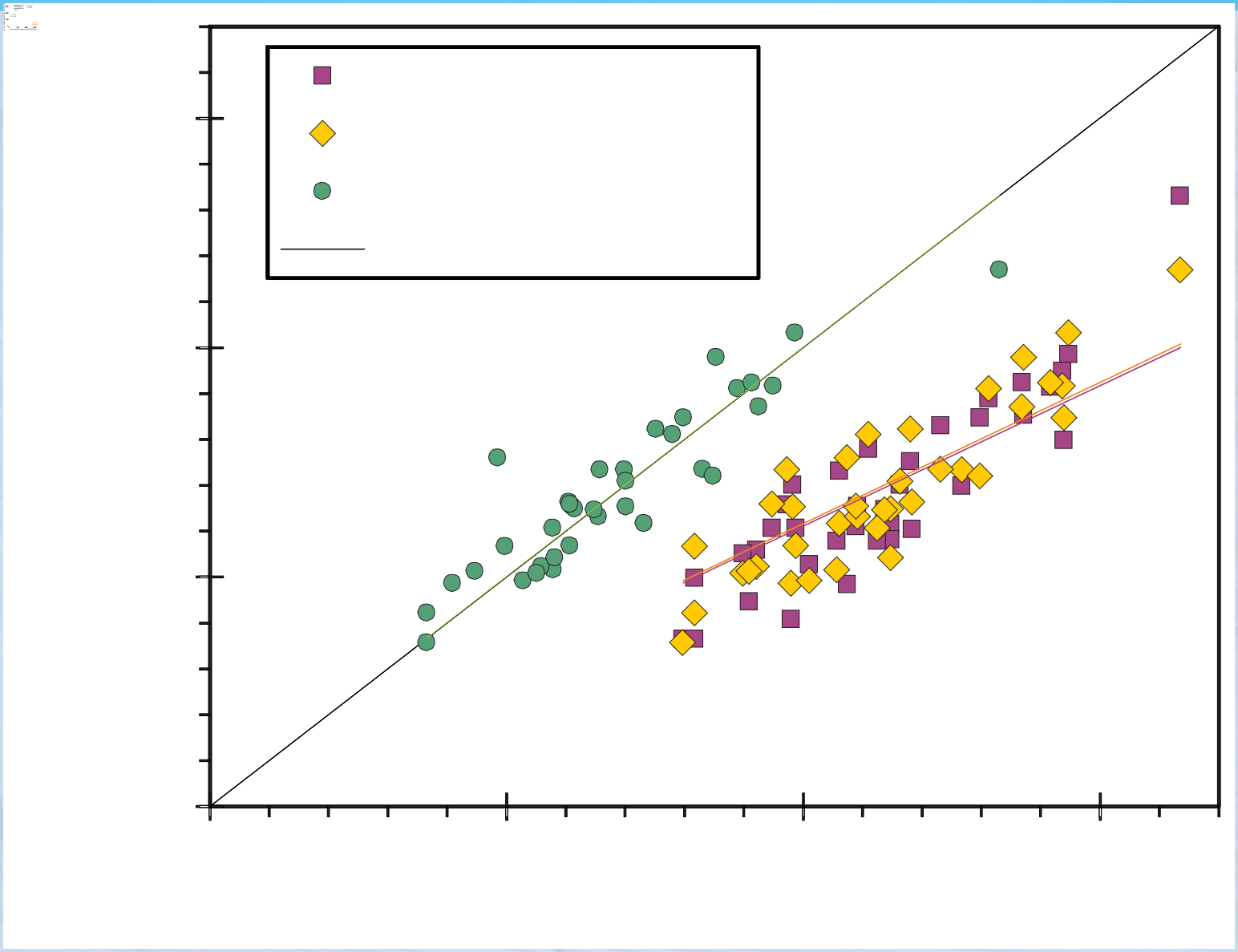
# Snow Water Equivalent (SWE)



# Daily Streamflow



# Peak SWE, Runoff, and Precipitation



# Outline

1. U.S. snow sampling
2. Datasets
3. Methodologies
4. Results
    i. Analysis
    ii. Modeled Data
    iii. (New) Remote Sensing
5. Challenges and Opportunities

# The Time of James Church

- Water uncertainty was causing political friction in Tahoe
- Flooding property damage on Lake Tahoe
- Homeowners demanded that dam operators release water before snowmelt
- Downstream opposed this
  - that water was security against a dry spring and summer

# James Church

- Mount Rose CA
- ~1906
- Federal Snow Sampler
- Measure a snow core
- Correlate SWE with runoff volumes

# Snow Course Stations

- 10+ measurements along 100s m transect
- First of month sampling
- Started in early 1900s (many since 1936)
- Measure $d_s$, SWE, estimate $\rho_s$
- Correlated to runoff
- Forecast spring/summer runoff from SWE

# Using the Federal Sampler

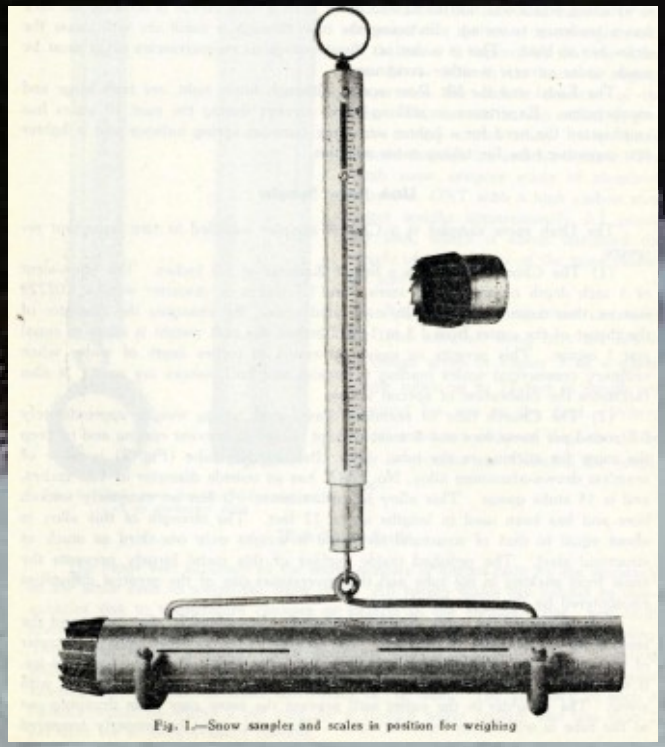


Fig. 1.—Snow sampler and scales in position for weighing

# Insert the Snow Sampler

# Weight the Snow Core

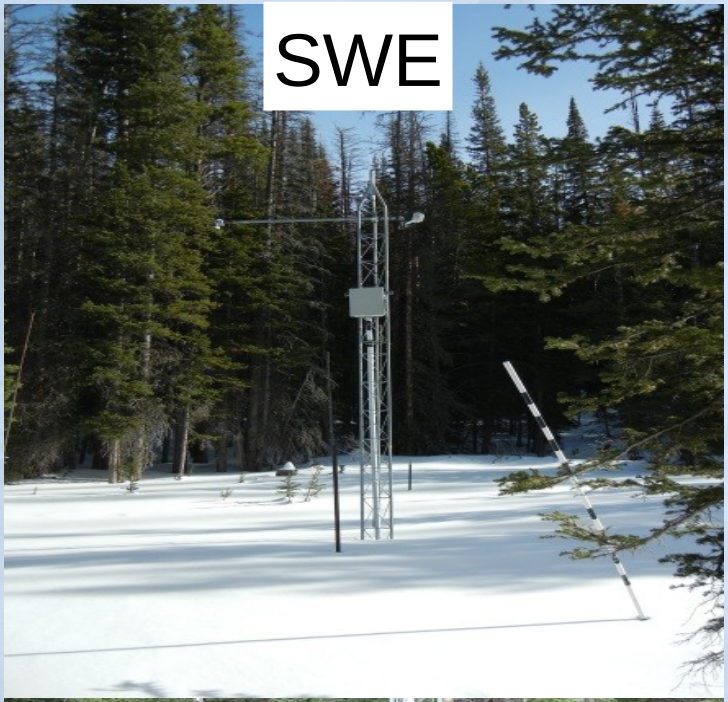
Ralph Parshall & colleague , Cameron Pass 1

# Snow Telemetry (SNOTEL)

- Daily data since late 1970s
- SWE
  - Snow pillow
- Precipitation
  - Sacramento Totalizer
- Temperature
- Snow Depth
- Soil Moisture and Soil Temperature

# SNOTEL station

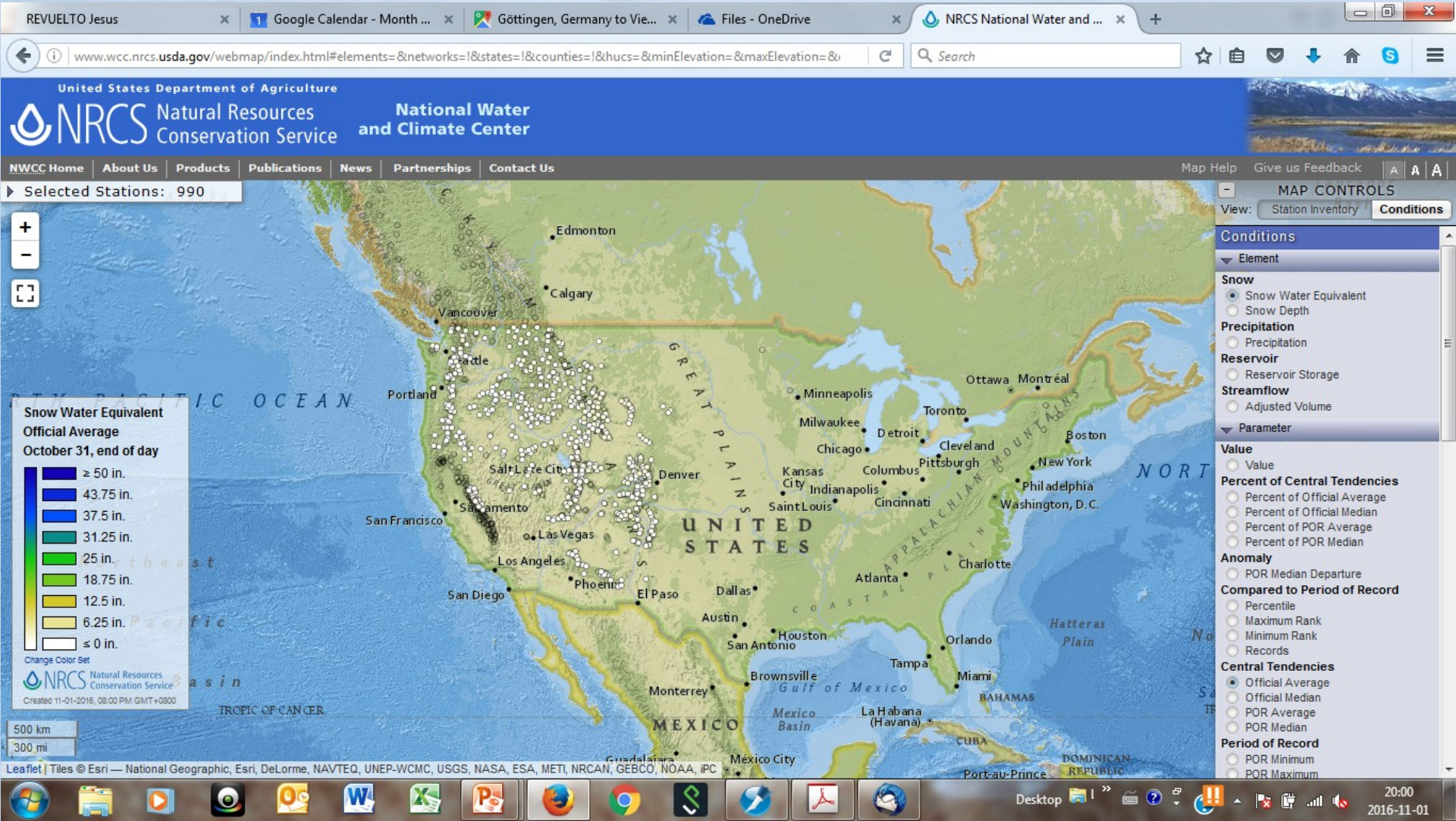
SWE



Precipitation

# SNOTEL station

# NRCS WCC Data

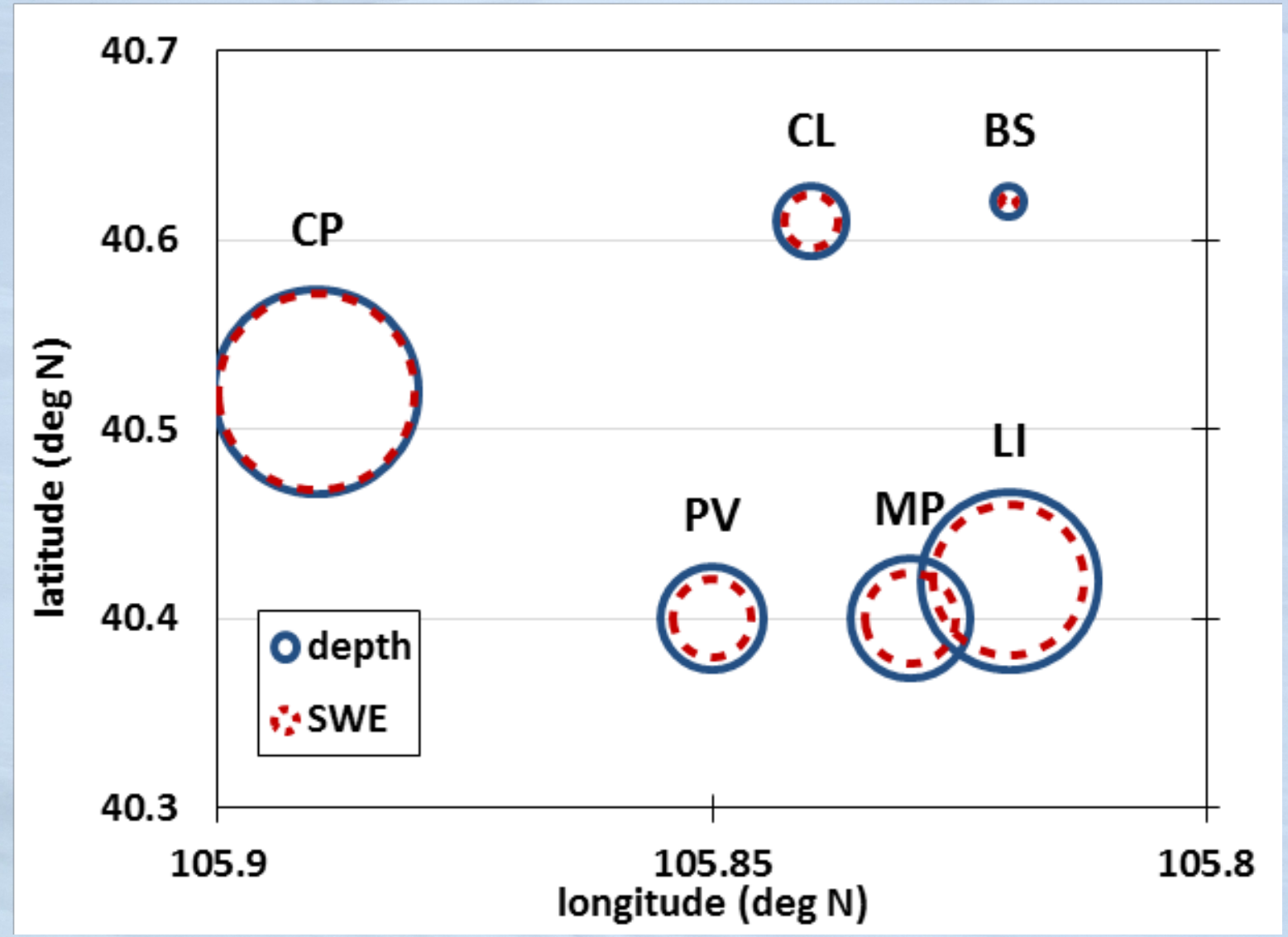


# Methodology: U.S. Stations

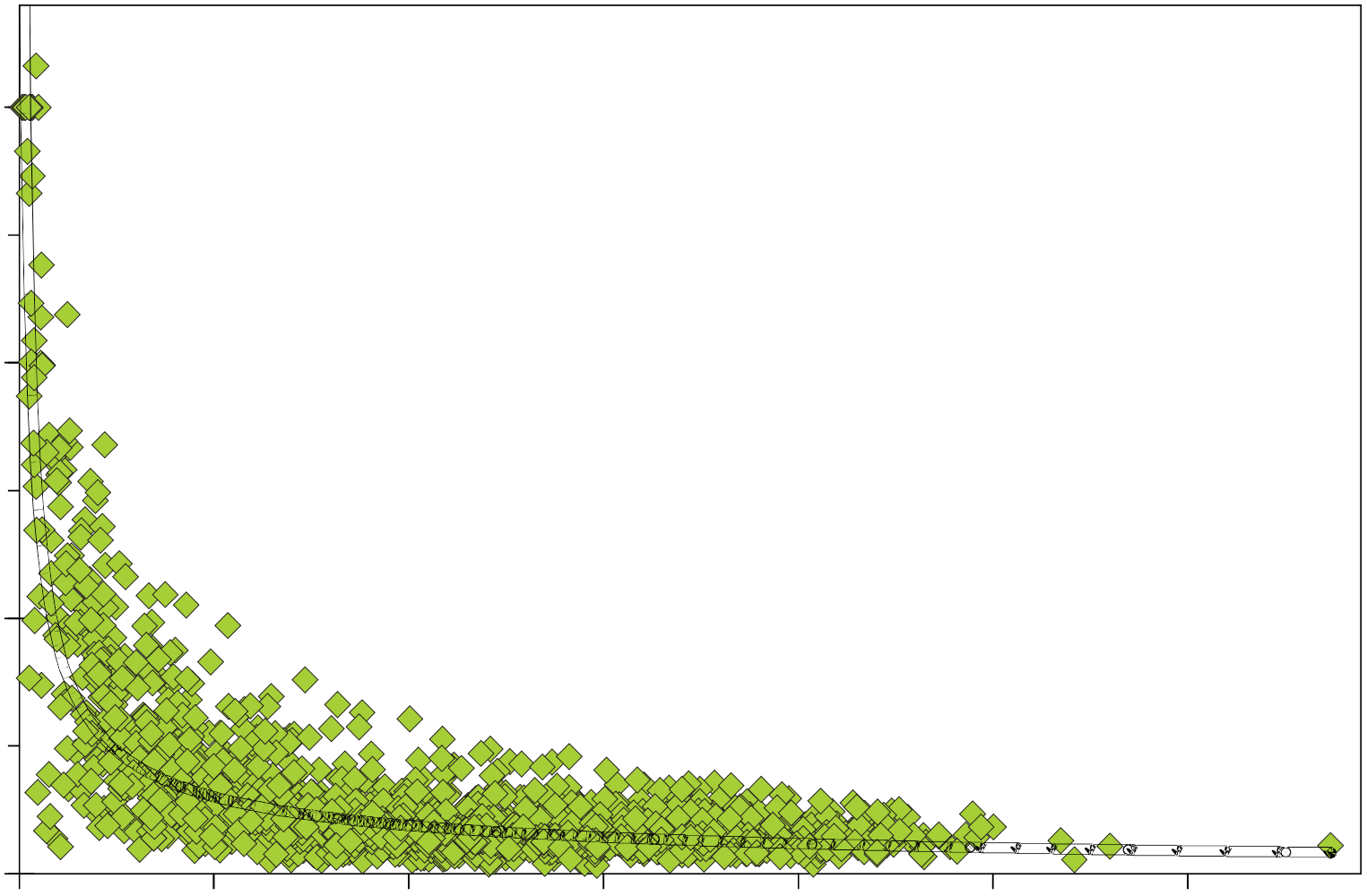
- Analysis
  - Assess variability
  - How representative is a point measurement?
- modeling
  - NOAA National Operational and Hydrologic and Remote Sensing Center SNODAS
- Remote Sensing
  - Lidar datasets
  - NASA Airborne Snow Observatory
- Data poor environments
  - Mongolia

# VARIABILITY

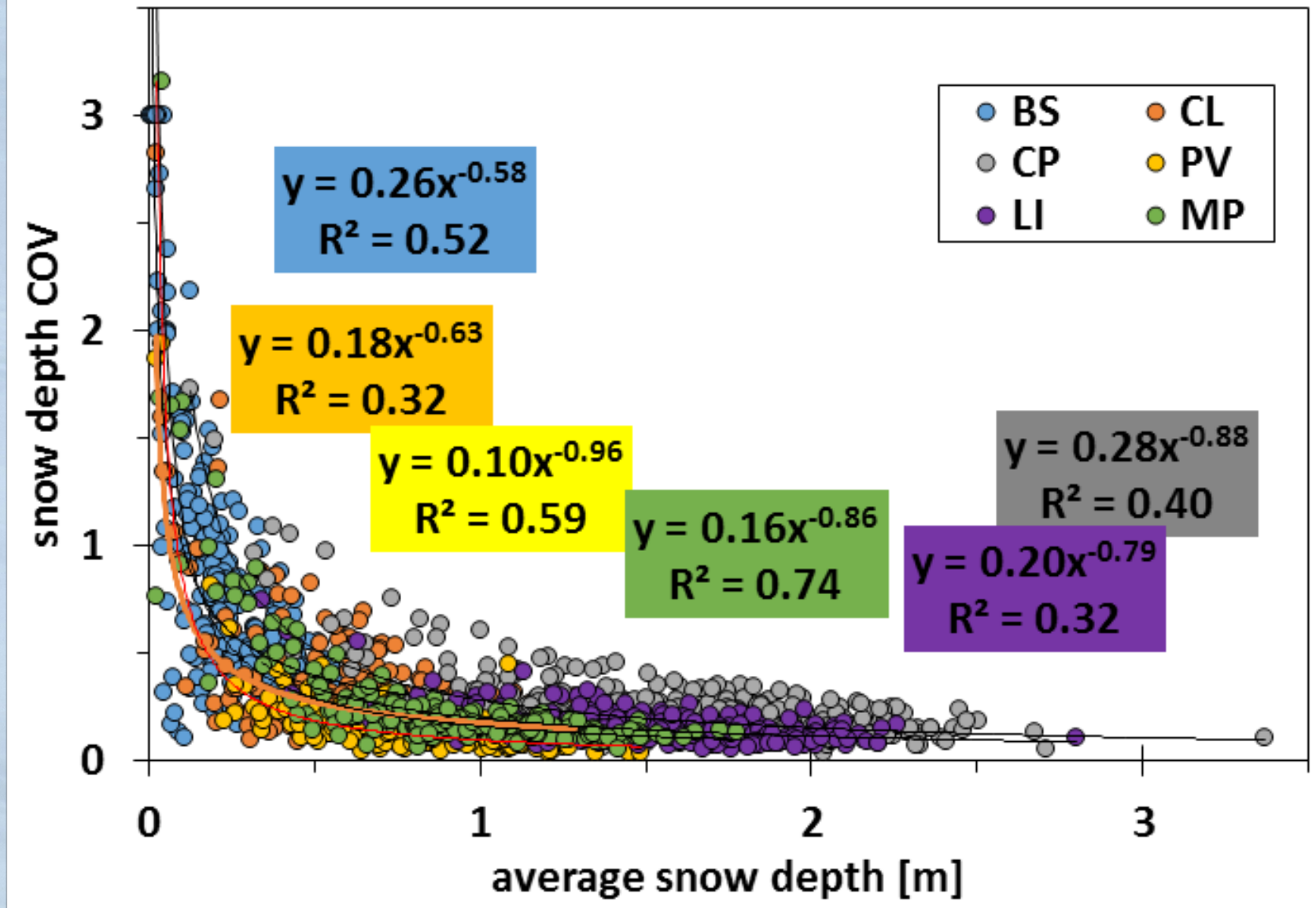
# Six Snowcourse Stations in N. Colorado



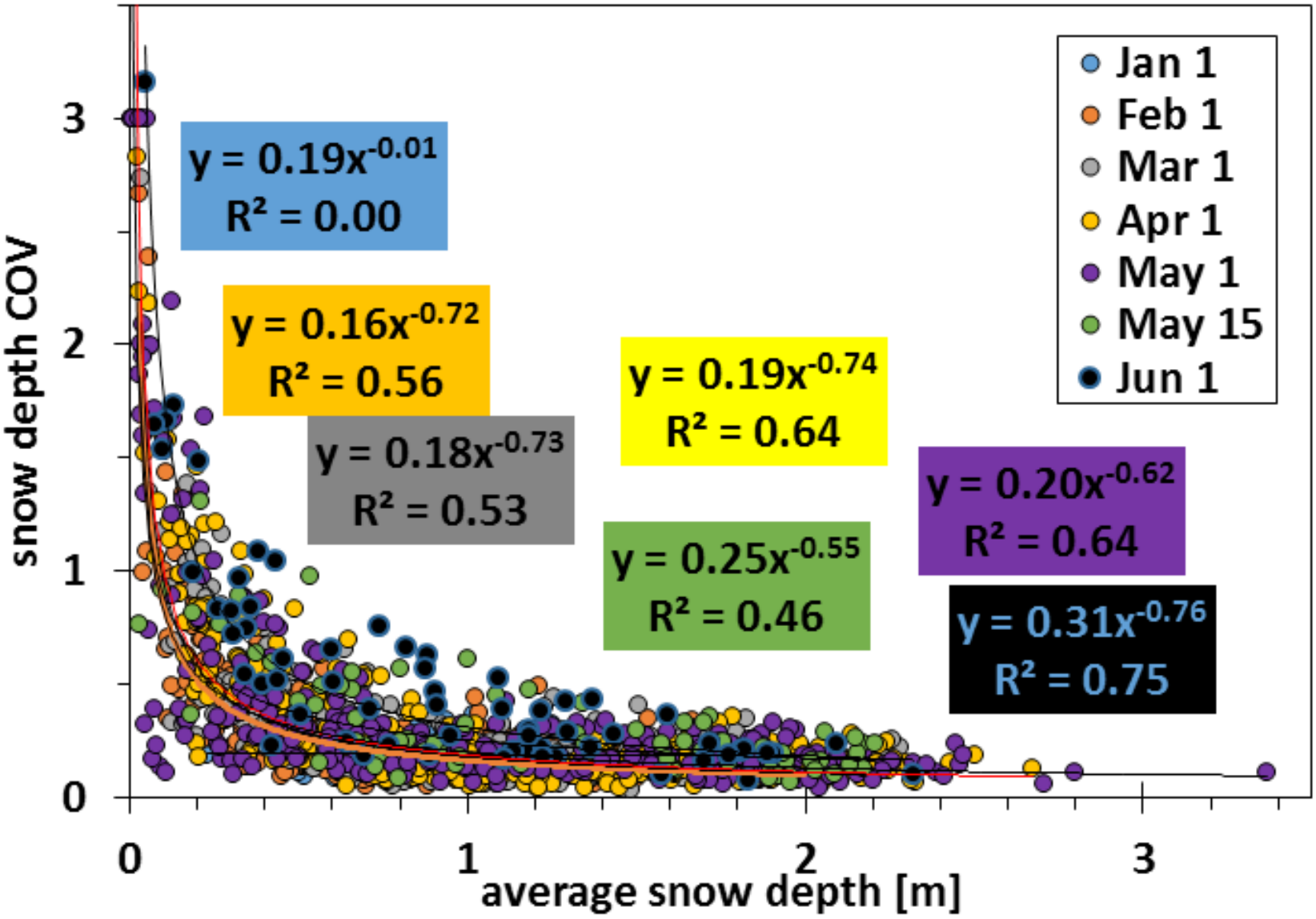
# All Snow Depth Measurements



# Snow Depth Variability – per Station



# Snow Depth Variability – per Time



# Estimating Variability

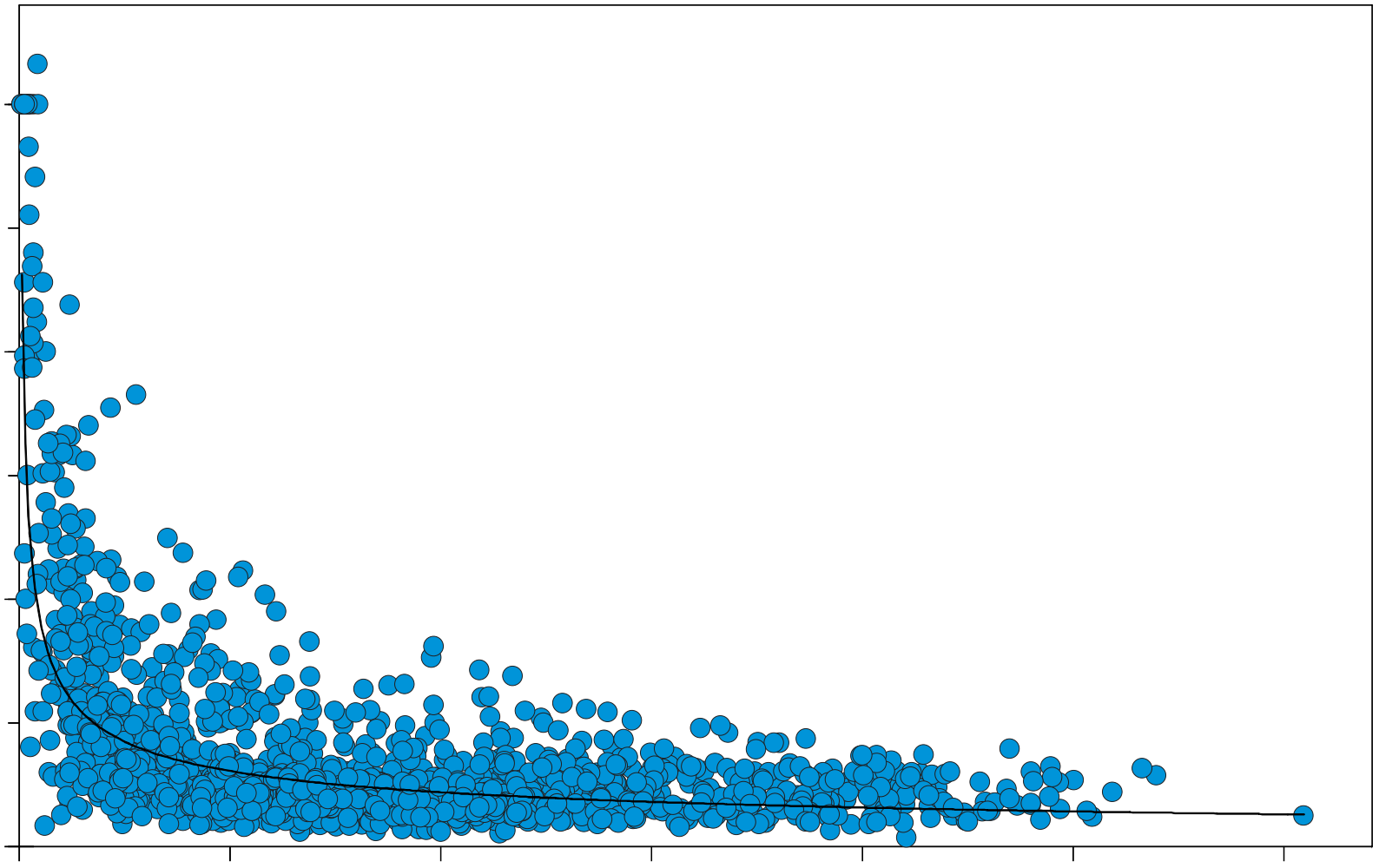
- Use the 10-15 individual measurements
- 1568 station-months of non-zero $d_s$

- $COV_{ds} = f(d_{sApr1}, t, d_s)$ with $R^2 = 0.71$

- $COV_{(ds,\ i)} = [1.32x10^{-2}\ d_{sApr1,i} + 1.31x10^{-4}\ t + 0.188]\ d_{s,i}^{\ -0.674}$

from *Fassnacht and Hultstrand* [2015]

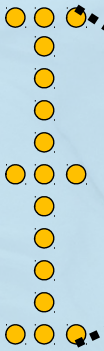
# All SWE Measurements

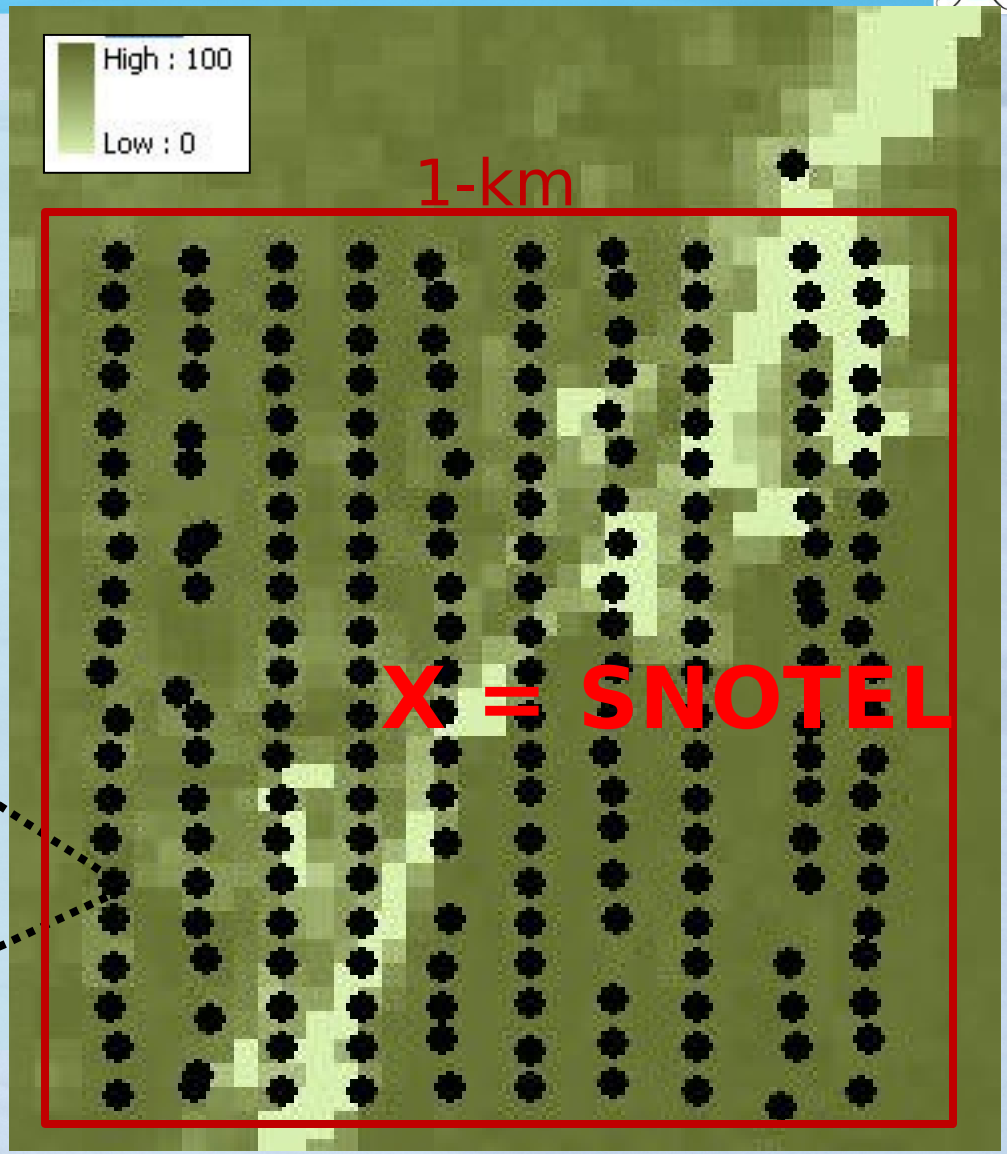


# REPRESENTIVITY

# Snow Sampling Strategy

- 1km$^2$ area around a SNOTEL station
- Snow depth measurements
  - 17 per sampling location
- Various sampling sites



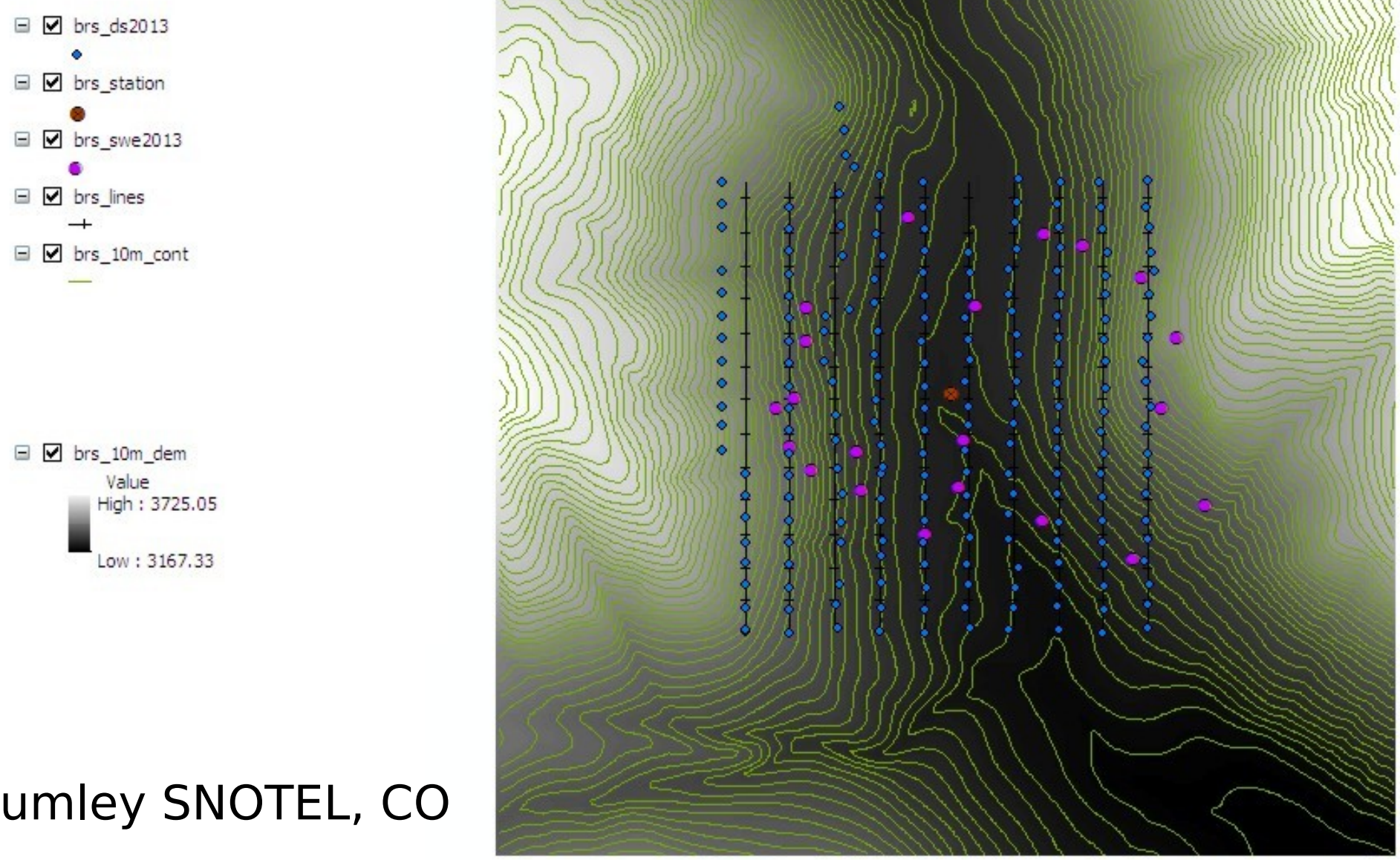


# Questions: Snow Depth Surveys

- What drives the distribution of snow?
  - Mean depth at a measurement location
- What drives the variability?
  - Standard deviation at measurement location
- How many points?
  - Variability from mean

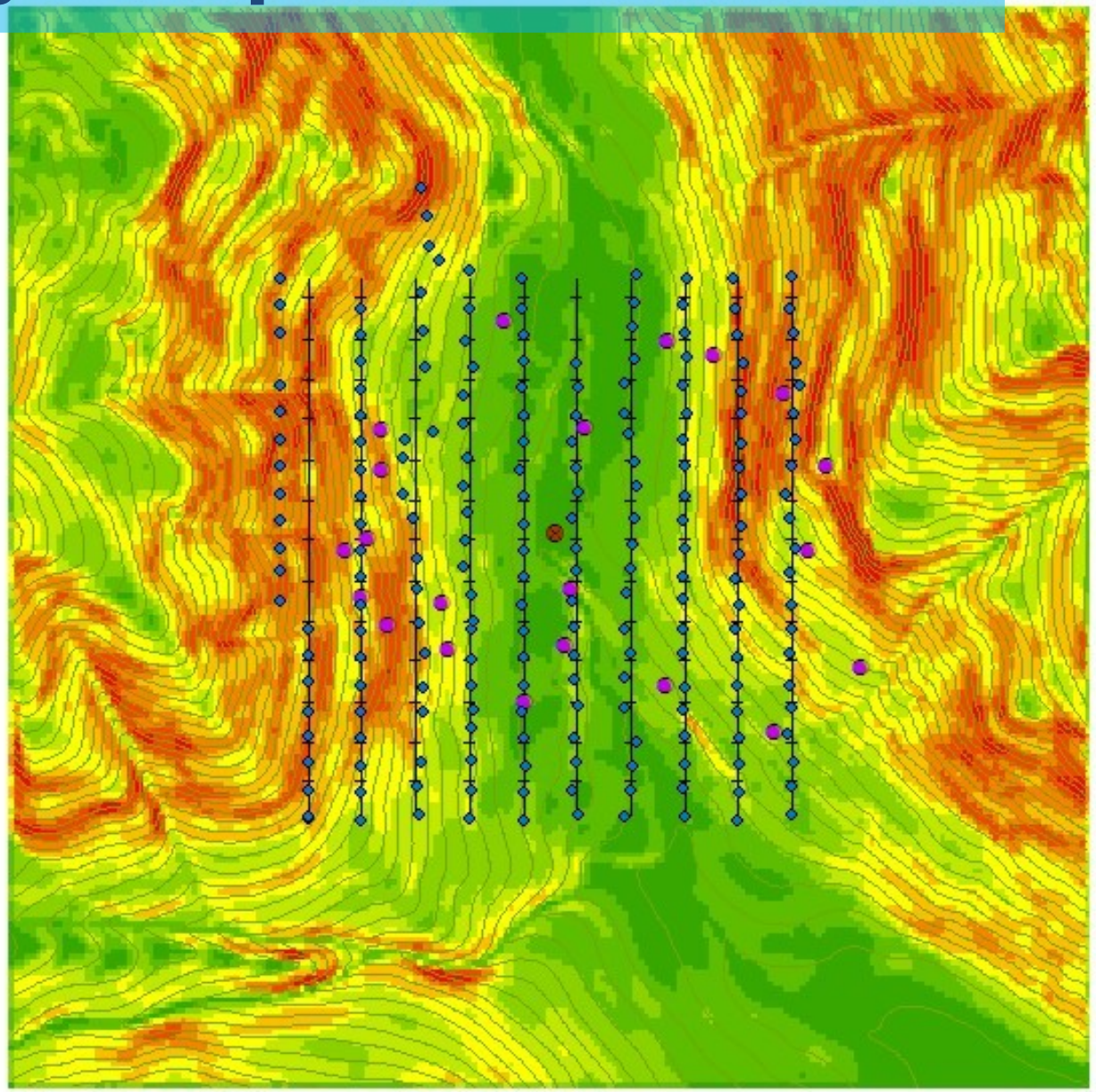
- How does the terrain/vegetation vary?

# Topography: Elevation




rumley SNOTEL, CO

# Topography: Slope

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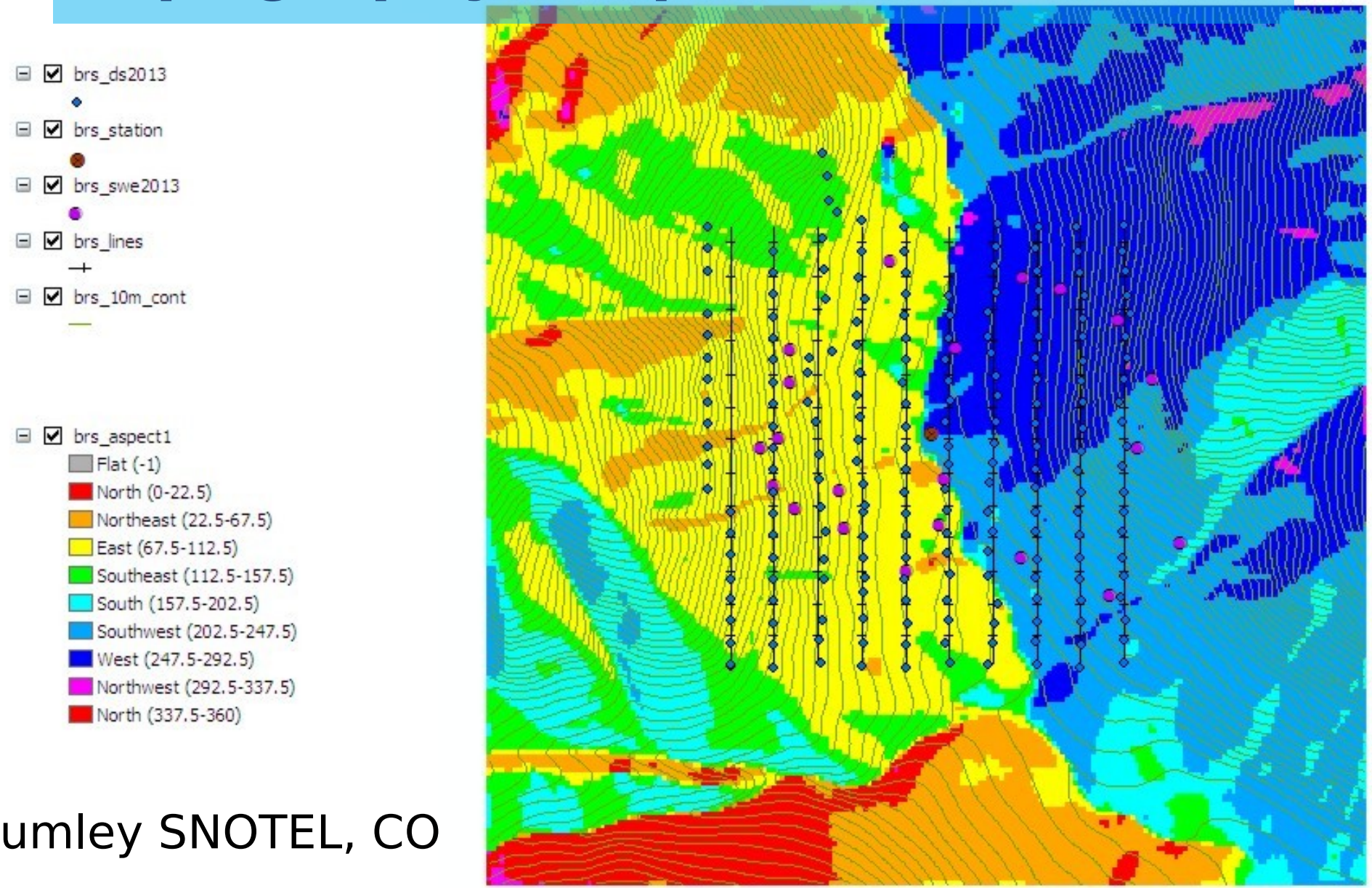
# Topography: Aspect

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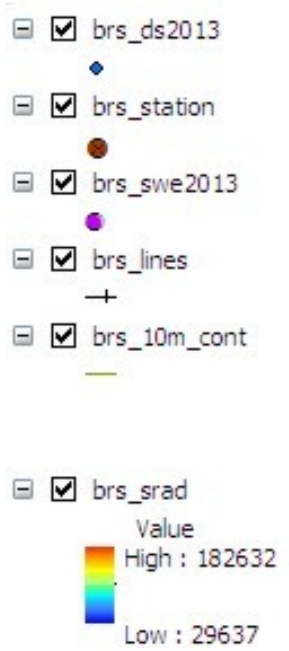
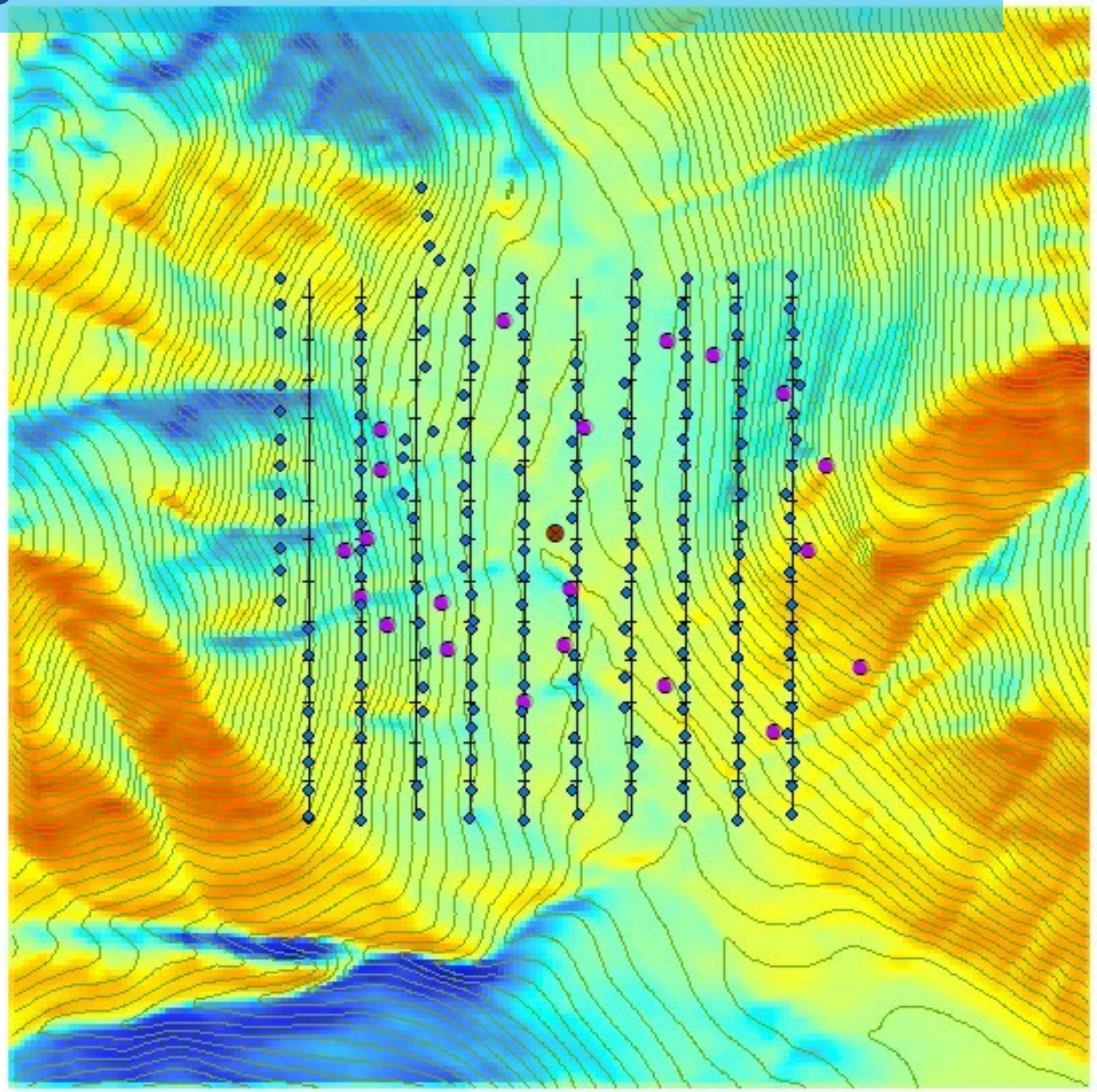
# Topography: Solar Radiation



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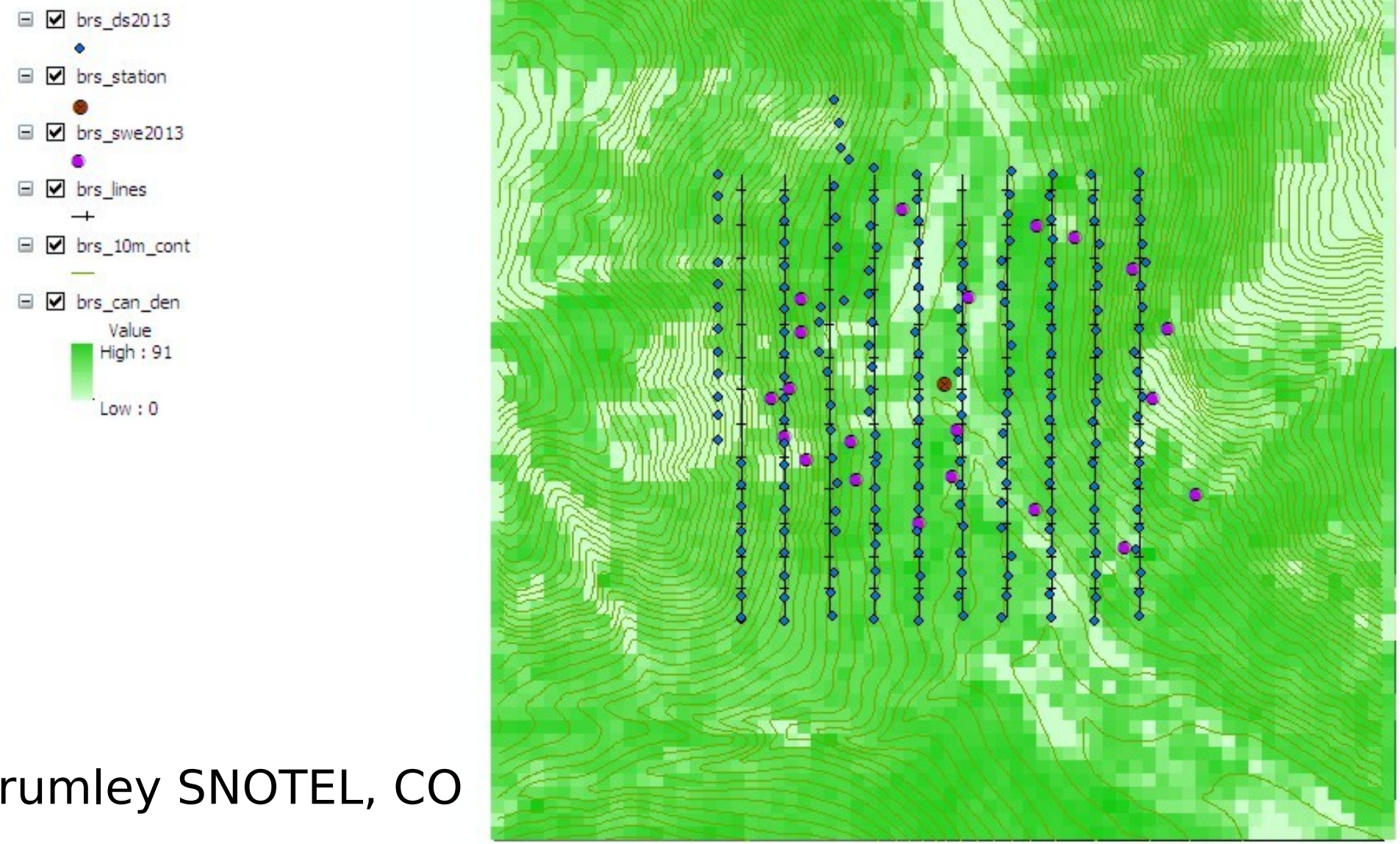
# Canopy Density

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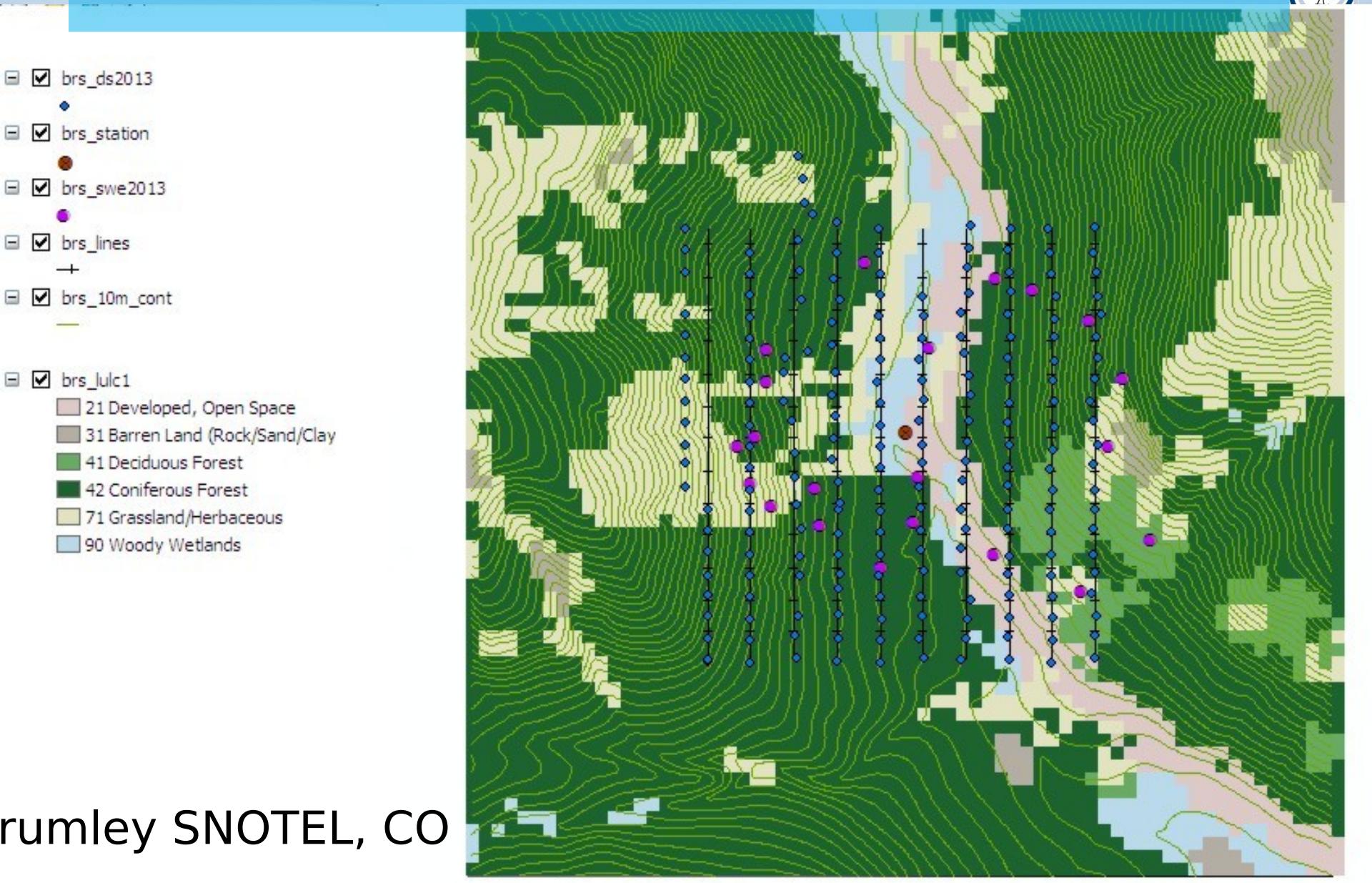
# Land Use/Land Cover

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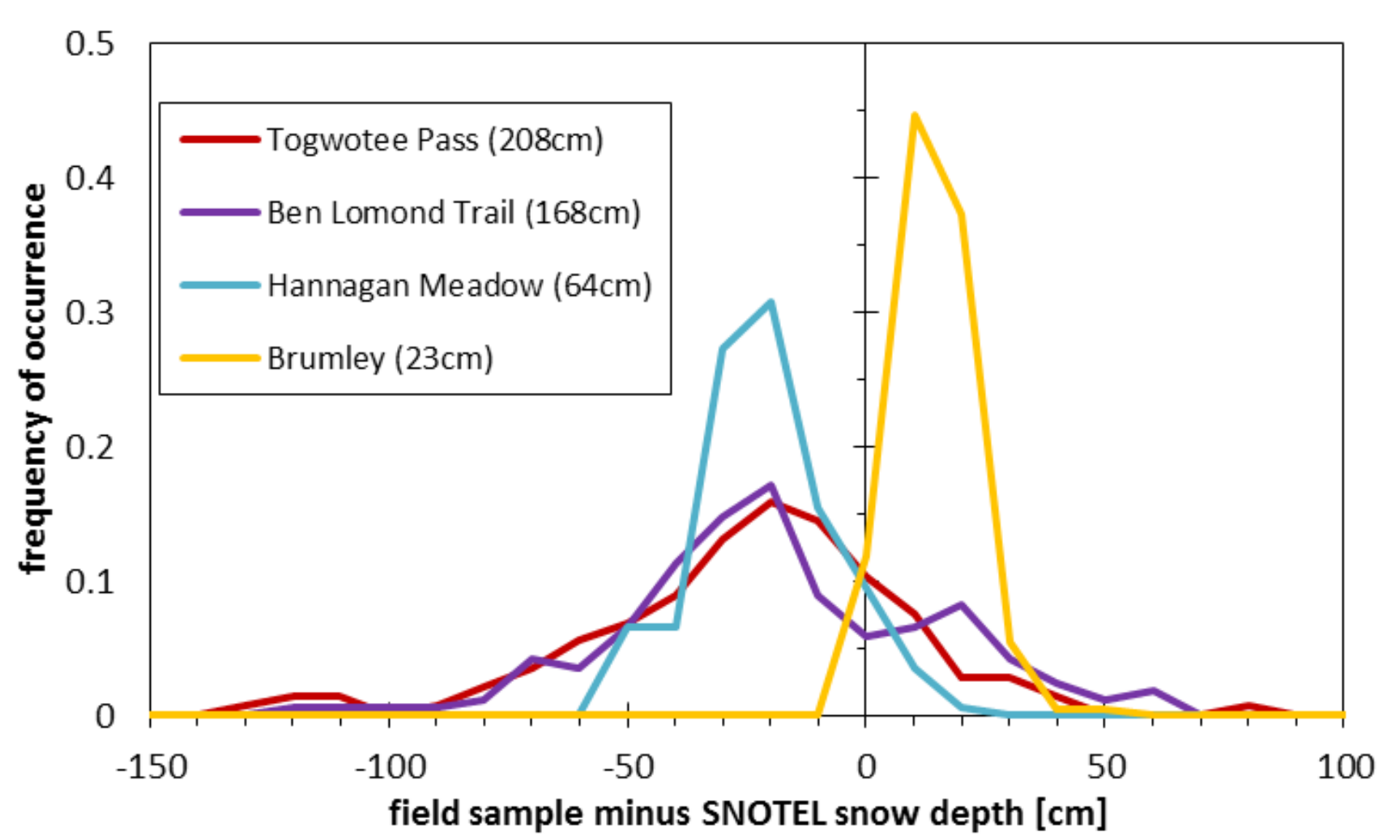
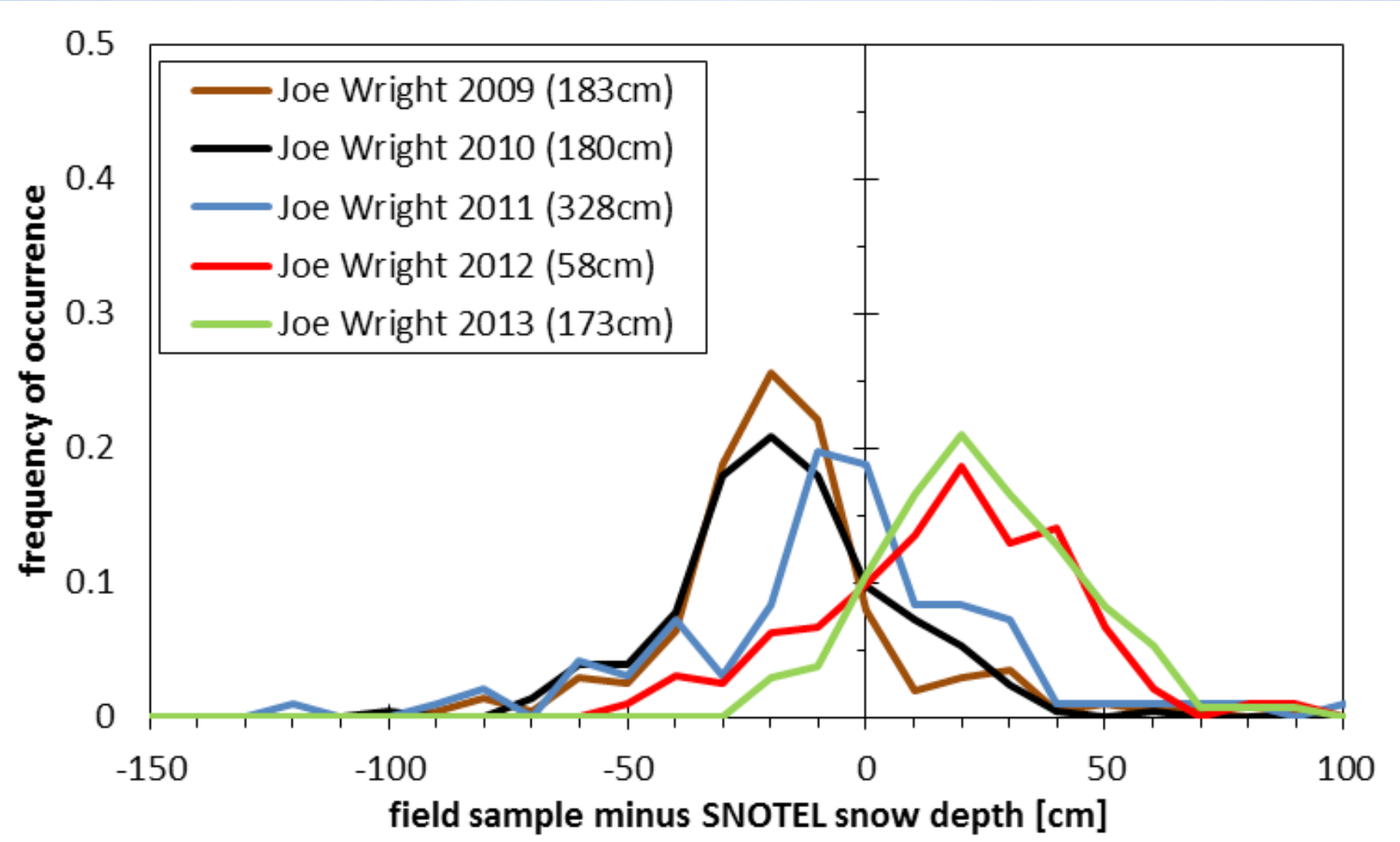
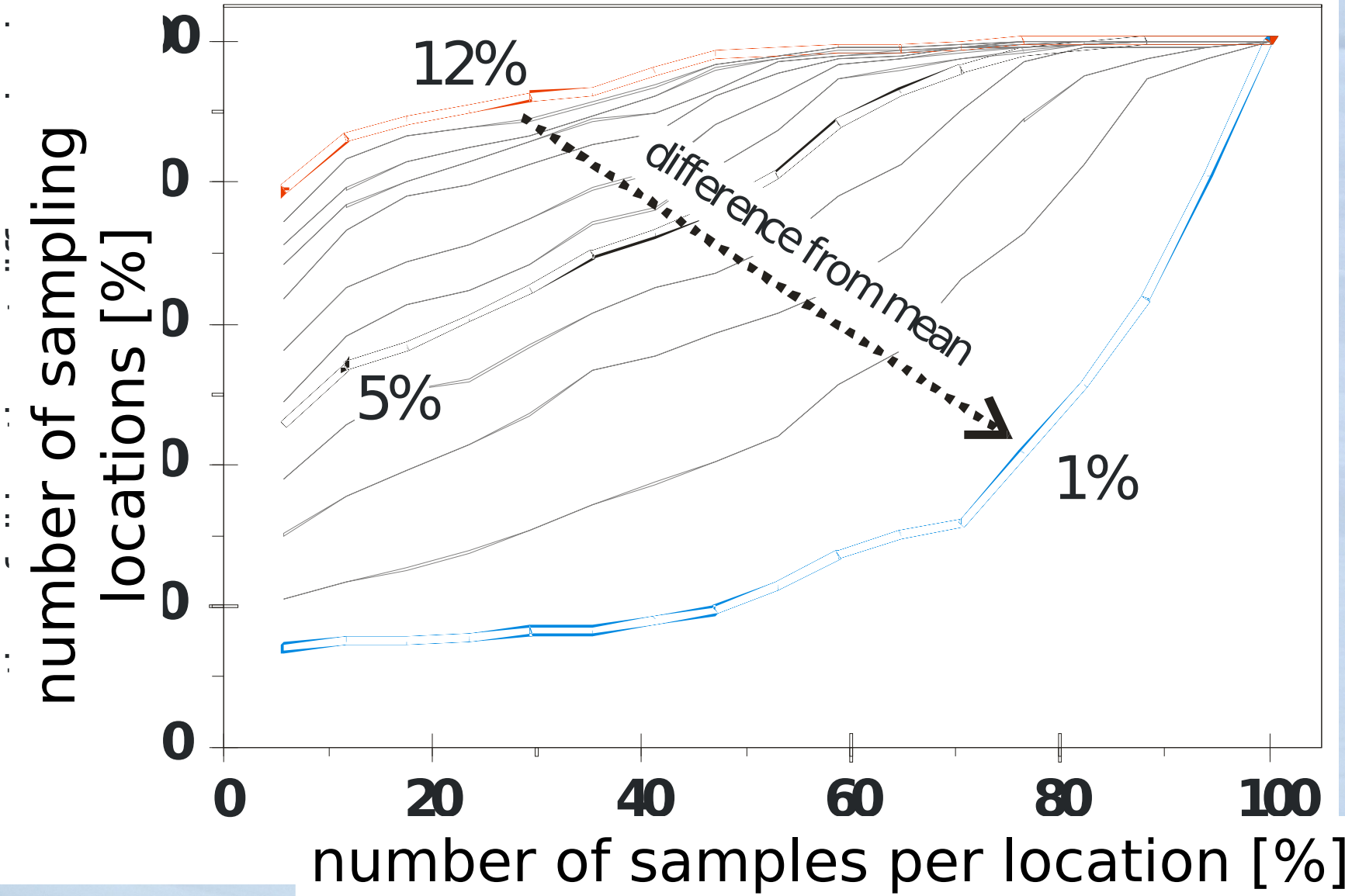
# How representative is a point?



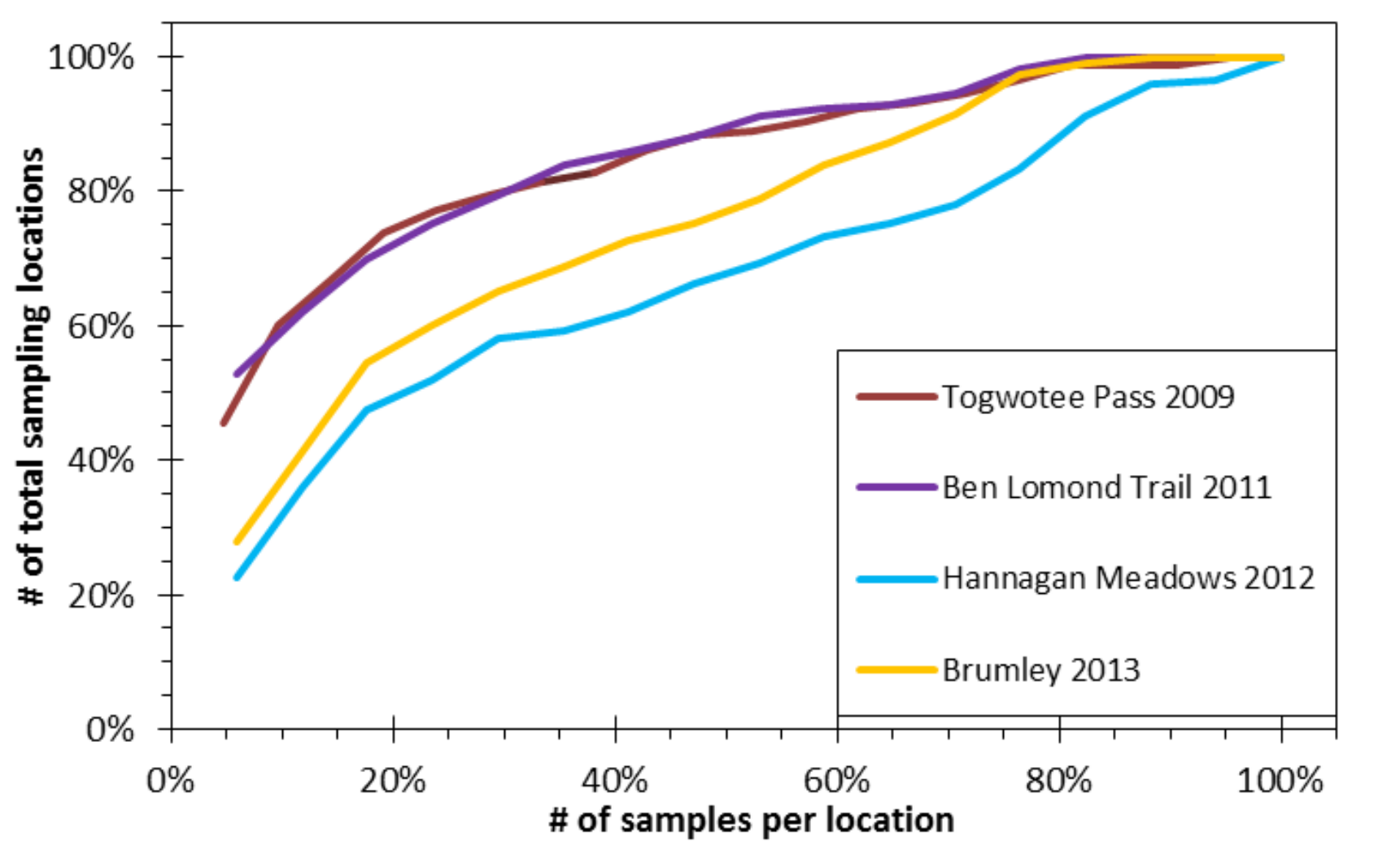
# May 1st at same location



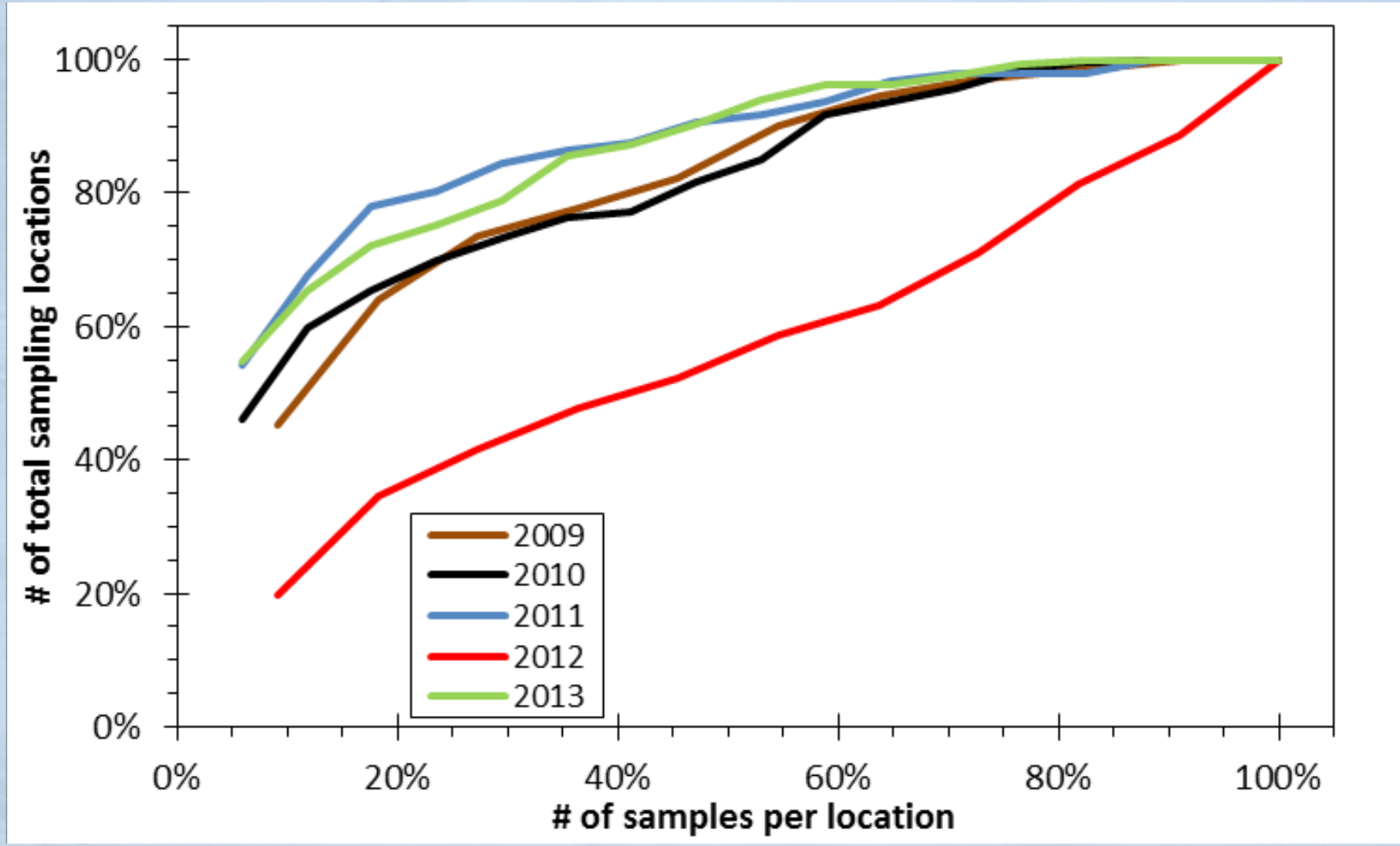
# Number of Samples per Location



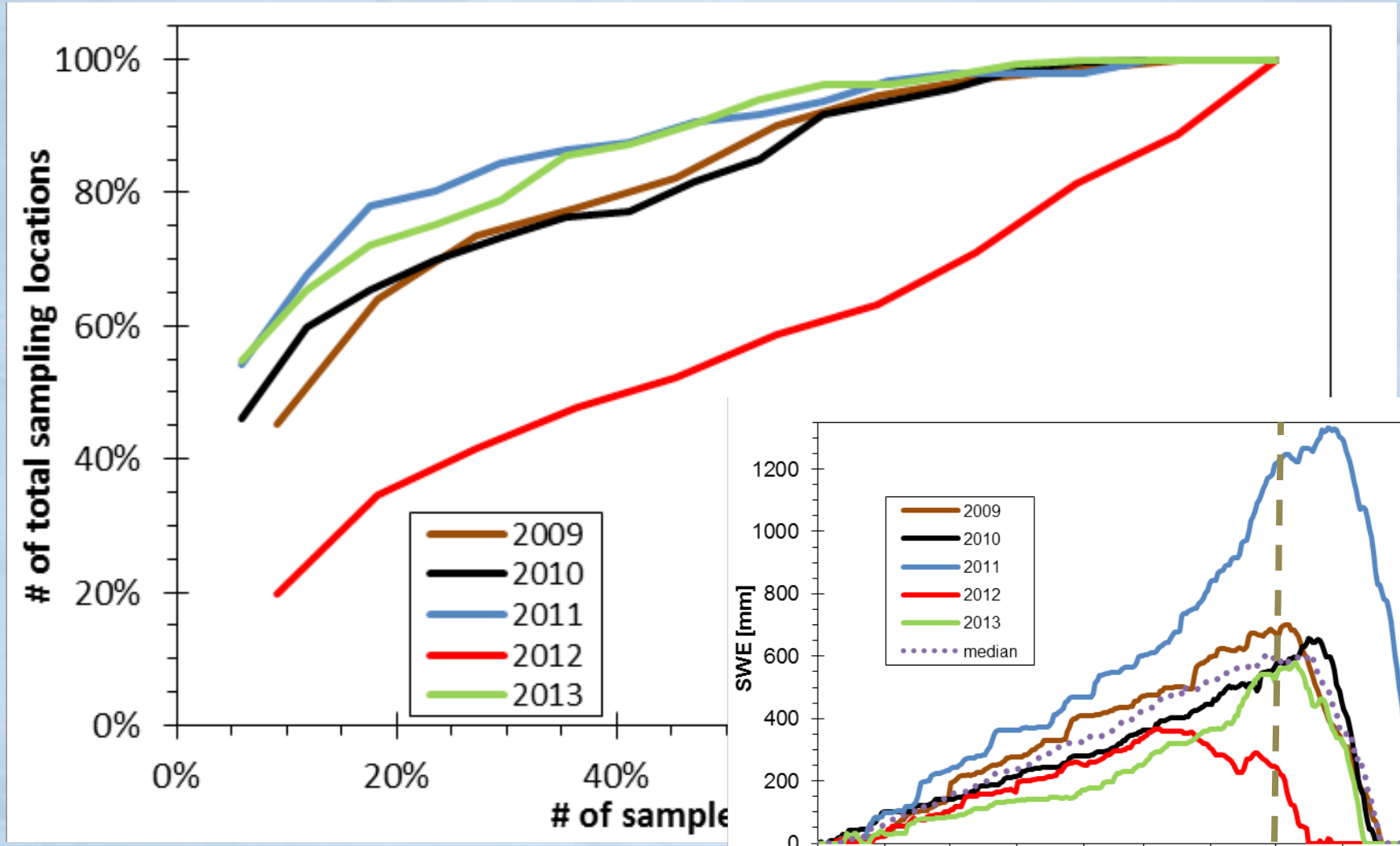
# Different stations



# Different years



# Different years, Same station



# Single Variable Correlation: Average

| **TP09** | **BLT11** | **HM12** | **Br13** |
|---|---|---|---|
| eastness | ***elevation*** | Solar Rad | eastness |
| slope | northness | **canopy** | **canopy** |
| | northing | easting | easting |

| **JW09** | **JW10** | **JW11** | **JW12** | **JW13** |
|---|---|---|---|---|
| **canopy** | ***elevation*** | slope | northness | **canopy** |
| northness | **canopy** | ***elevation*** | easting | ***elevation*** |
| ***elevation*** | northness | **canopy** | ***elevation*** | slope |

# Correlation (*cont'd*): Standard Deviation

| **TP09** | **BLT11** | **HM12** | **Br13** |
|---|---|---|---|
| easting | easting | ***elevation*** | slope |
| | max up slope | Solar Rad | Solar Rad |
| | Solar Rad | easting | |

| **JW09** | **JW10** | **JW11** | **JW12** | **JW13** |
|---|---|---|---|---|
| slope | ***elevation*** | slope | ***elevation*** | **canopy** |
| ***elevation*** | slope | ***elevation*** | **canopy** | ***elevation*** |
| **canopy** | **canopy** | slope | slope | |

# Correlation (*cont'd*): Points at 5% Difference

| **TP09** | **BLT11** | **HM12** | **Br13** |
|---|---|---|---|
| eastness | max up slope | Solar Rad | easting |
| easting | eastness | ***elevation*** | eastness |
| | northing | slope | |

| **JW09** | **JW10** | **JW11** | **JW12** | **JW13** |
|---|---|---|---|---|
| slope | max up slope | slope | easting | easting |
| ***elevation*** | northness | ***elevation*** | **canopy** | max up slope |
| **canopy** | | | northness | **canopy** |

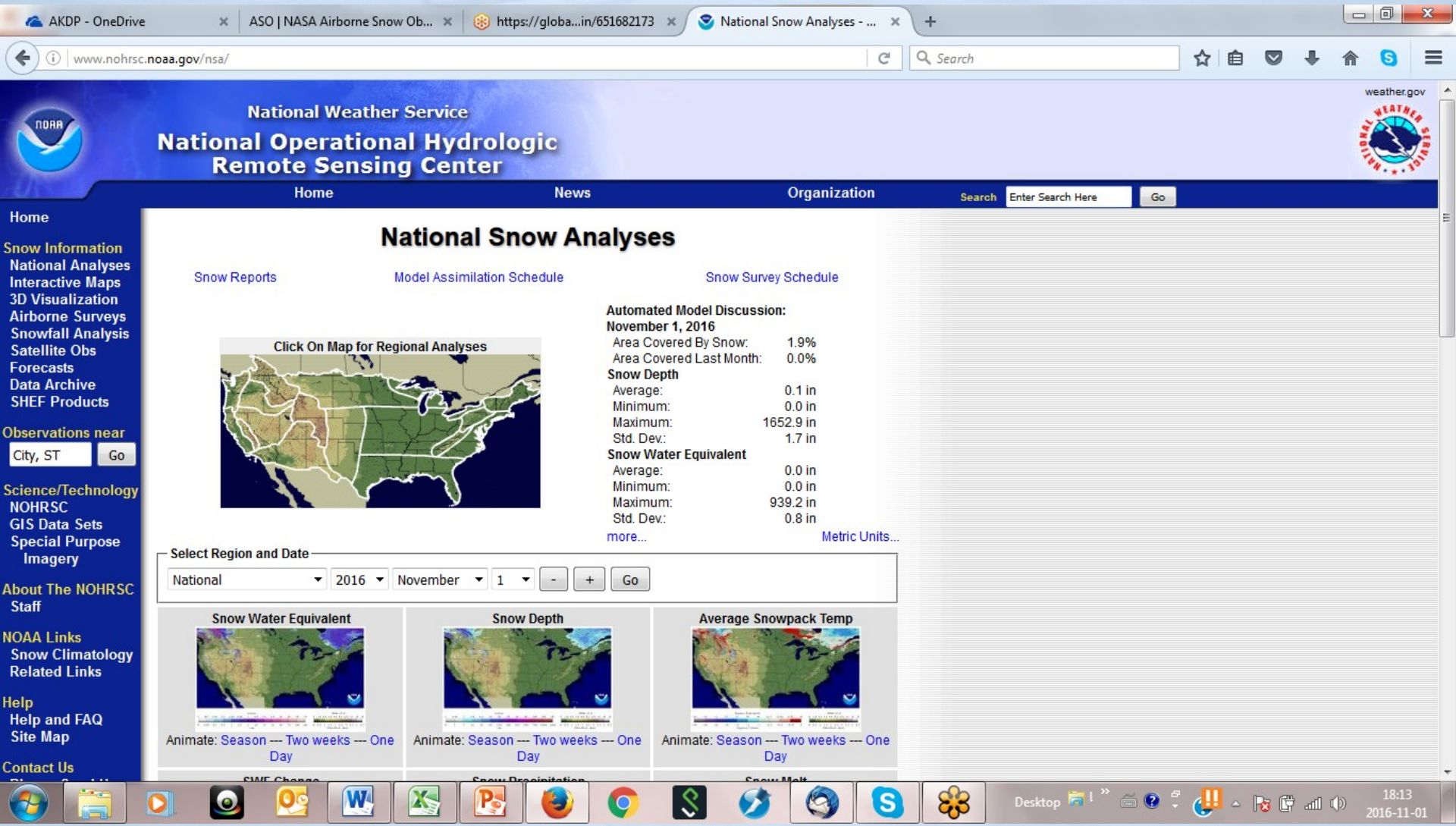
# Results Summary

- … are messy
  - Station representivity varies

- But …
  - Remote sensing is useful
    - Needs to be compared to “truth”
  - Field sampling allows us to ponder variability
  - Great student exercise

# MODELED SNOW

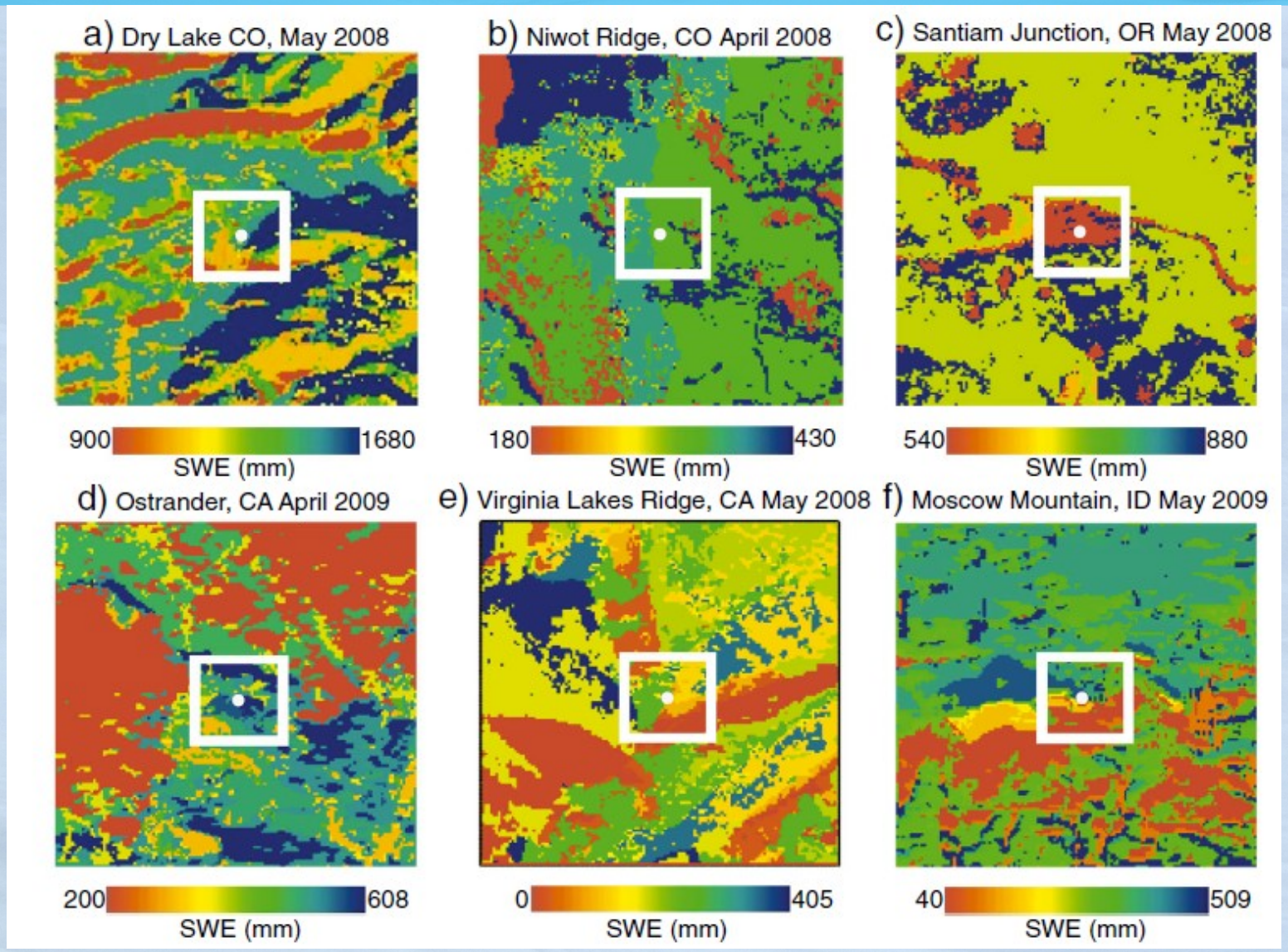
# NOAA NOHRSC NSA



# Modeling the Snowpack

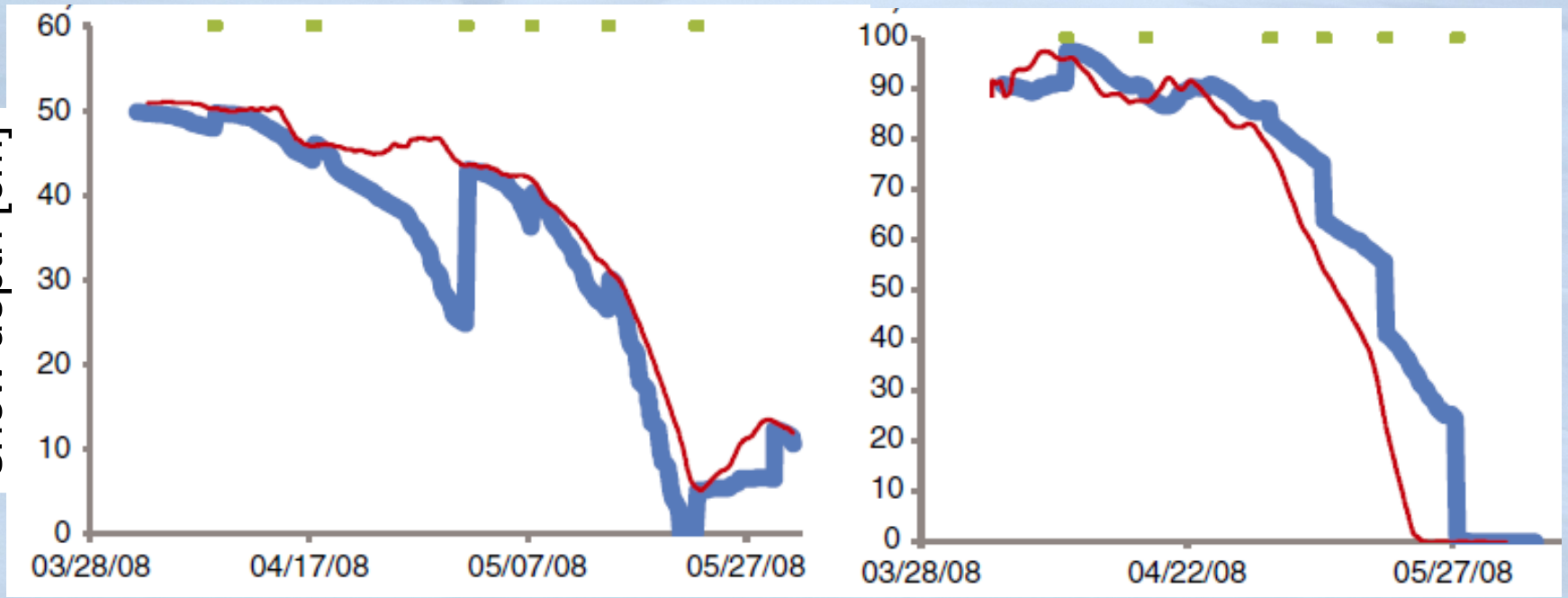
- Assimilates many datasets
- Including SNOTEL
- How representative are these point?

# Point to Area Interpolation




from *Meromy et al.* [2013]

# Snow Data Assimilation

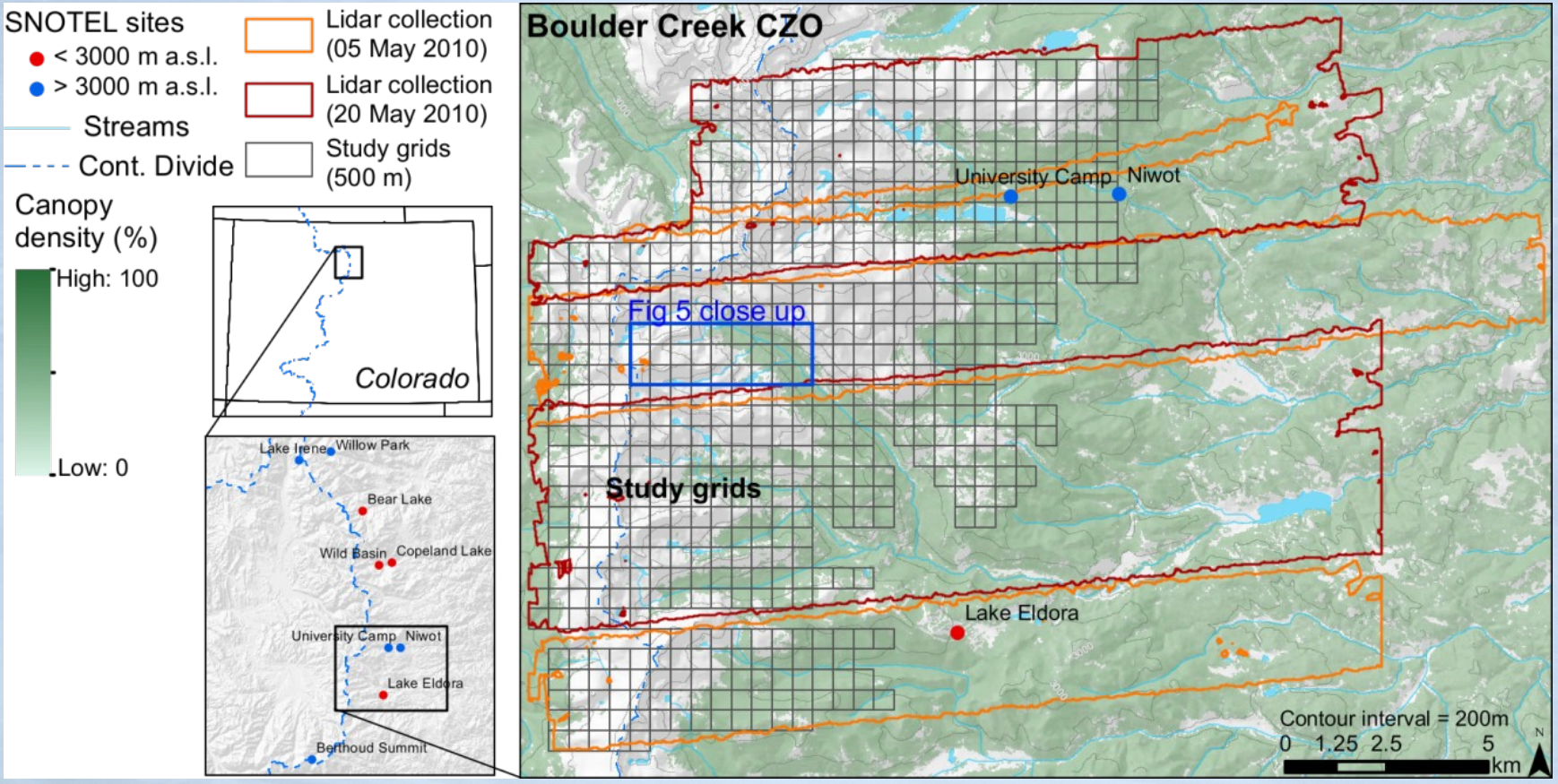



- Is precipitation wrong?

from *Meromy et al.* [2013]

# REMOTE SENSING

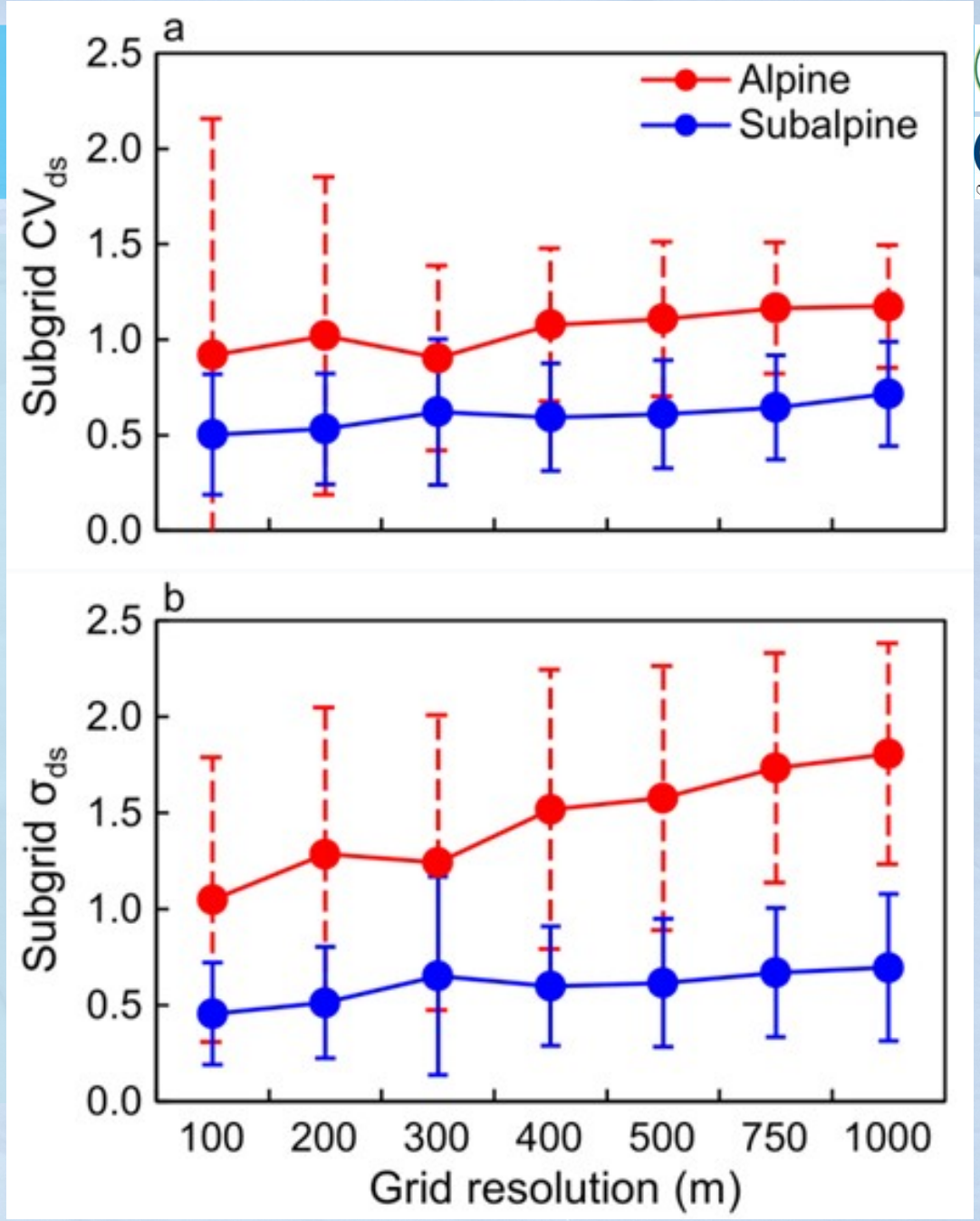
# Airborne Lidar: Snow On – Off




from *Sexstone et al.* [in review]

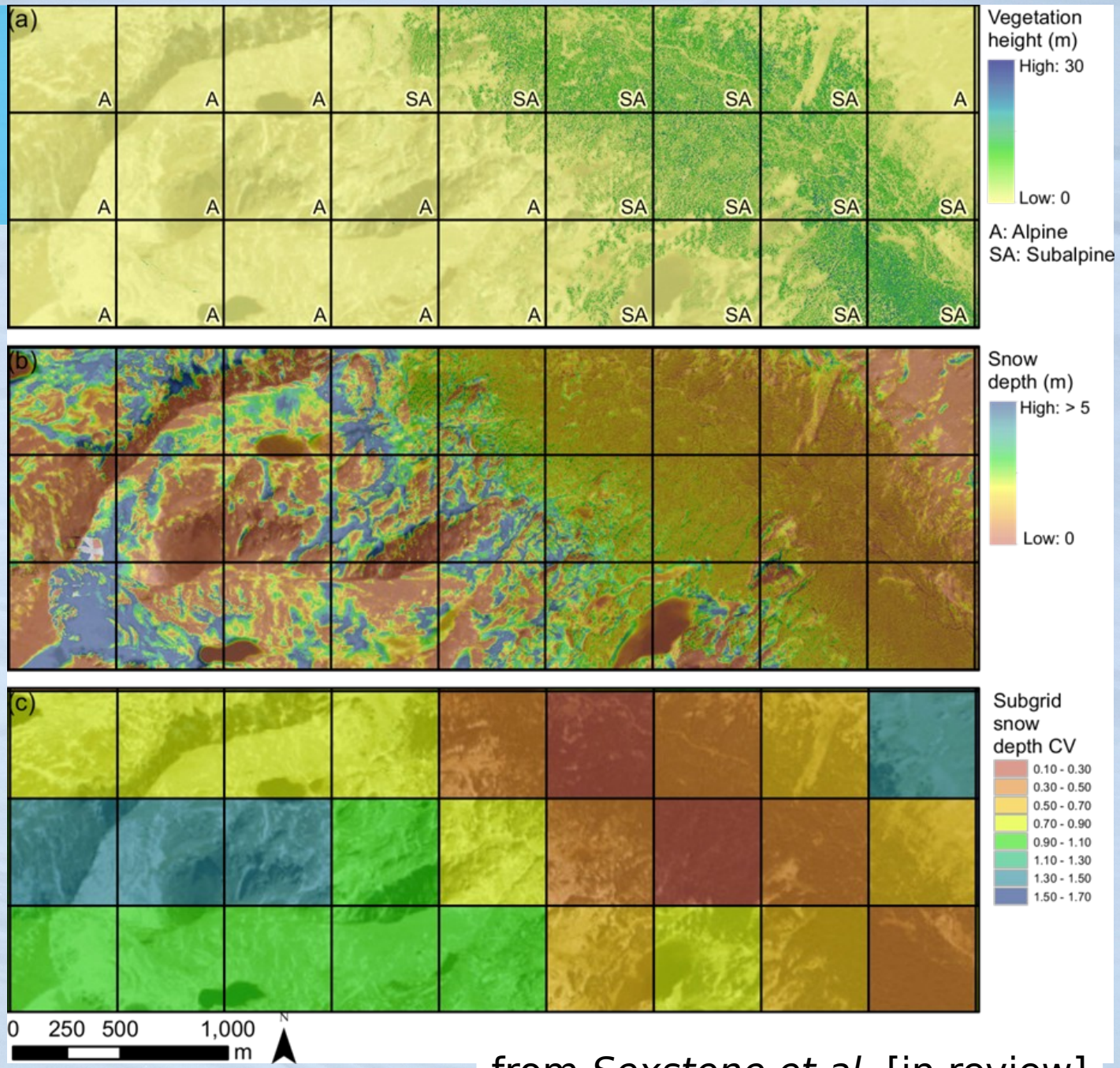
# Lidar $d_s$

- Variability as a function of scale




from *Sexstone et al.* [in review]

# Spatial Patterns




from *Sexstone et al.* [in review]

# Repeat Airborne Lidar for Snow

# NASA JPL ASO

AKDP - OneDrive | ASO | NASA Airborne Snow Ob... | https://globa...in/651682173

aso.jpl.nasa.gov

HOME ABOUT US DATA INSTRUMENTS MEDIA LOCATION CONTACT

TYPE OF WORK

All Maps

2016 Maps

- 2016 SWE (50 m)

2015 Maps

- 2015 SWE (50 m)

- 2015 Albedo (50 m)

2014 Maps

- 2014 SWE (50 m)

- 2014 Albedo (50 m)

## 2016

Download GeoTIFF


April 1, 2016

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April 7, 2016

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April 16, 2016

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April 26, 2016

Download GeoTIFF


May 27, 2016

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Desktop 18:07 2016-11-01

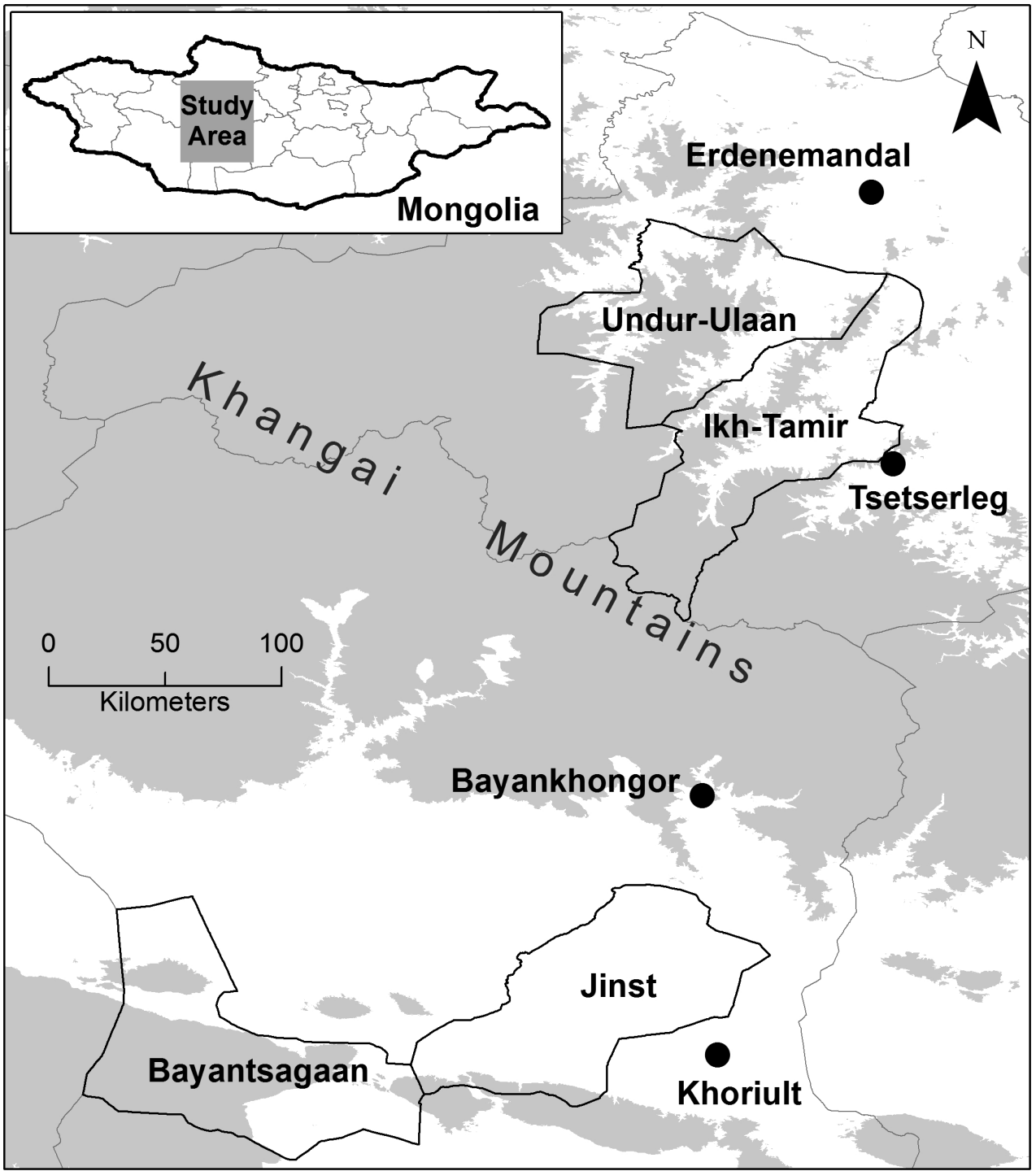
# NASA JPL ASO

- Watershed scale
- Weekly to biweekly flights
- 1-m resolution snow depth
- 50-m SWE
  - from SNOTEL SWE and depth

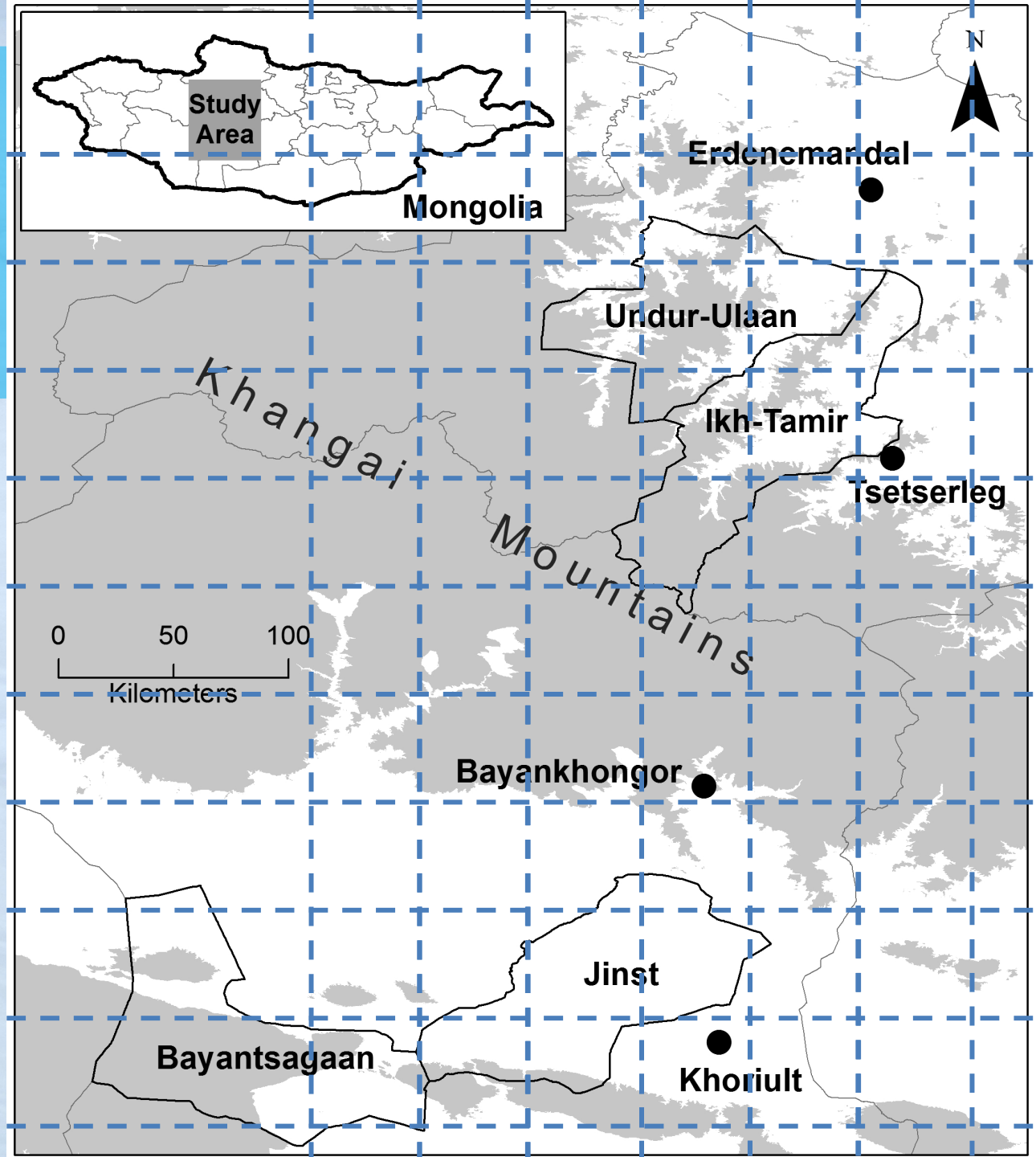
- Big effort, using SNOTEL and other data
- Can use ground truth …

# SPARSE DATASETS

# Khangai Mountain Mongolia



# Khangai Mountain Mongolia

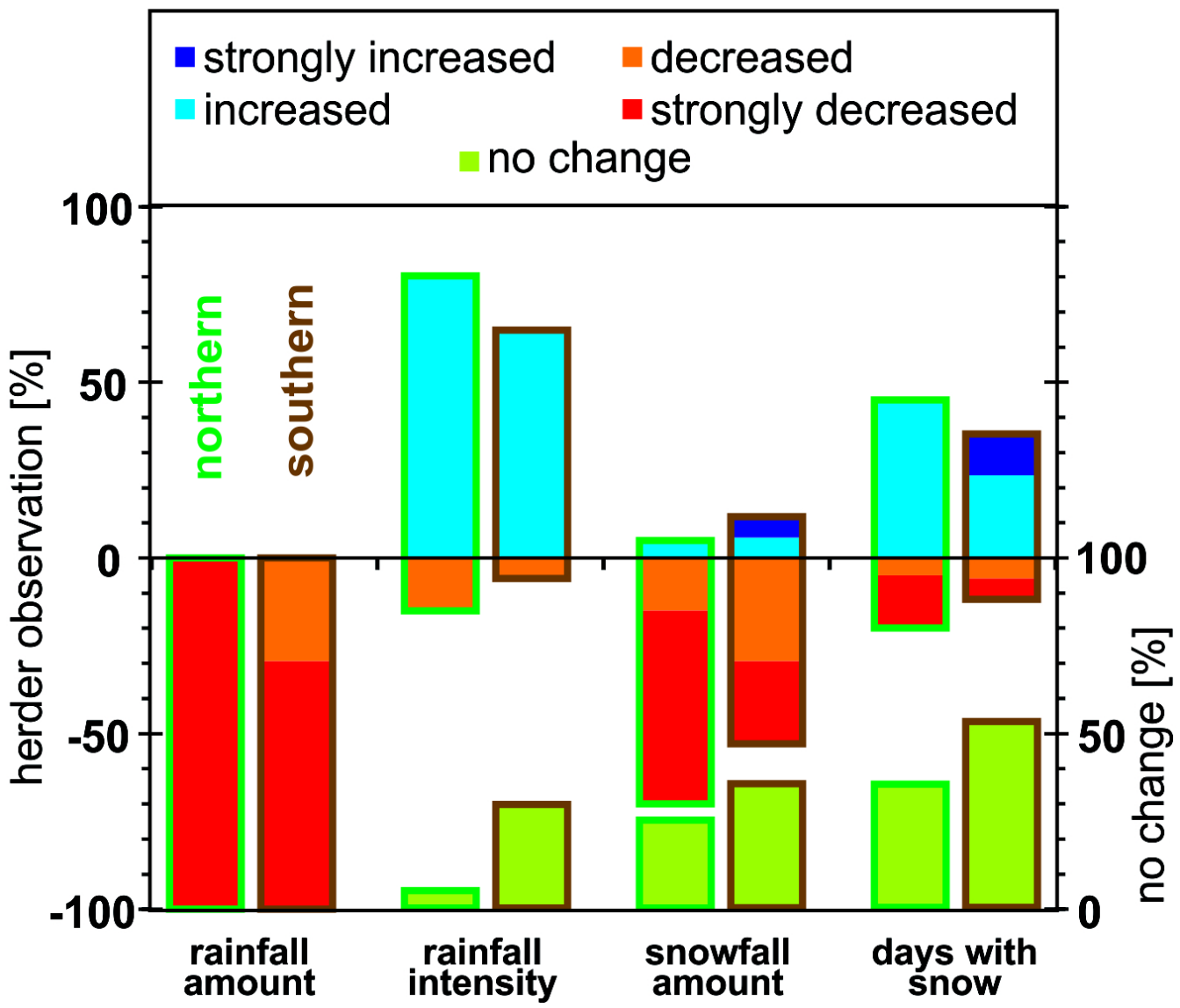


# Example Herder Question (Q3a)

- The rainfall amount has:
  1. decreased a lot
  2. decreased somewhat
  3. no change
  4. increased somewhat
  5. increased a lot

- Responses scaled from -2 to +2

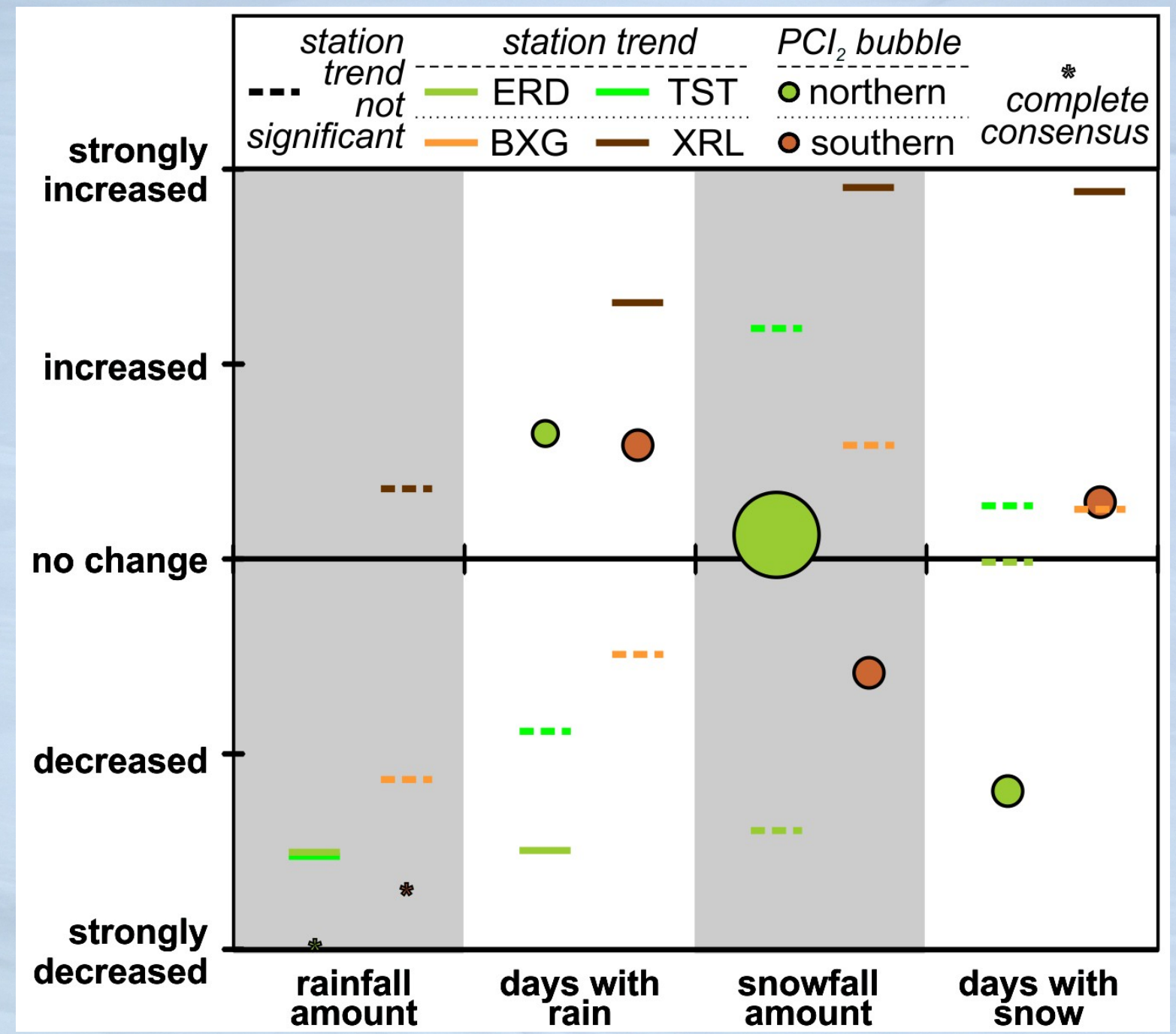
# Herder Responses



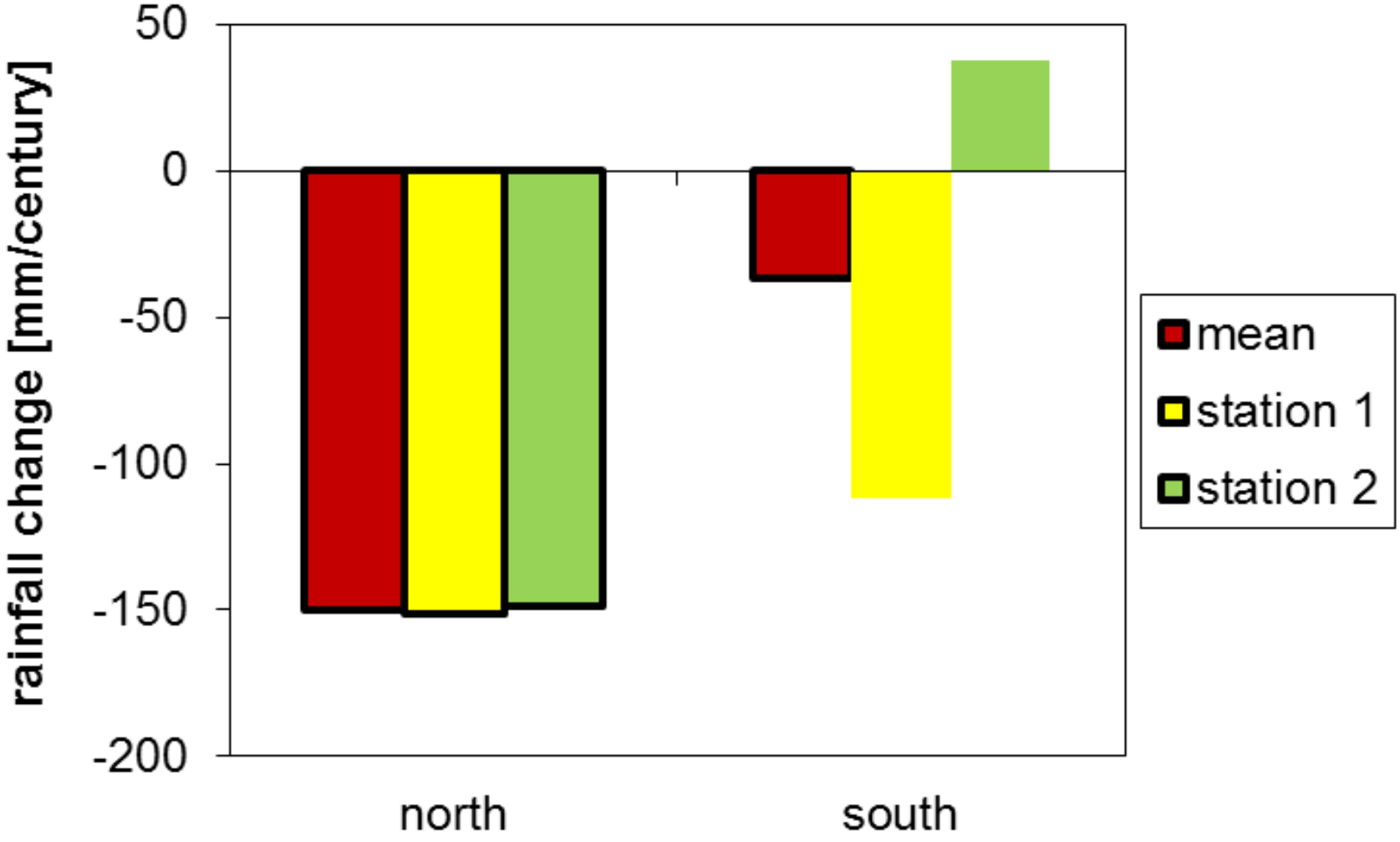
# Potential for Conflict Index 2 ($PCI_2$)

- Using a discrete point scale with neutral
- Statistical conversion
- $PCI_2$ (mean and) consensus
  - Scale from 0 (agreement) to 1 (complete disagreement)

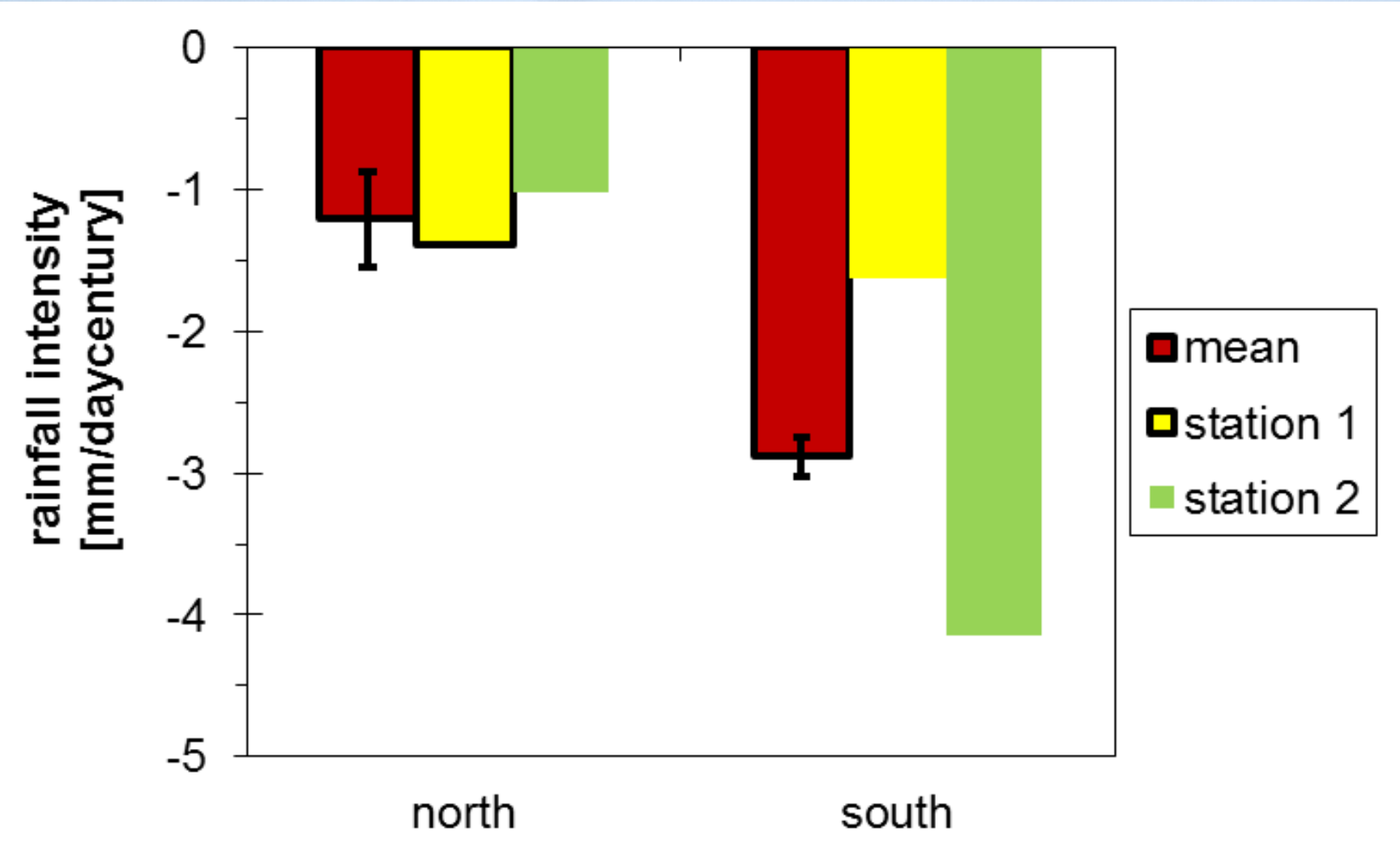

  - Vaske, J.J., J. Beaman, H. Barreto, and L.B. Shelby, 2010. An extension and further validation of the potential for conflict index. *Leisure Sciences, 32,* 240-254.
  - <http://warnercnr.colostate.edu/~jerryv/PCI2>


station trend not significant
station trend
ERD
TST
BXG
XRL
PCI2 bubble
northern
southern
complete consensus
strongly increased
increased
no change
decreased
strongly decreased
rainfall amount
days with rain
snowfall amount
days with snow

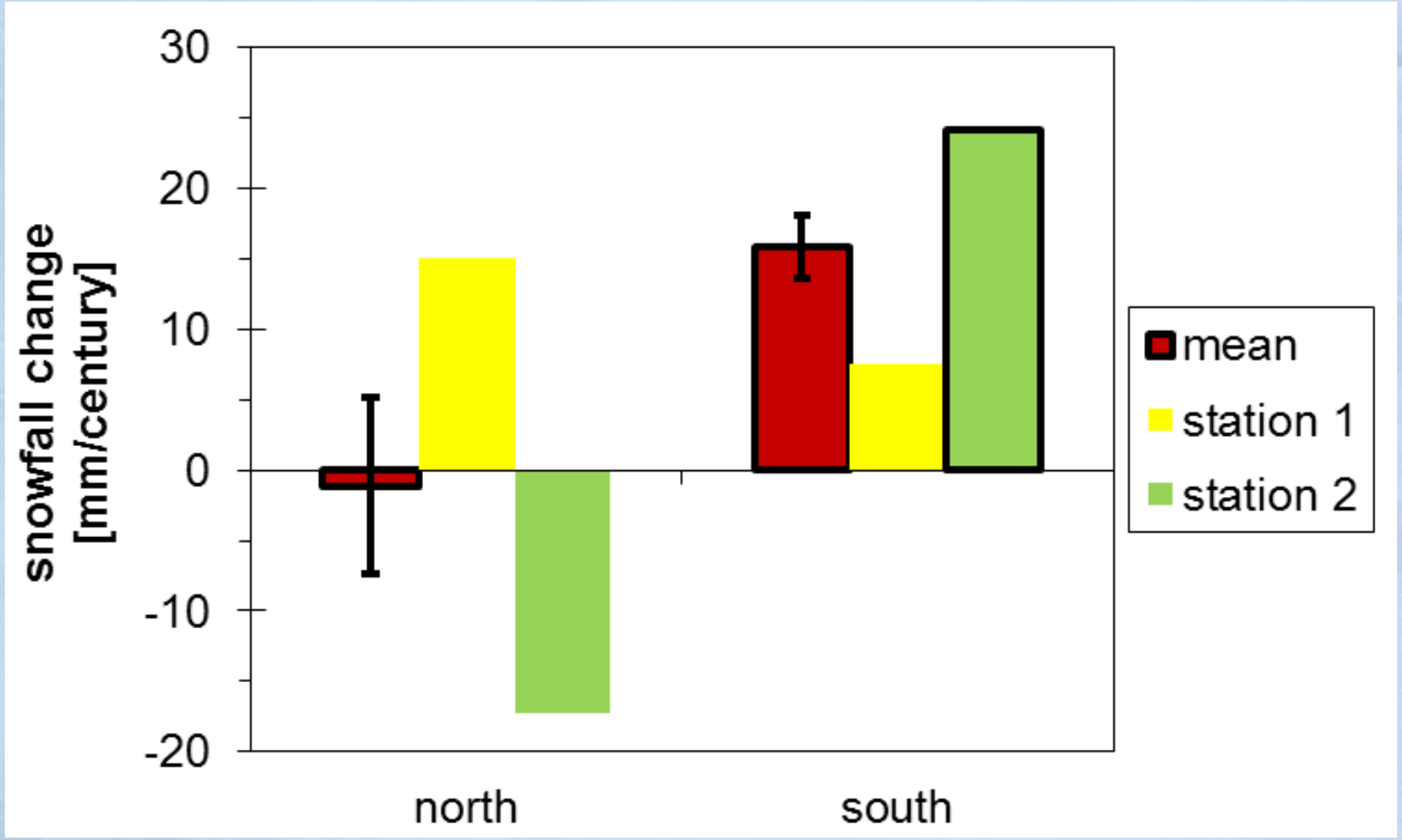
# Trend with $PCI_2$ : Rainfall Amount



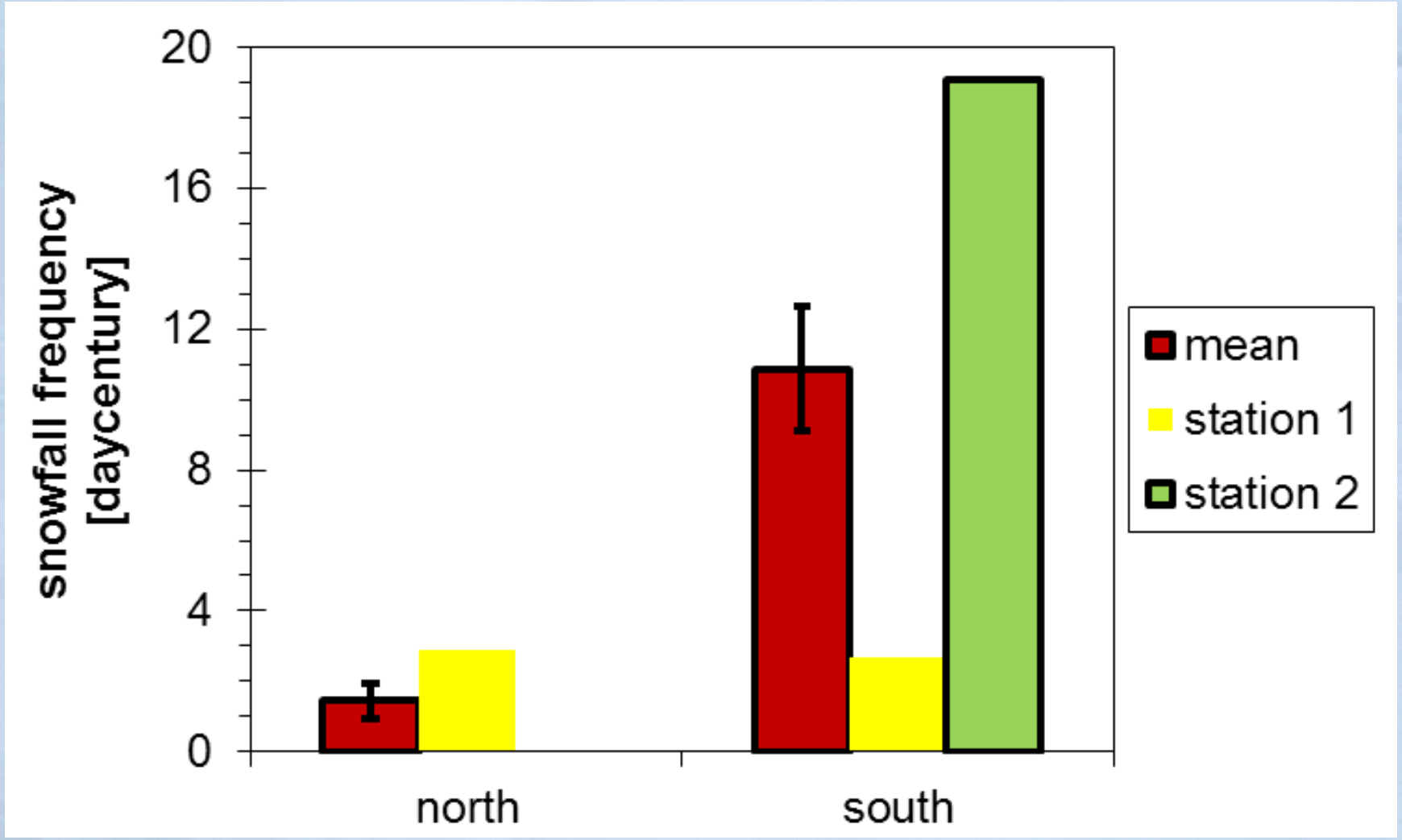
# Trend with $PCI_2$: Rain Intensity



# Trend with $PCI_2$: Snowfall Amount



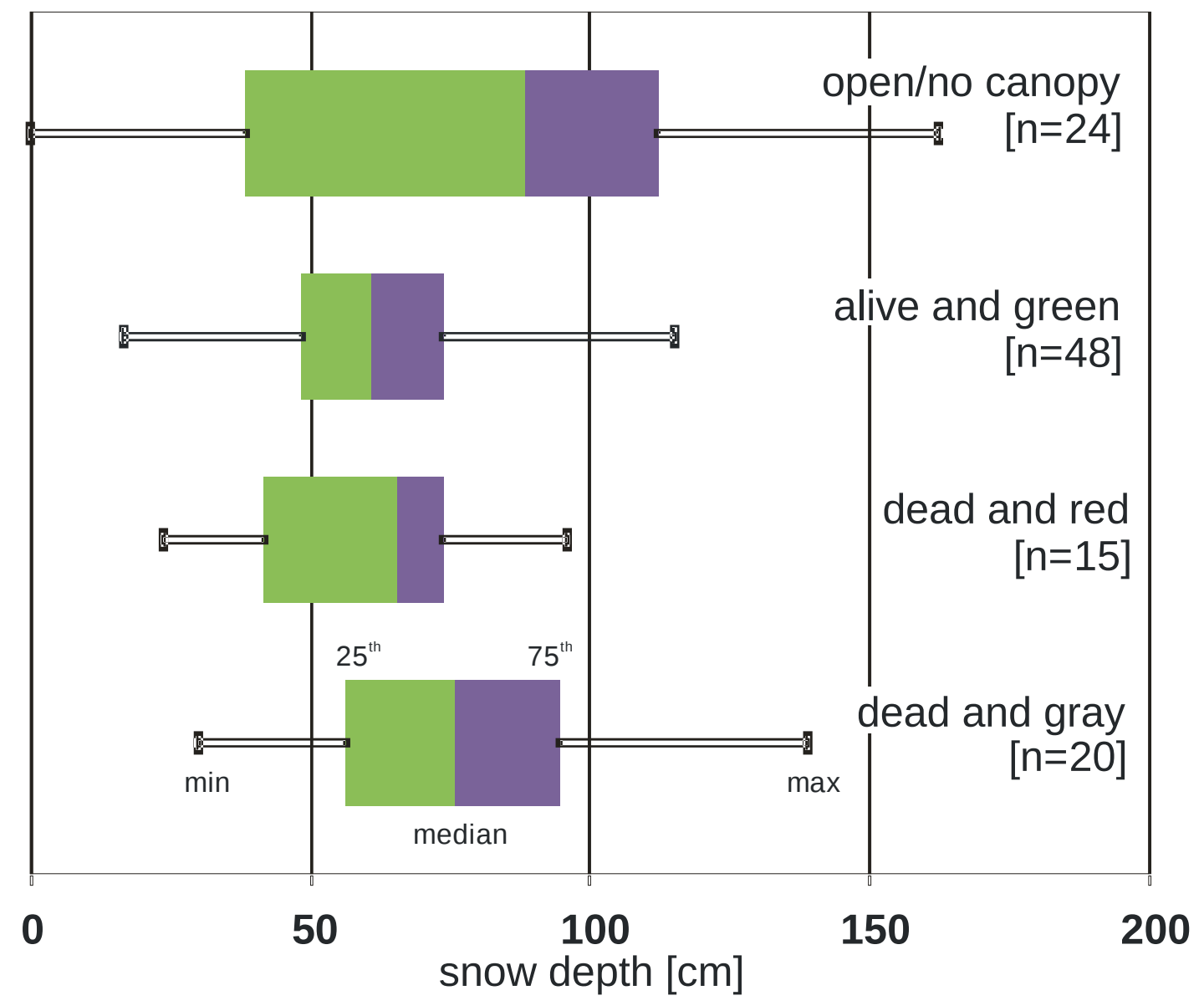
# Trend with $PCI_2$: Snow Frequency



# OTHER CHANGES

# Changes to the Forest?

# Our Forests are Changing



# Challenges and Opportunities

- Variability
  - Spatial and Temporal
- Point vs. Area
  - Extrapolation
- Different scales
  - Resolutions and extent
- Changes
  - Climate
  - Land cover/use

- Merge different dataset
  - Remote sensing and ground based
  - Varying resolution
- Evaluate changes
  - Different sensors
  - Different methods
  - Different canopy closure

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# Questions we should ask

- What are relevant/important processes?
- What are we measuring?
- How should we measure it?
- How do we scale up or down?
- What data do we need:
  - to parameterize models?
  - to evaluate remote sensing?

# Acknowledgements


- NOAA Office of Hydrologic Development
  - Project #NA07NWS4620016
  - **PI Dr. Noah Molotch**
- NASA Terrestrial Hydrology Program
  - Project NNX11AQ66G *"Improved Characterization of Snow Depth in Complex Terrain Using Satellite Lidar Altimetry*"
  - **PI Dr. Michael Jasinski**

# QUESTIONS?

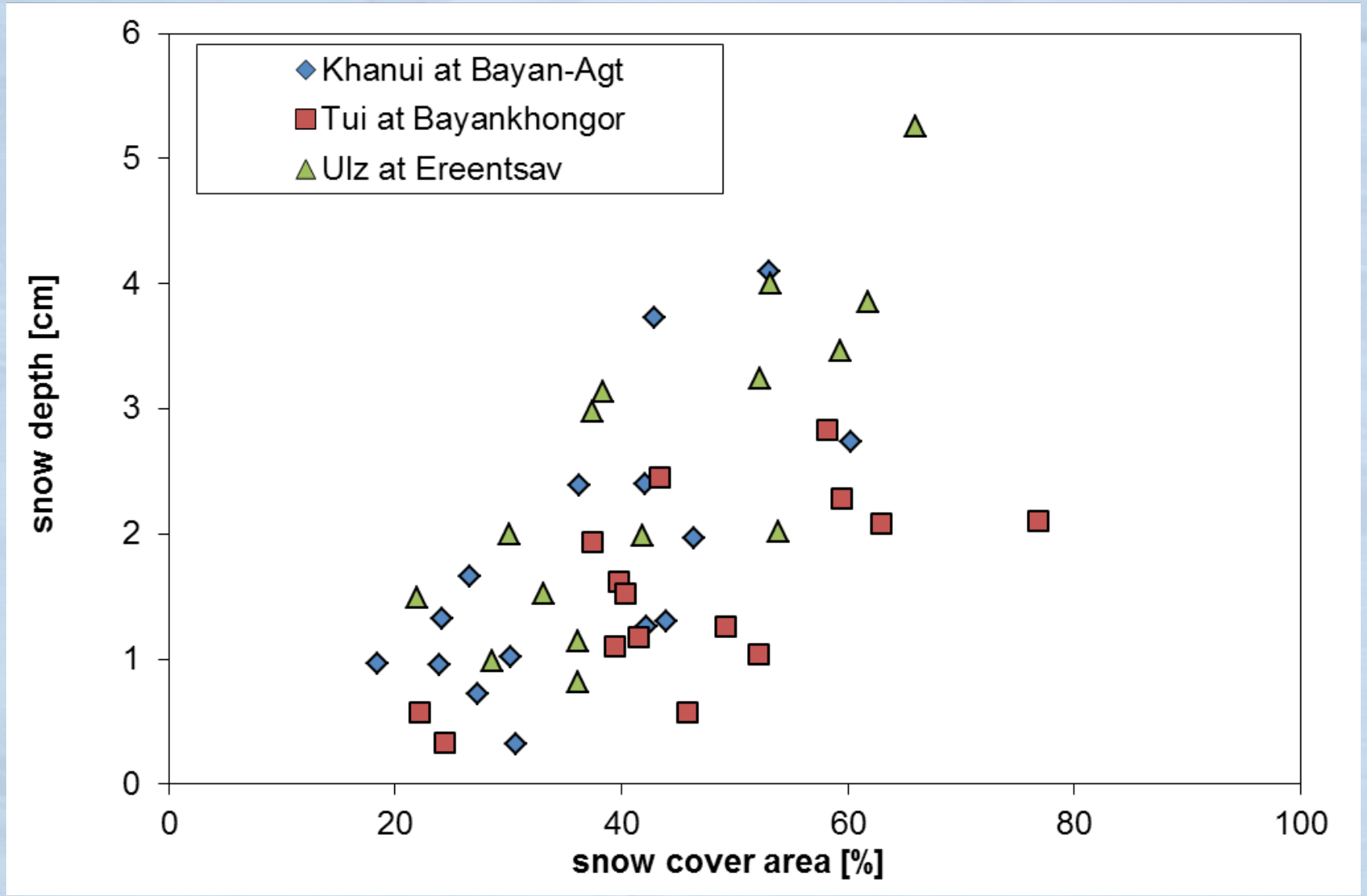
Cameron Pass 194

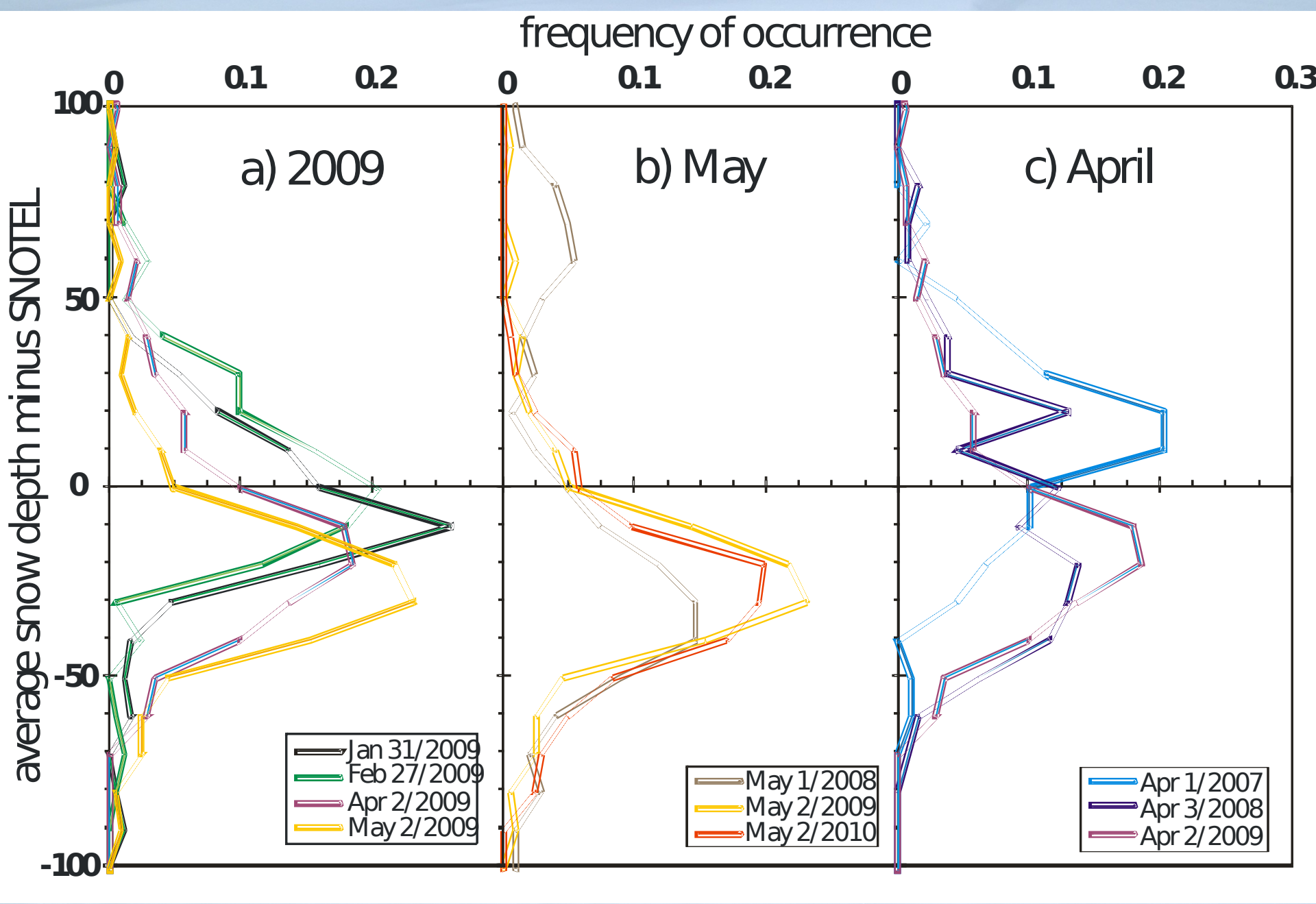
# Abstract


- Professor James Church started measuring the snowpack in the Mount Rose/Lake Tahoe (California/Nevada United States) area for snowmelt runoff estimation over 110 years ago. Across the western US, this prompted the implementation of the snow course data that comprised monthly snowpack measurements at up to 2000 locations. In the late 1970s, this network was supplemented by the automated snow telemetry (SNOTEL) network that now has over 800 stations measuring snow and related variables on a daily or even hourly basis. These two network provide a wealth of information, but have a variety of limitations too. Issues, solutions and opportunities will be presented that begin with the snow course and SNOTEL datasets and move to modeling (e.g., the NOAA National Operational and Hydrologic and Remote Sensing Center SNODAS data) and remote sensing initiatives (e.g., the NASA Airborne Snow Observatory). Since these monitoring and modeling efforts focus on the "data-rich" US, an additional example will be provided for several watersheds in the less data-rich Mongolia.

# OTHER

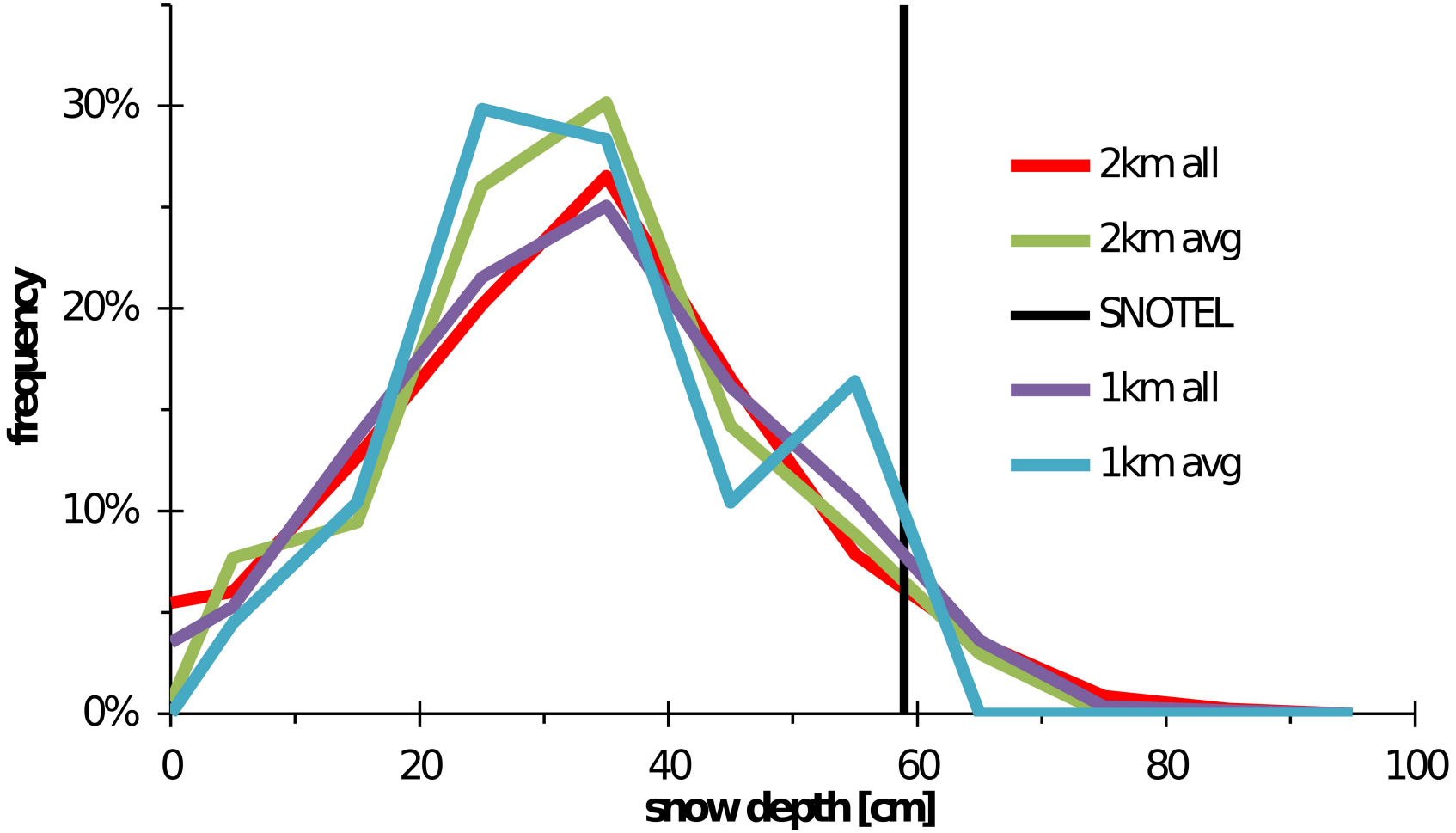
# Snow Cover Depletion curves






pe Wright SNOTEL, CO

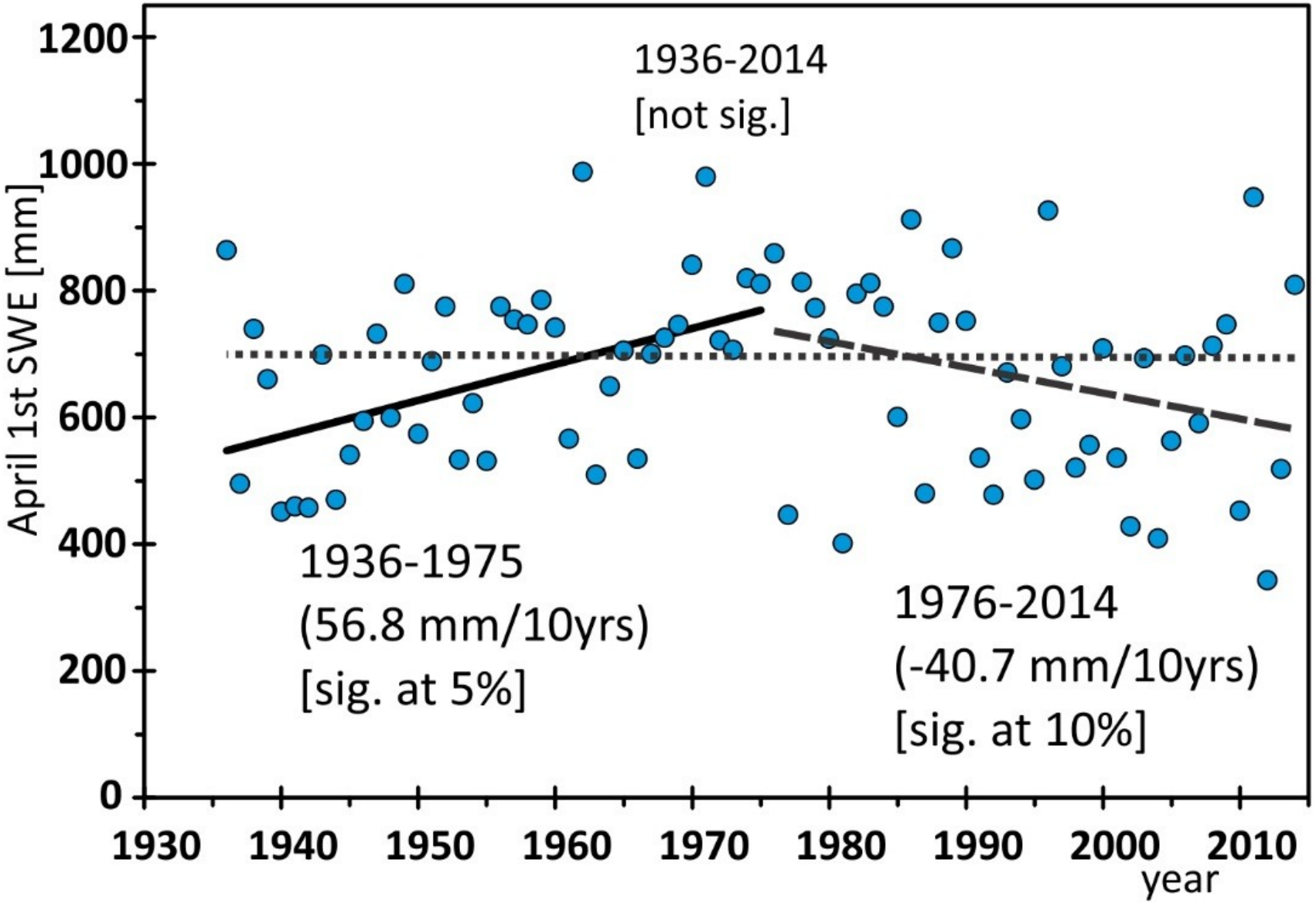
# Spatial Variability



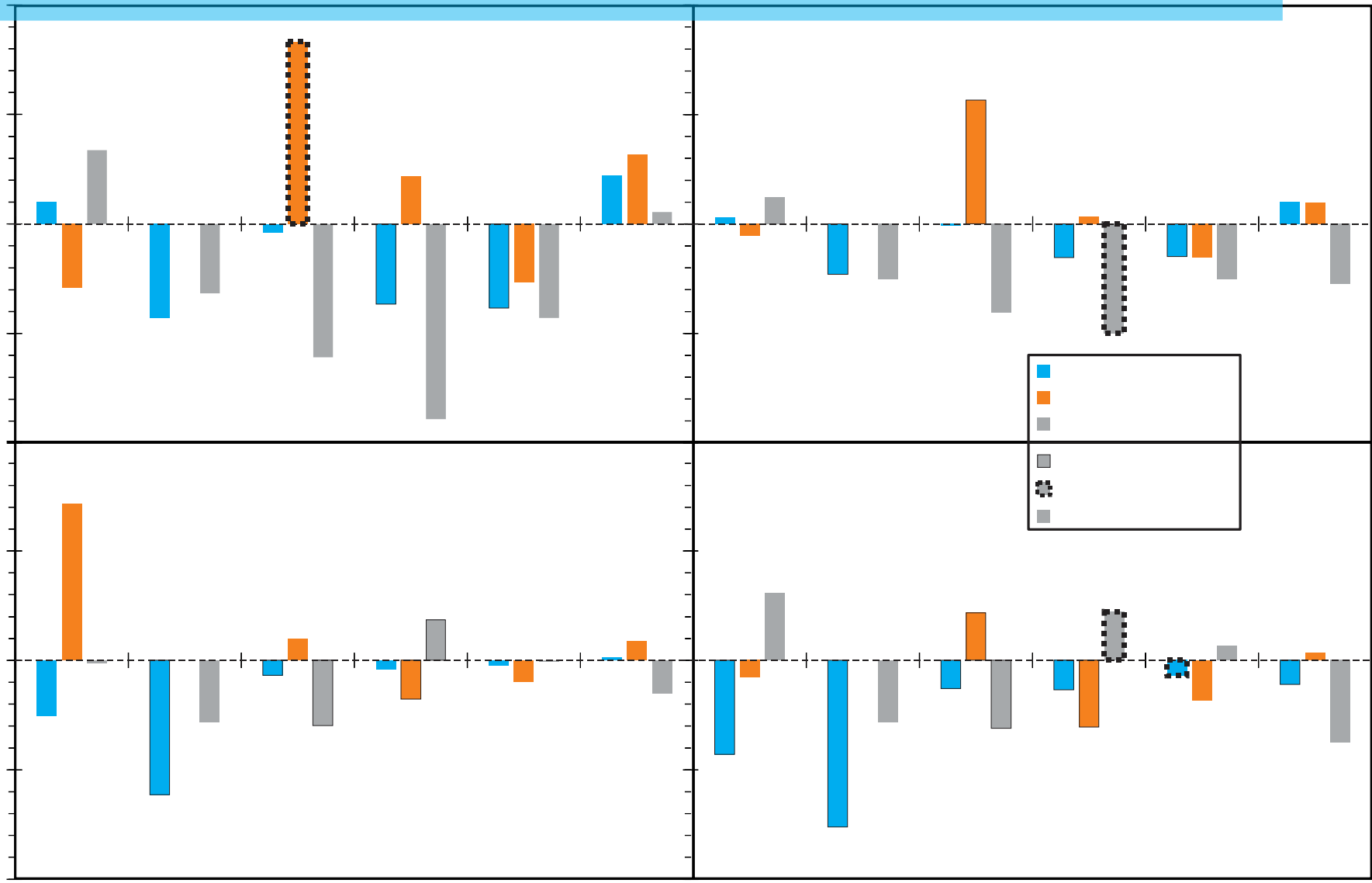

nnagan Meadow SNOTEL, AZ

# TRENDS

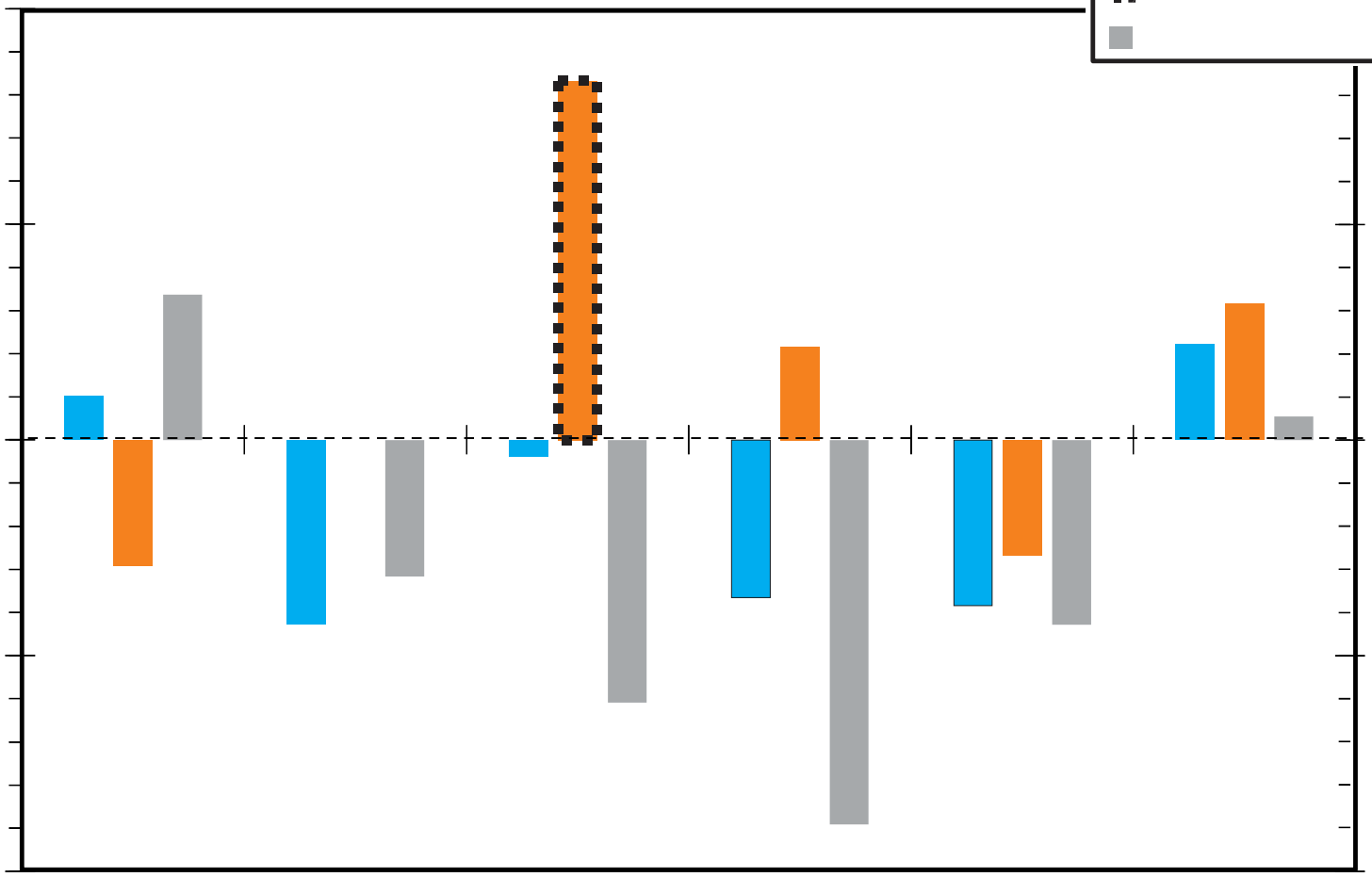
# Cameron Pass April 1st SWE



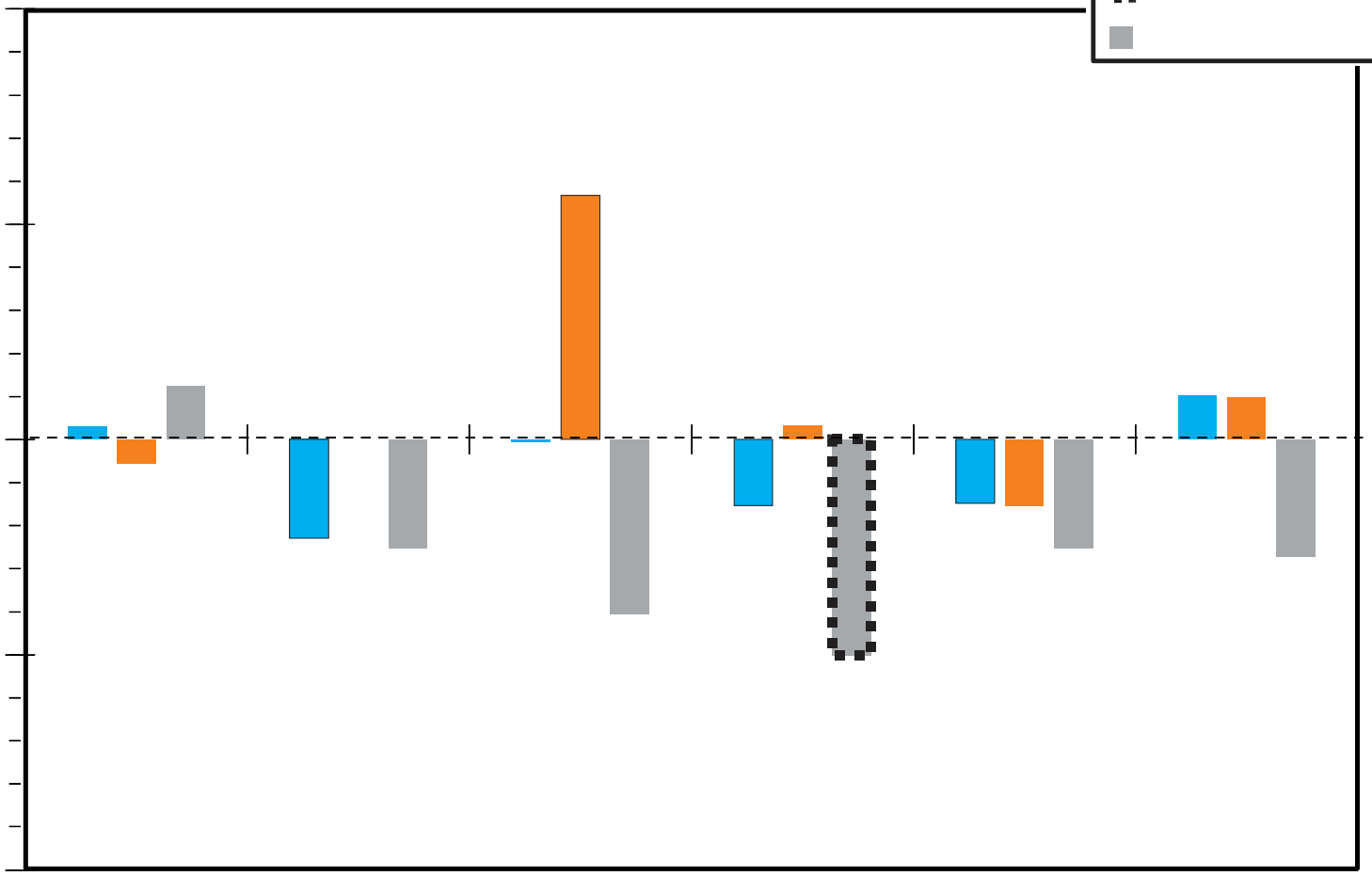
# Depth/SWE Average and COV Trends



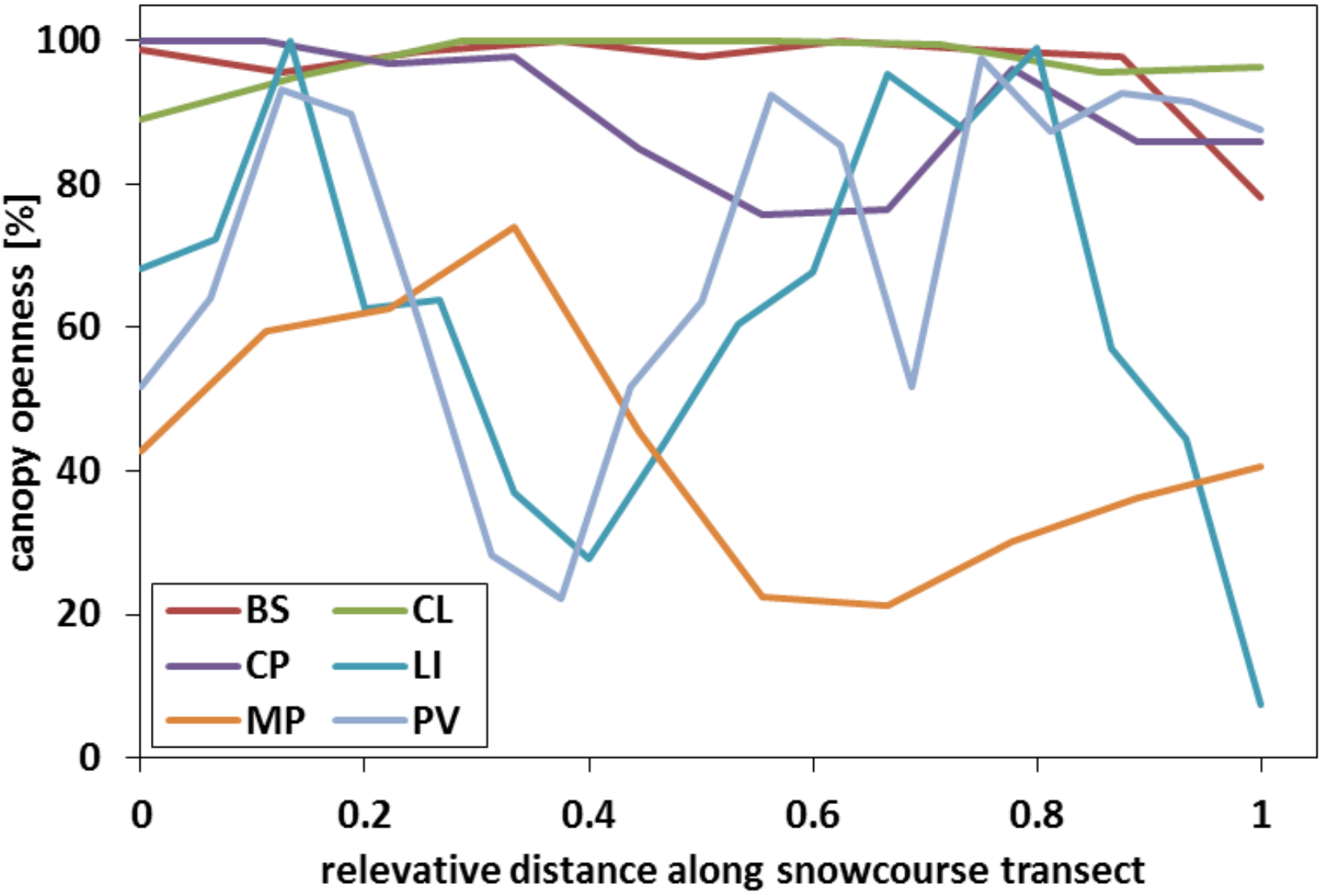
# Snow Depth Trends



# SWE Trends



# Canopy Closure along Transect



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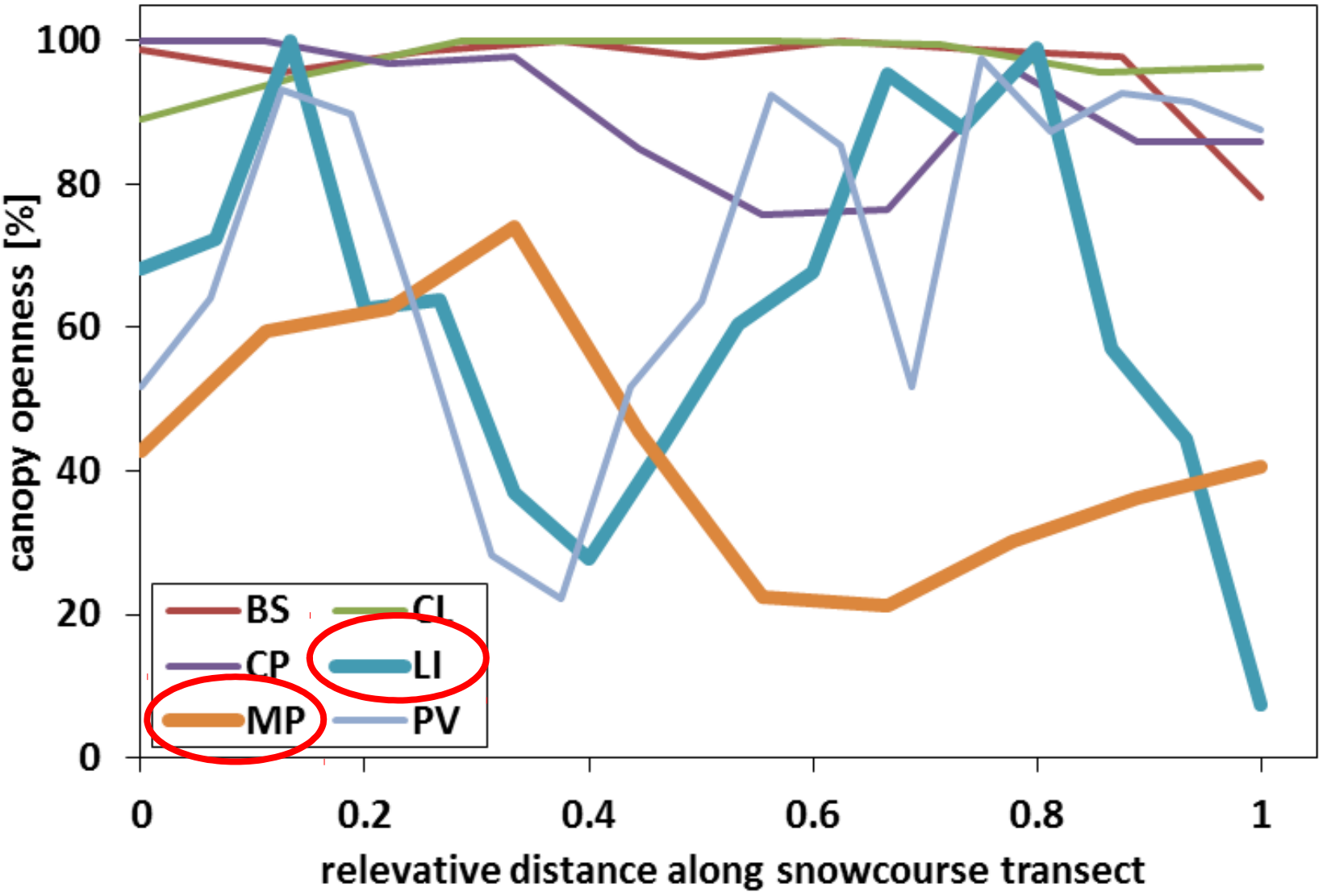

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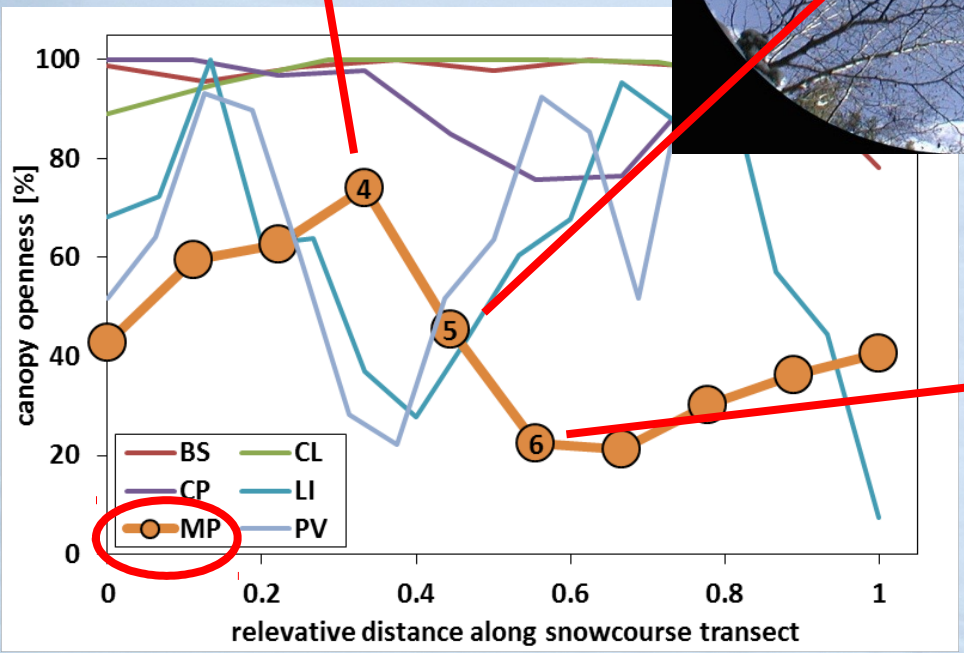
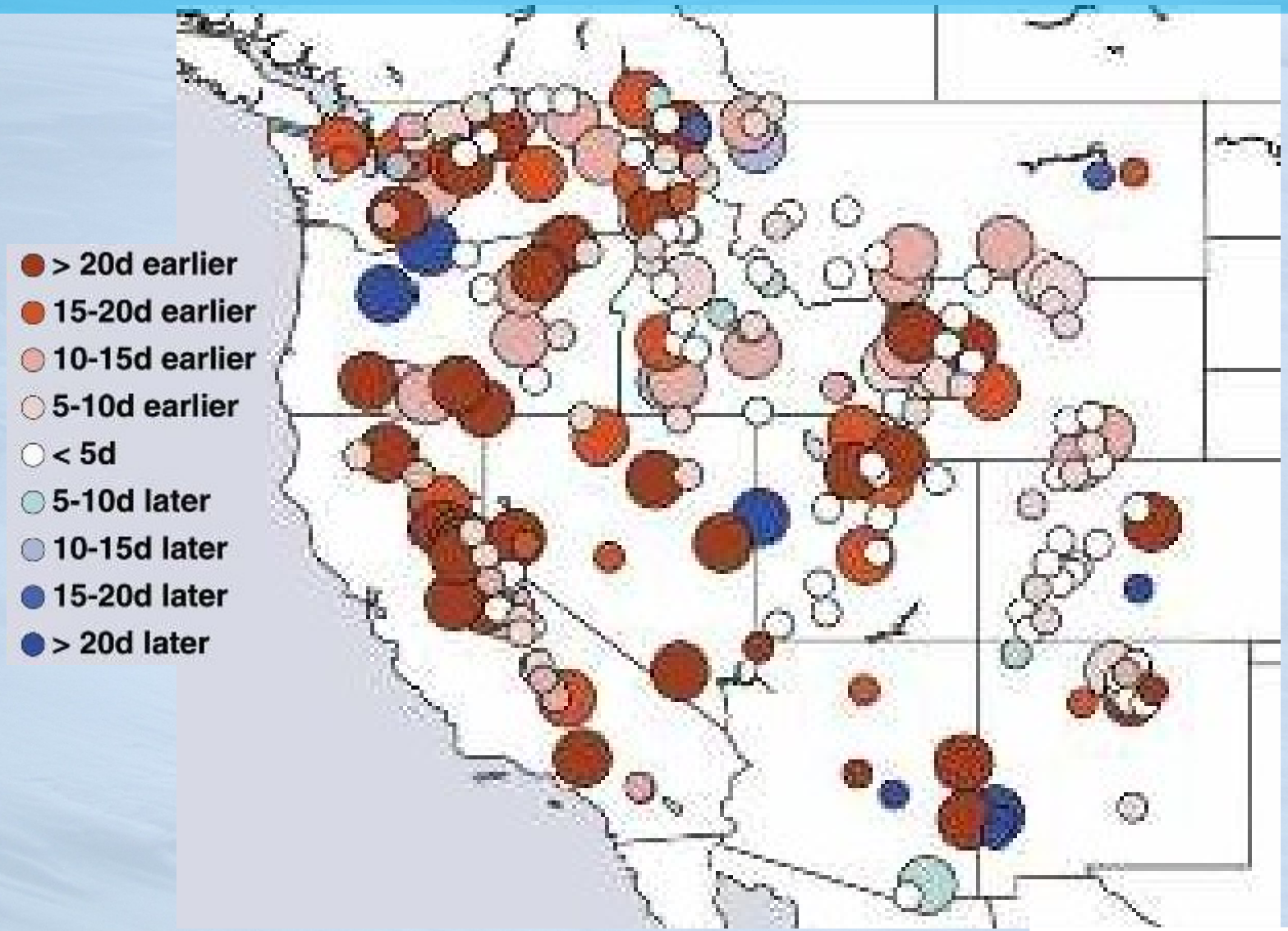
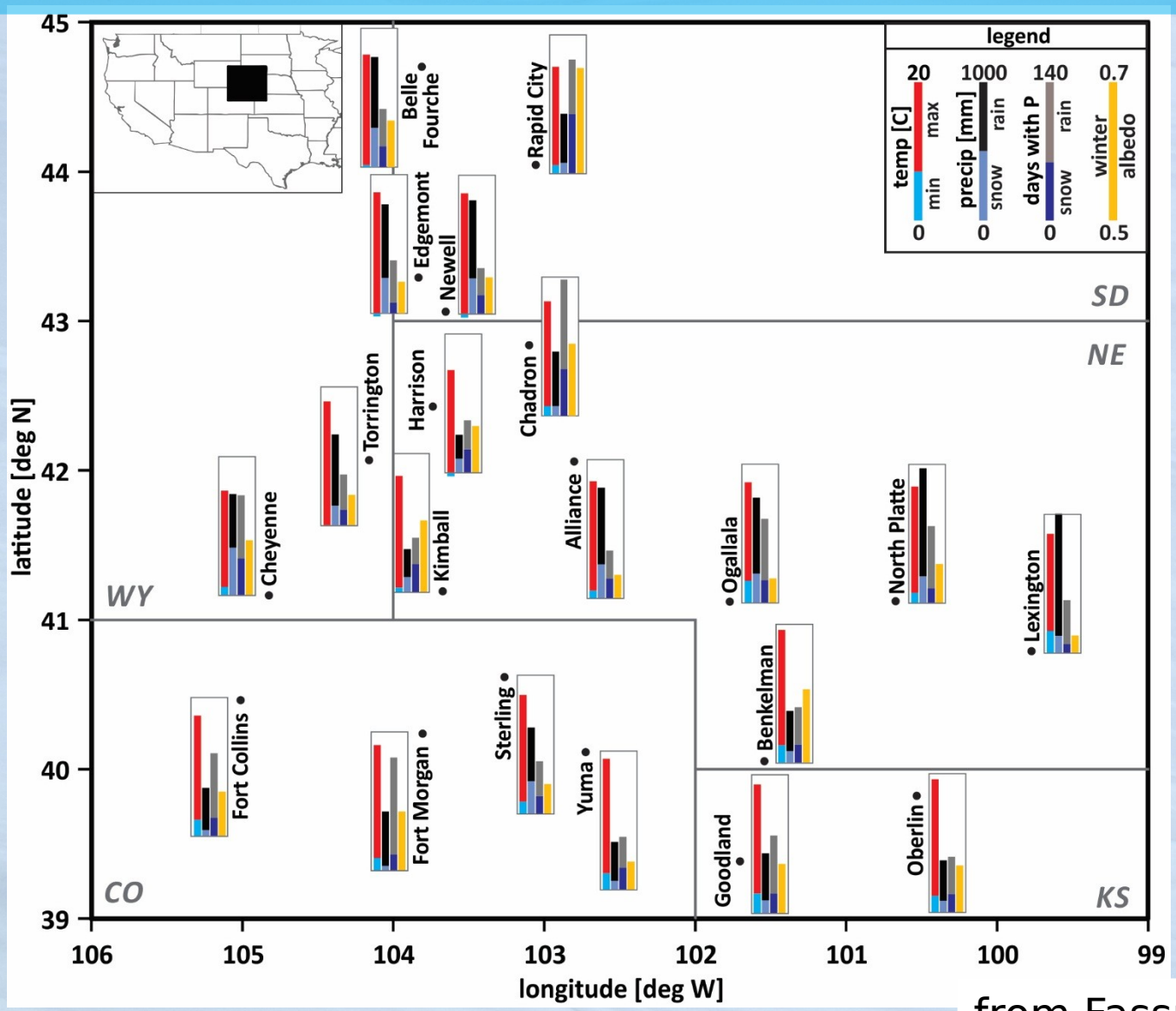


# Trends on Onset of Snowmelt Streamflow




from Stewart *et al.*, 200

# Case Study: Northern Great Plains




from Fassnacht *et al.*, 201

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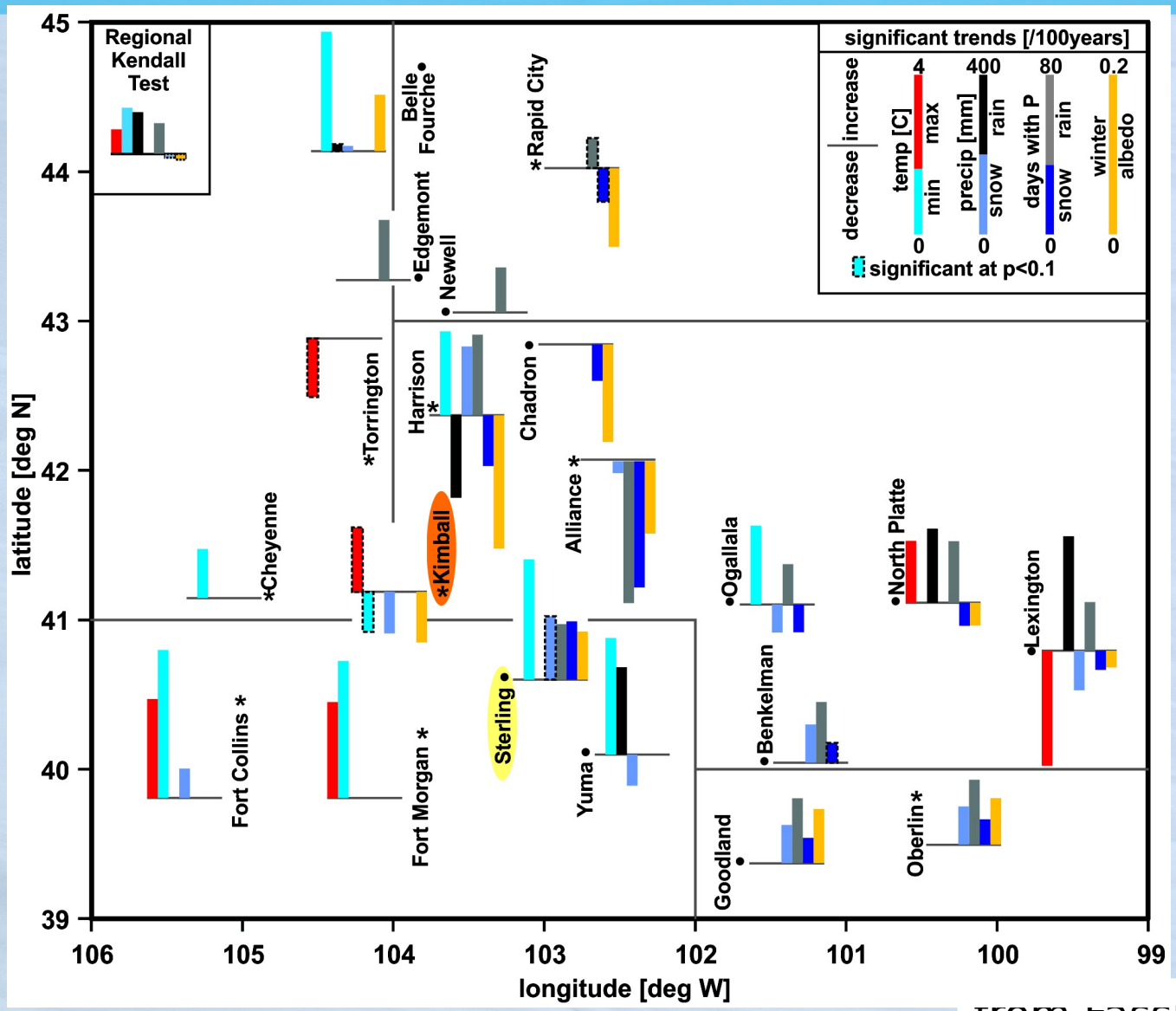
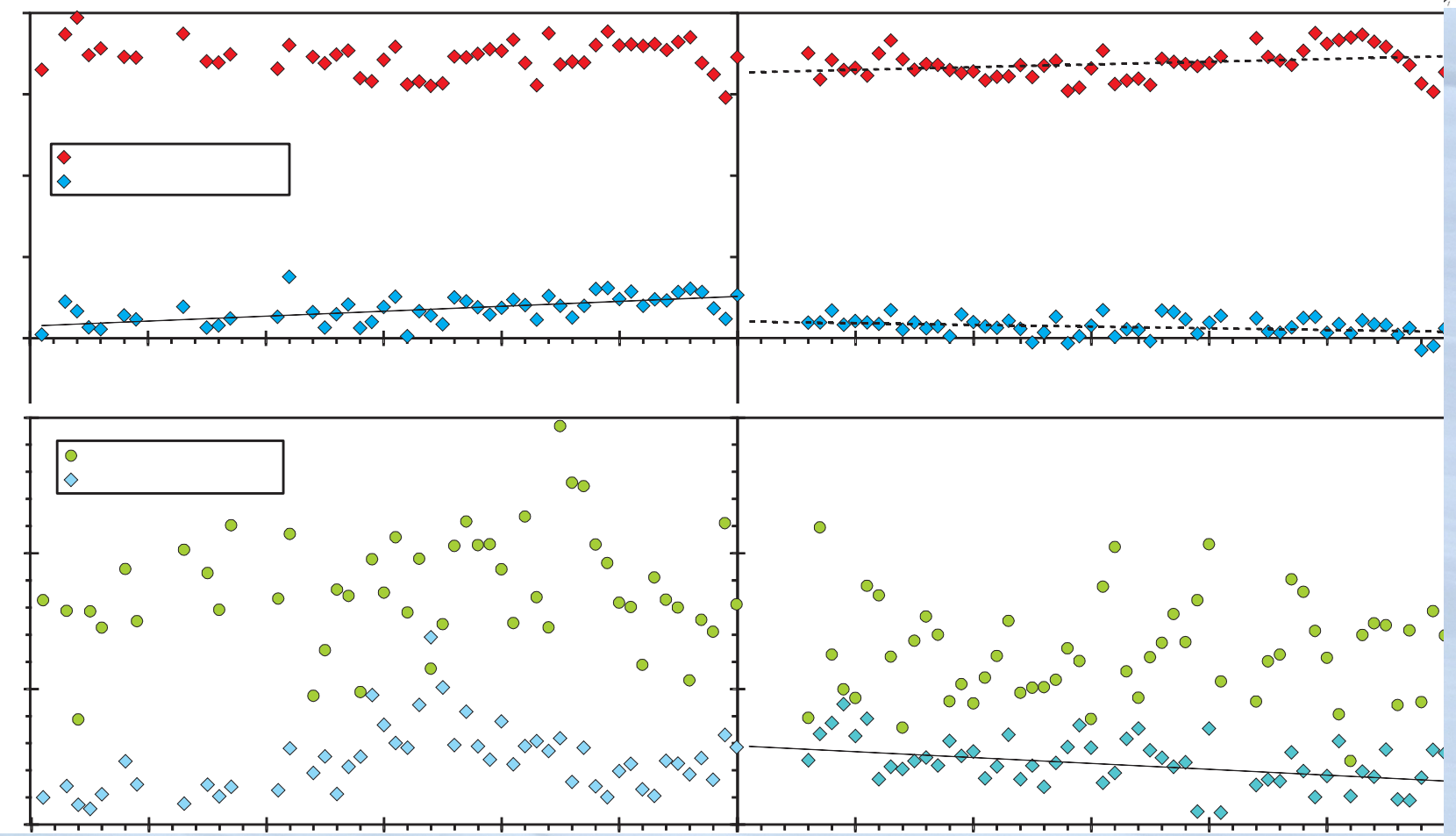



from Rassnacht *et al.*, 201

# Sterling CO vs. Kimball NE

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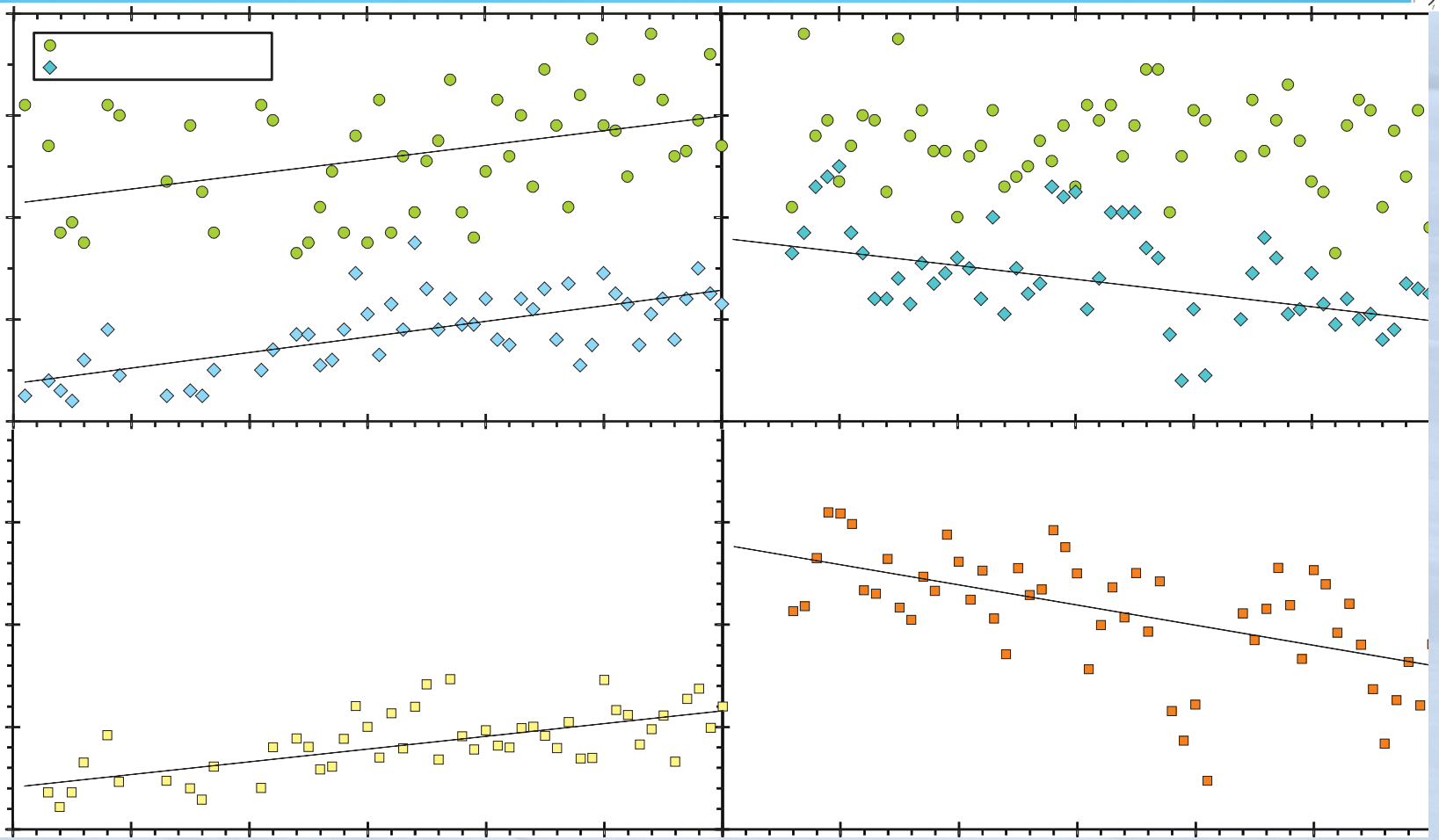


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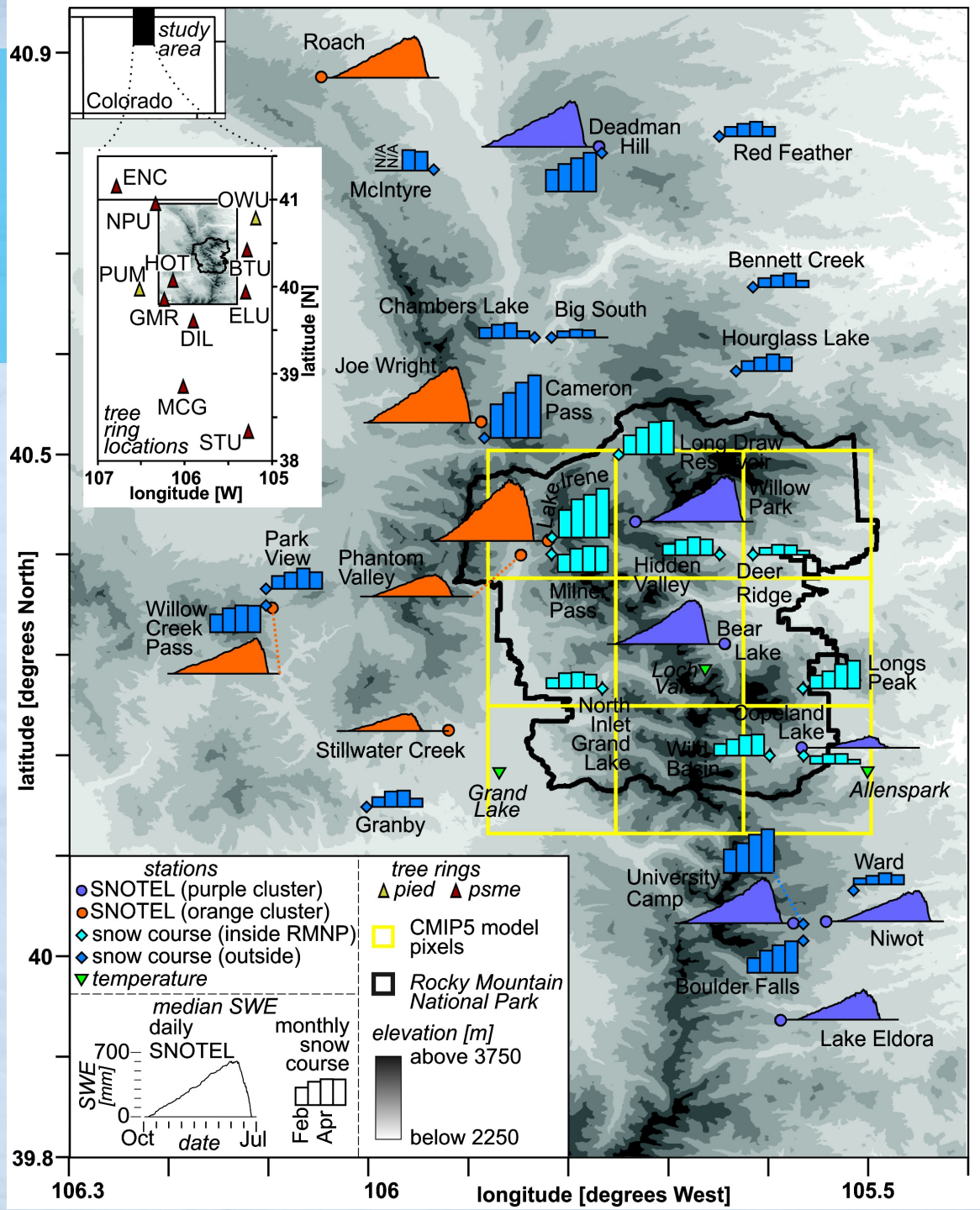

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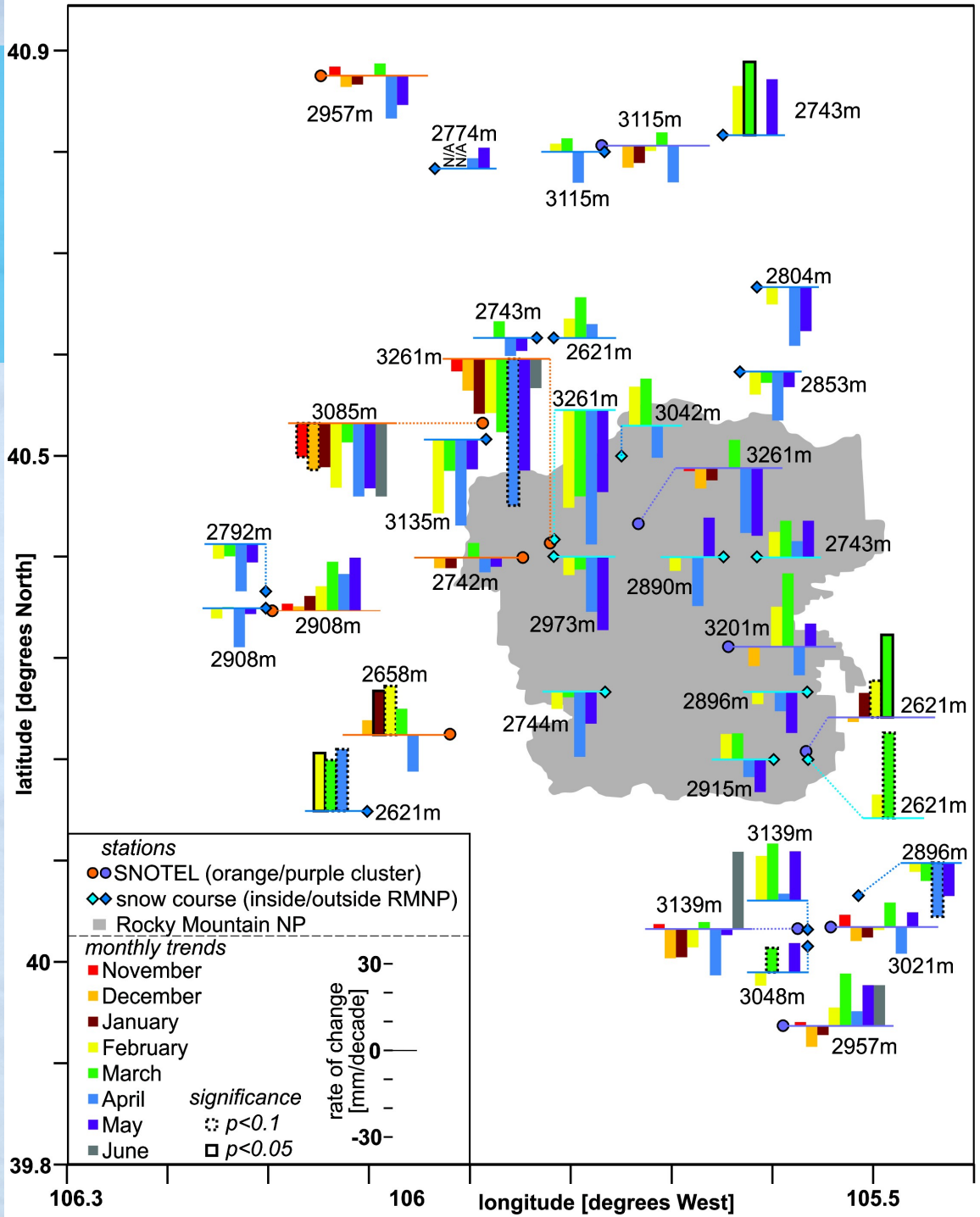

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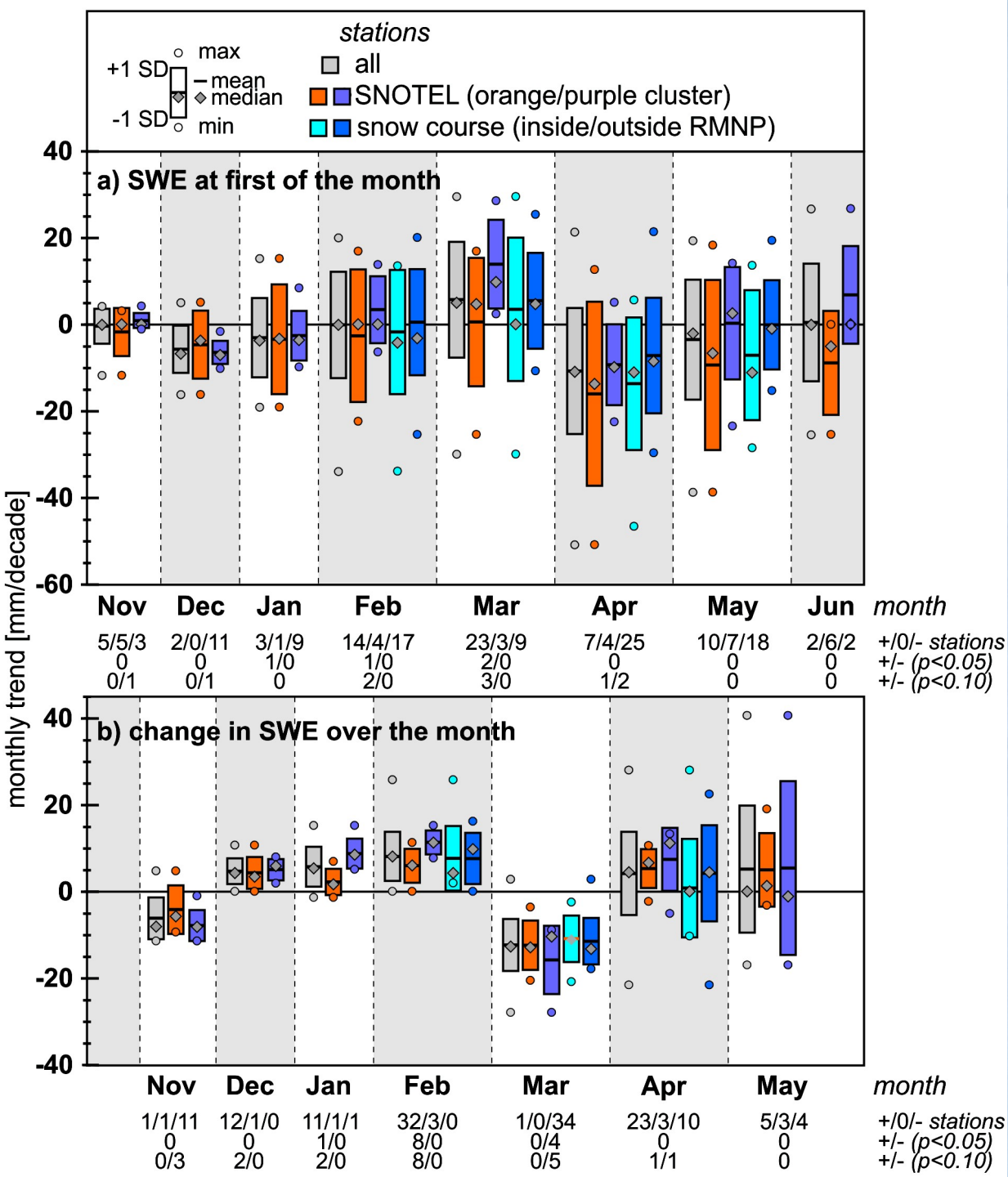


# Snow Course 75 ybp – looks same

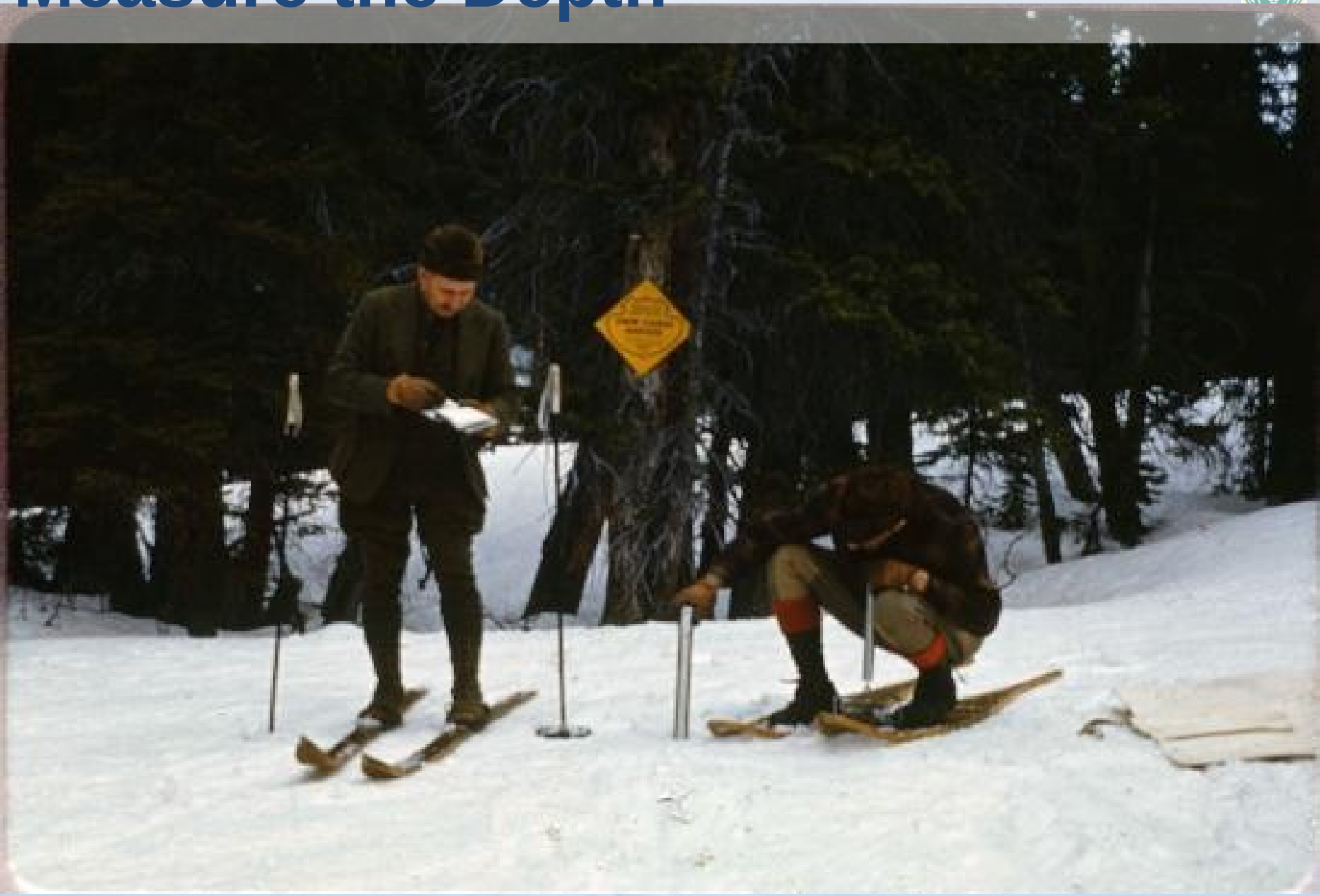
# Assemble the Sampler

Ralph Parshall & colleague , Cameron Pass 1

# Line up the Sampler

# Insert the Snow Sampler

# Measure the Depth



# Weight the Snow Core

# Go to Next Sampling Point

photos in CSU Water Archiv