Snow depth observations from Sentinel-1 over the Northern Hemisphere mountain ranges

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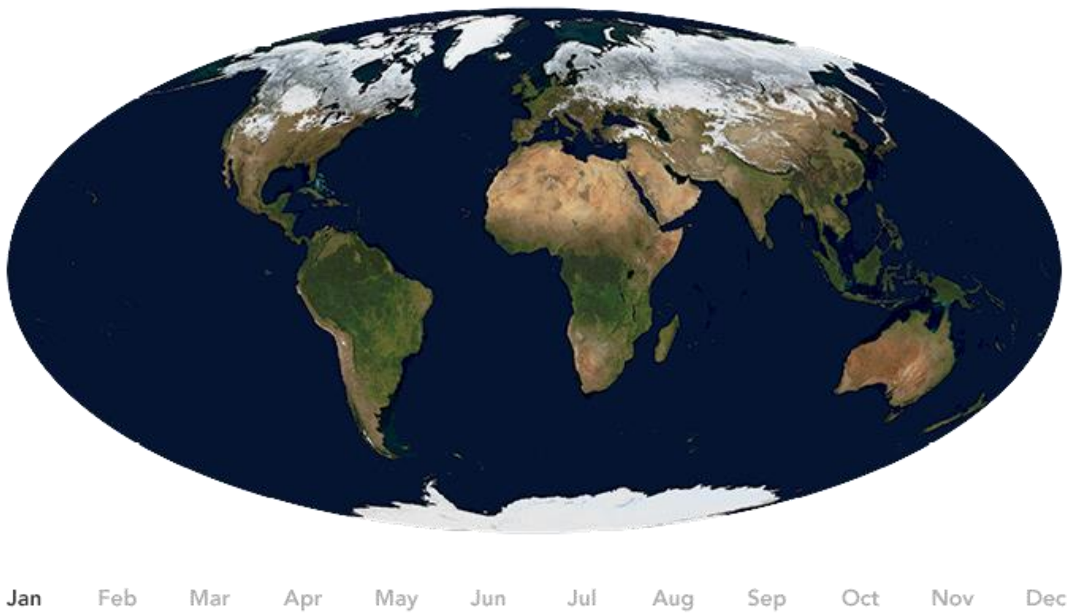
5 NASA
6 ECMWF
7 METEO FRANCE
8
9 SLF
10 ICIMOD
11 NVE
12 tiroler wasser kraft

The importance of snow

Snow covers ±20% of the Northern Hemisphere

Global cooling effect

- Reflects ±90% of incoming solar radiation, vegetation only 10-20%
- Reduces ground heat exchange with the atmosphere



Critical water resource

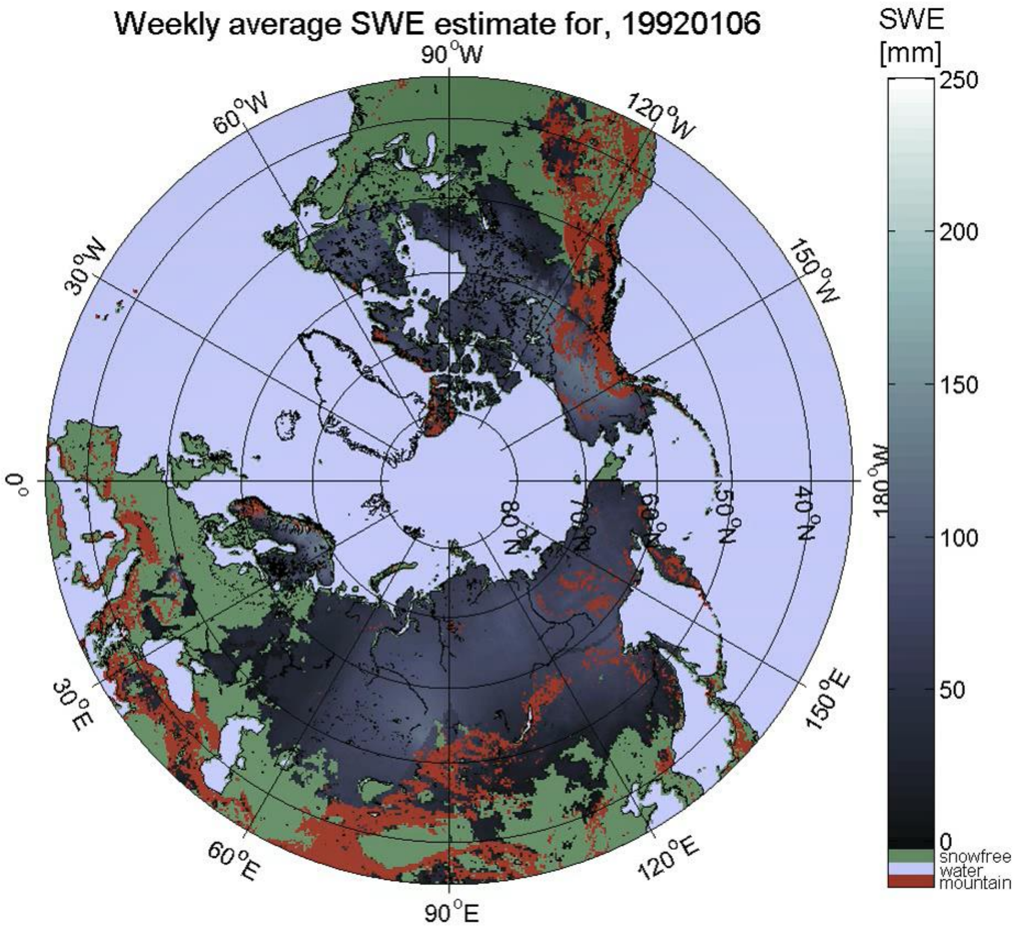
- Drinking water for >1 billion people
- 75% of the agricultural water use in western US
- Hydropower generation, industry, …

Flood and avalanche prediction, wildlife migration, tourism, …

Current snow depth estimates

- Measurements: sparse
- Models: poor snowfall
- Passive microwave: coarse
- Airborne observations: local

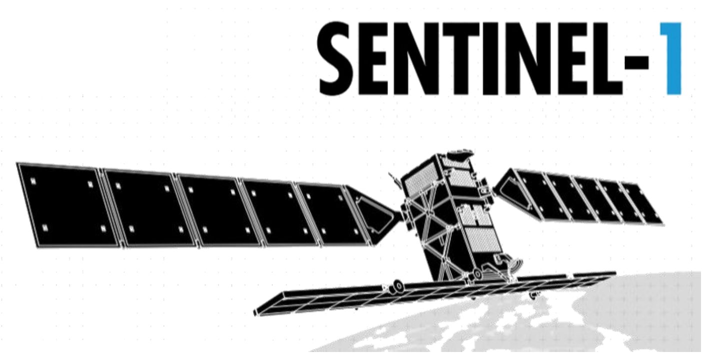
We lack basic understanding of how much snow we have on Earth, particularly in mountain areas



Current snow depth estimates

Active microwave remote sensing

- Preferred frequency (Ku-band) not in space
- Adequate satellite observations only in C-band (e.g. Sentinel-1)



2-satellites (1A & 1B)

5.4 GHz (C-band) radar

5 m x 20 m resolution

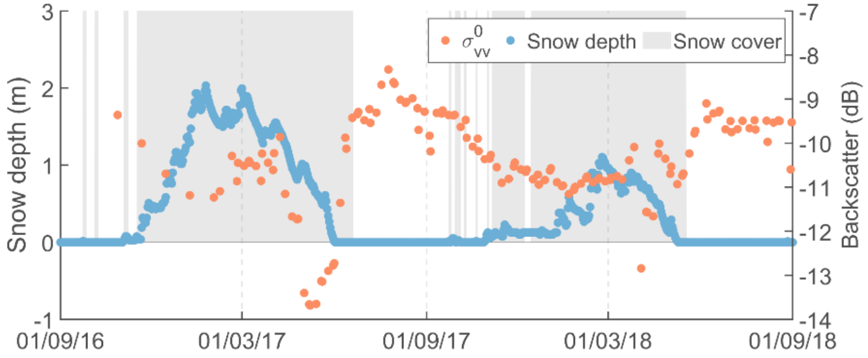
6-day repeat cycle

Long-term continuity

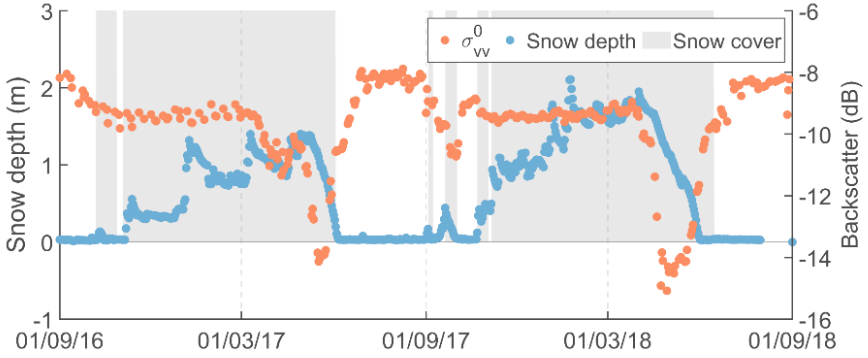
Sentinel-1 backscatter time series

σ^0_{vv} (dB)

San Juan Mountains, Colorado, USA
37.71°N, -107.51°E, 3535 m



European Alps, Austria
46.87°N, 10.71°E, 2464 m



Sentinel-1 snow depth algorithm

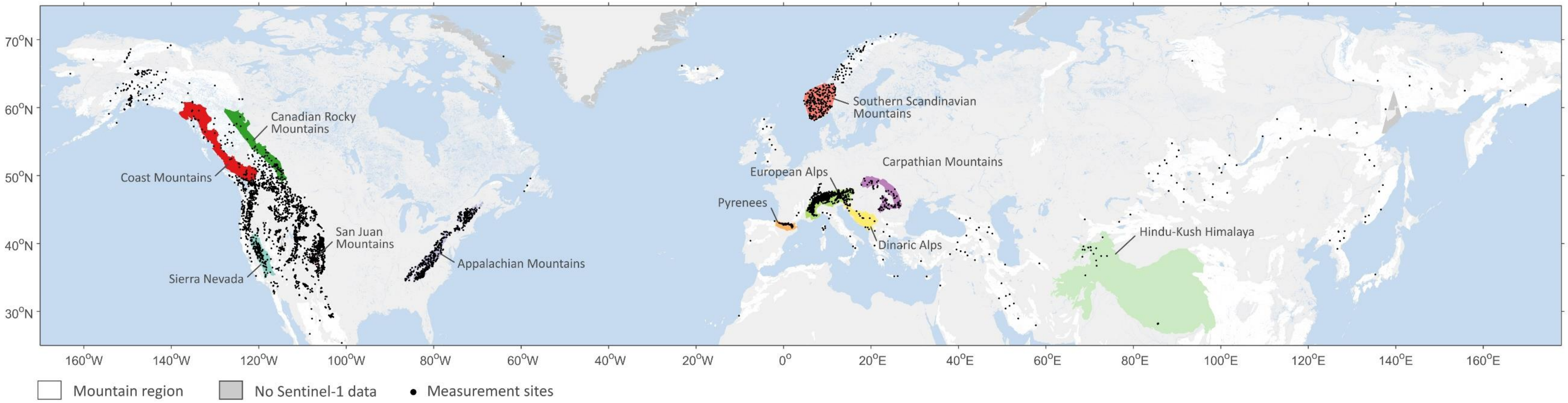
- Snow Depth (SD) = Snow Index (SI) × Scale Factor (SF) × Snow Presence (SP)

$\mathrm{SI}_t = \mathrm{SI}_{t-1} + \frac{\Delta\sigma^0}{\Delta t}$	Relate change in $\sigma^0{}_{vh}/\sigma^0{}_{vv}$ with snow accumulation/ablation
$\mathrm{SF} = \frac{a}{1-b\times\mathrm{FC}}$	Rescale to snow depth and correct forest (FC) attenuation
$\mathrm{SP(t)} = \{1, 0\}$	Mask with snow presence (1) or absence (0) from IMS

- Processing

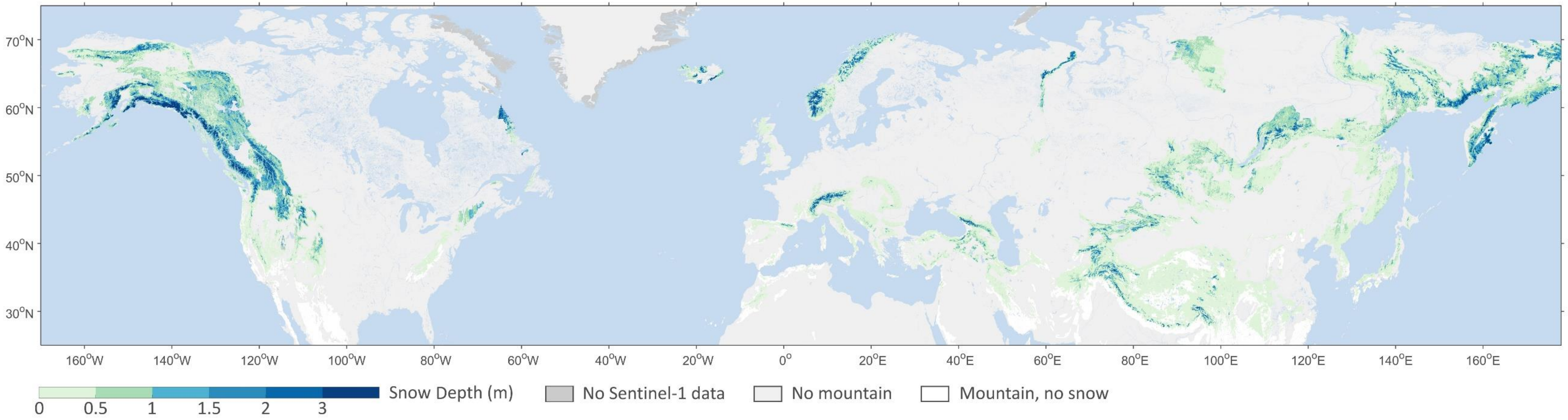
  - Sentinel-1 data: Google Earth Engine and HPC
  - Full archive over Northern Hemisphere (> 20°N), updated continuously
  - 1-km² spatial resolution and ~weekly temporal resolution
  - Automated with ~5 days latency

In situ measurements

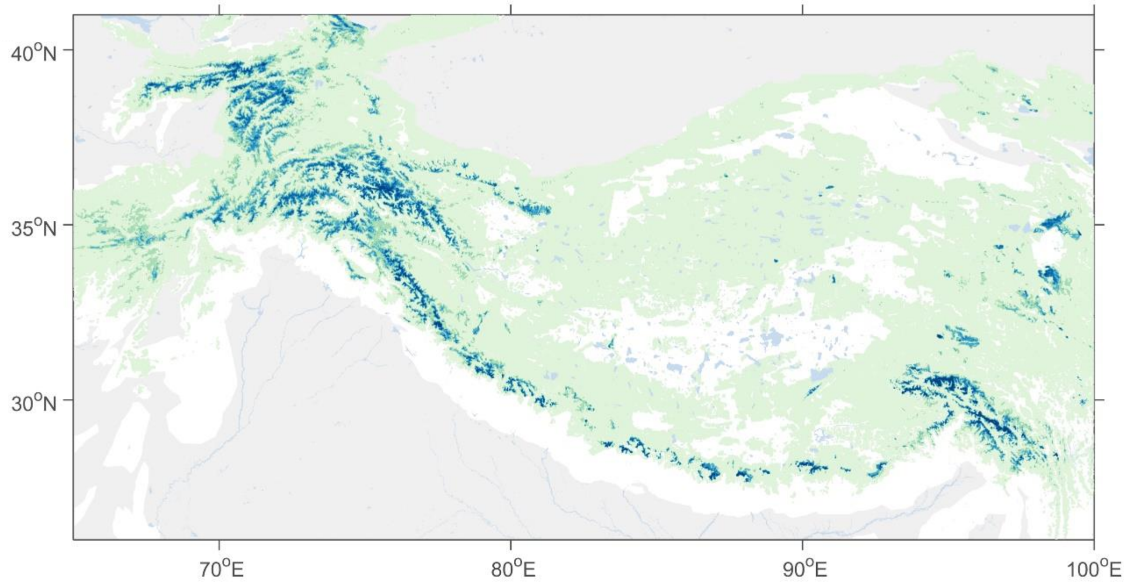


- Snow depth measurements (point-scale) in mountain areas for Sep 2016 – Aug 2018
- 4175 grid cells with validation data
  - Global networks from NOAA (GHCN-D) and ECMWF (SYNOP)
  - Regional networks over the US, Canada, Alps, Scandinavia, Himalaya, …

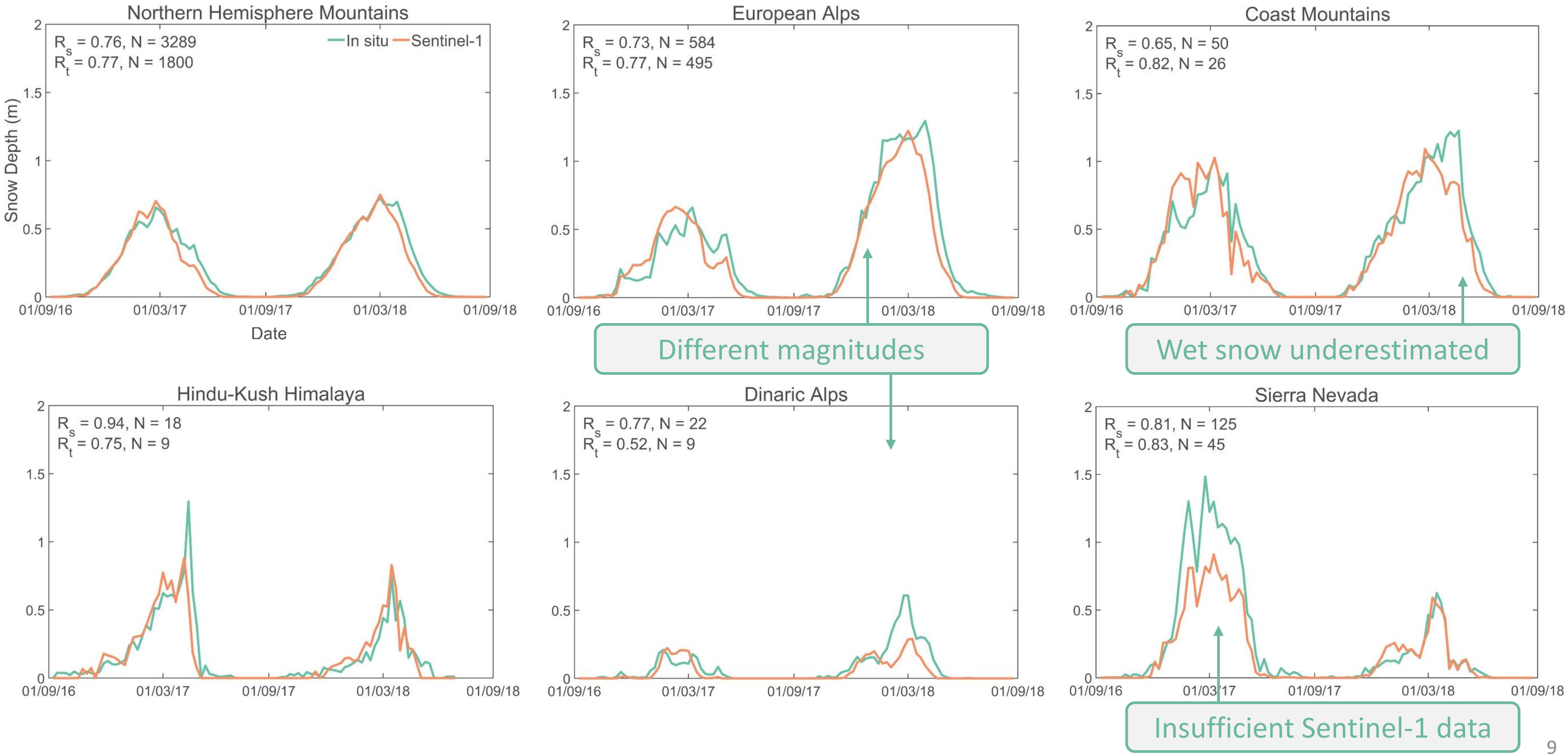
Sentinel-1 spatial validation



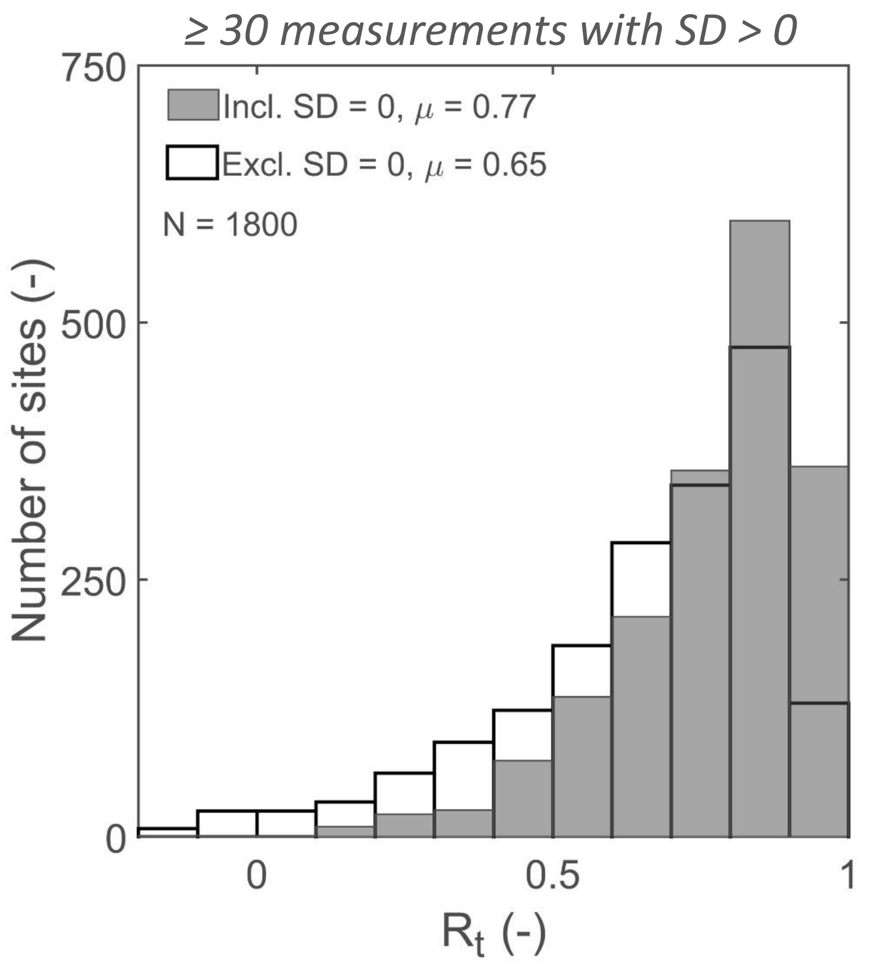
2018 Month	R_s overall	R_s between ranges	R_s within ranges
Dec	0.67	0.96	0.58
Jan	0.72	0.93	0.60
Feb	0.76	0.92	0.72
Mar	0.69	0.85	0.67
Apr	0.72	0.84	0.60

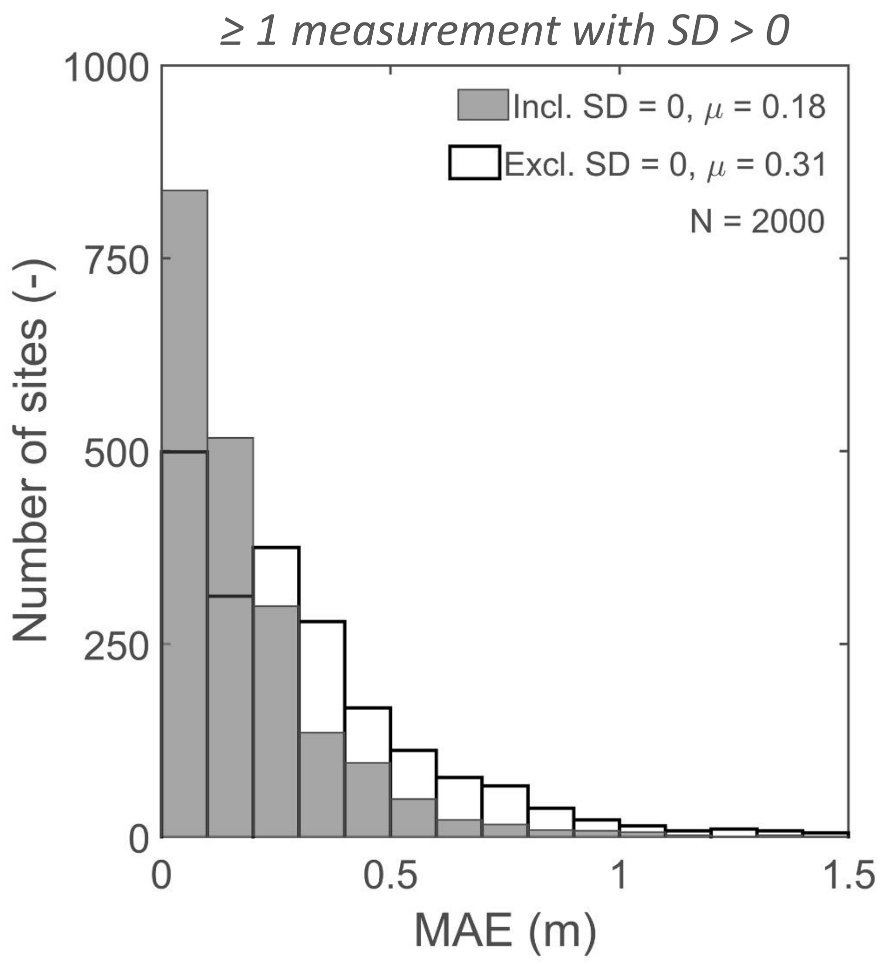


Sentinel-1 snow depth time series



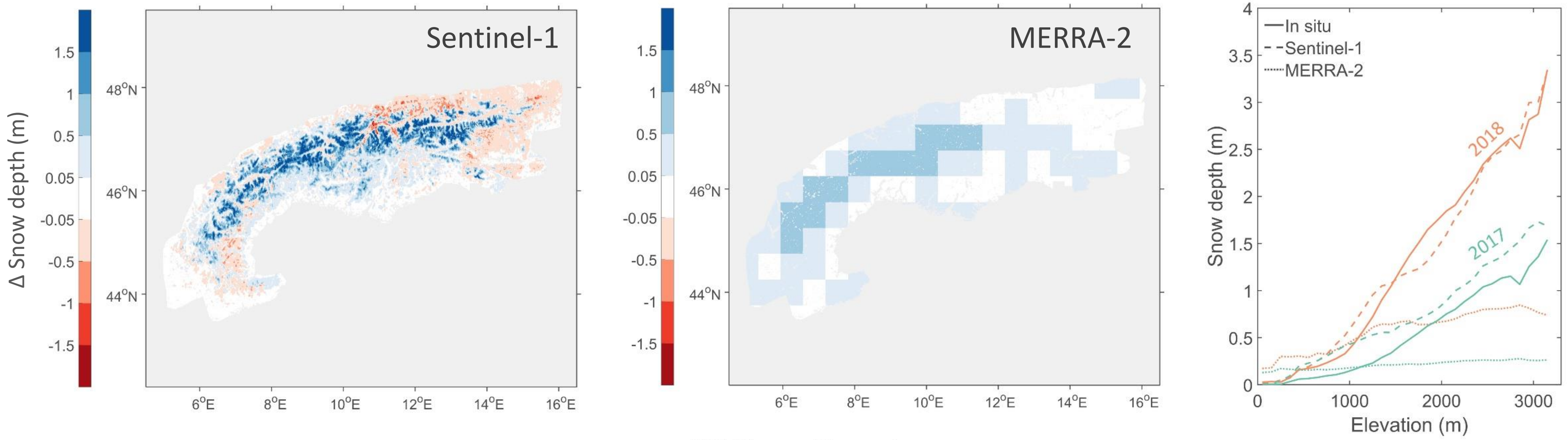
Snow depth time series validation



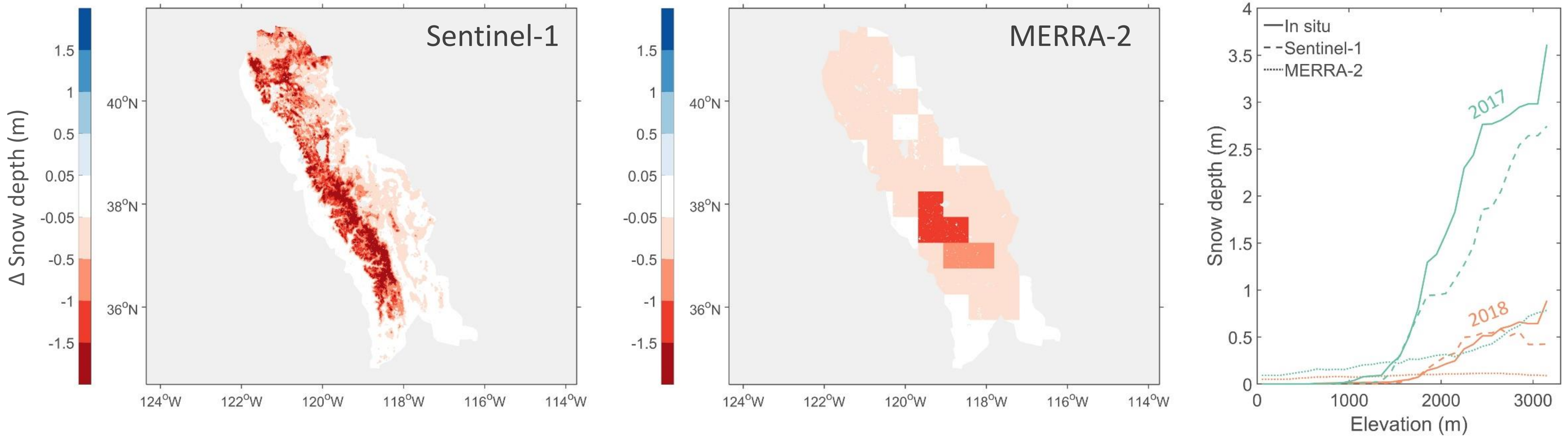


Inter-annual differences (Feb ‘18 – ’17)

European Alps

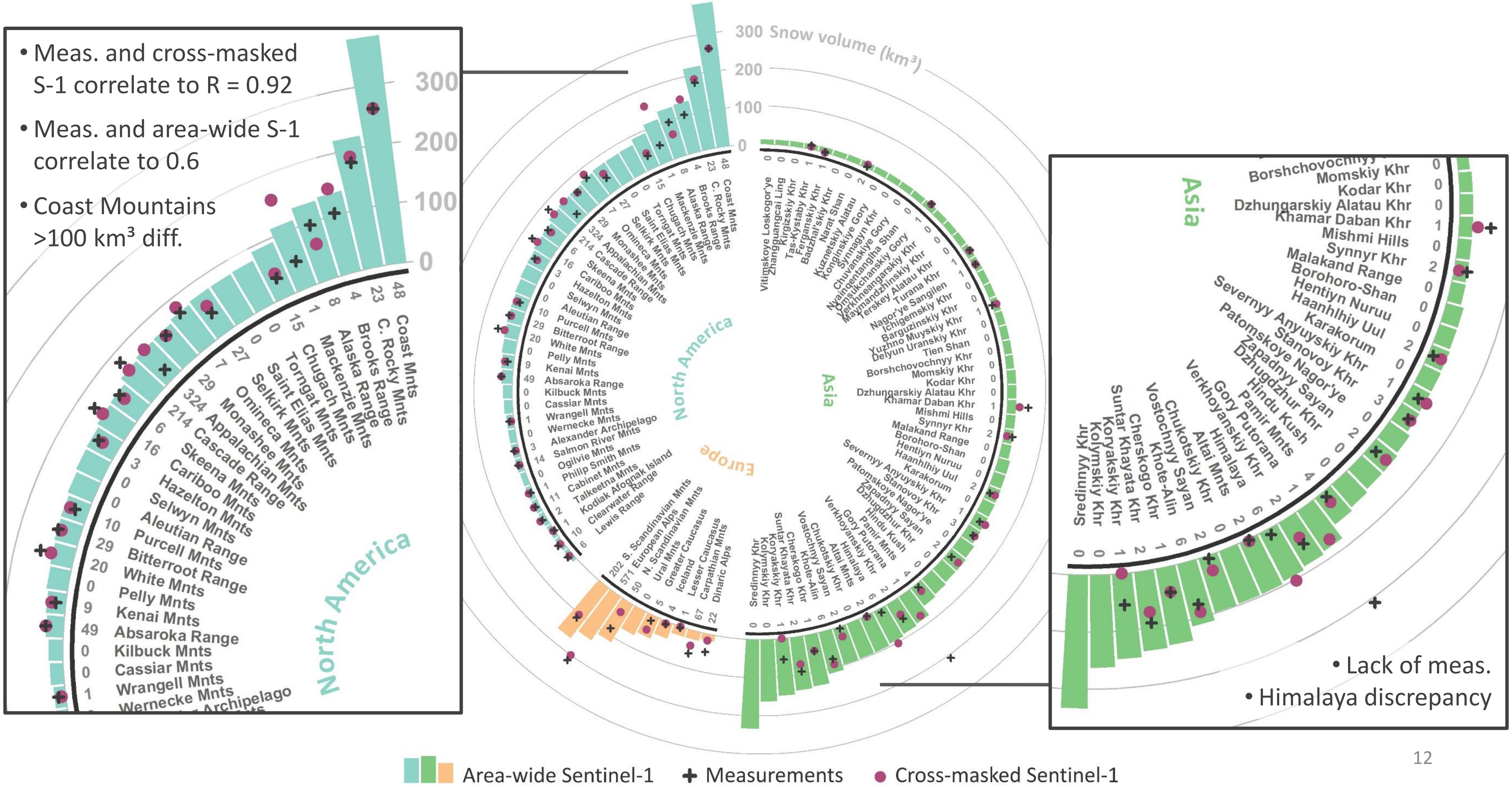


US Sierra Nevada



Top-100 mountain range snow volumes

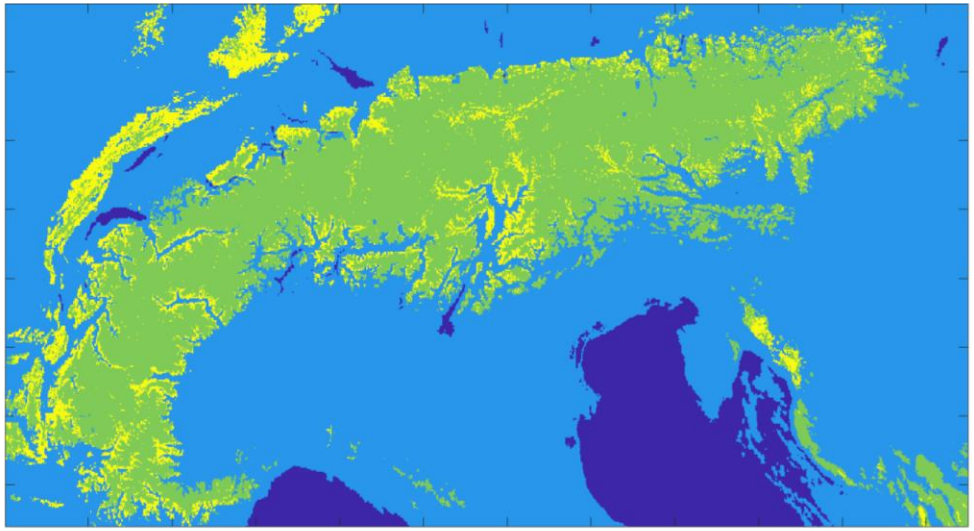
- Meas. and cross-masked S-1 correlate to R = 0.92
- Meas. and area-wide S-1 correlate to 0.6
- Coast Mountains >100 km³ diff.



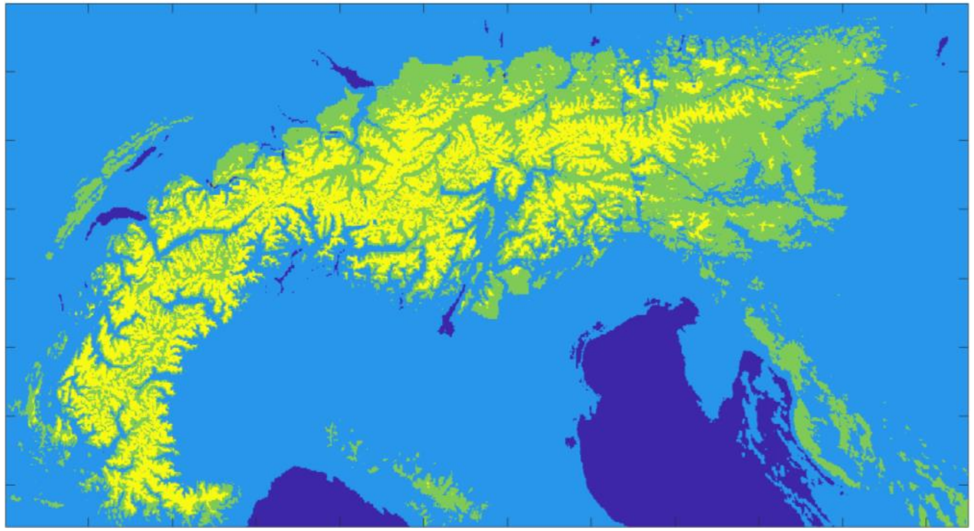
Ongoing activities

- Algorithm improvements
  - Detecting onset of snowmelt (+ masking of retrievals afterwards)
    - Wet snow causes strong absorption of radar signal: uncertain retrievals
    - Detection: $\Delta\sigma^0/\Delta t <$ threshold

February 1-7, 2018



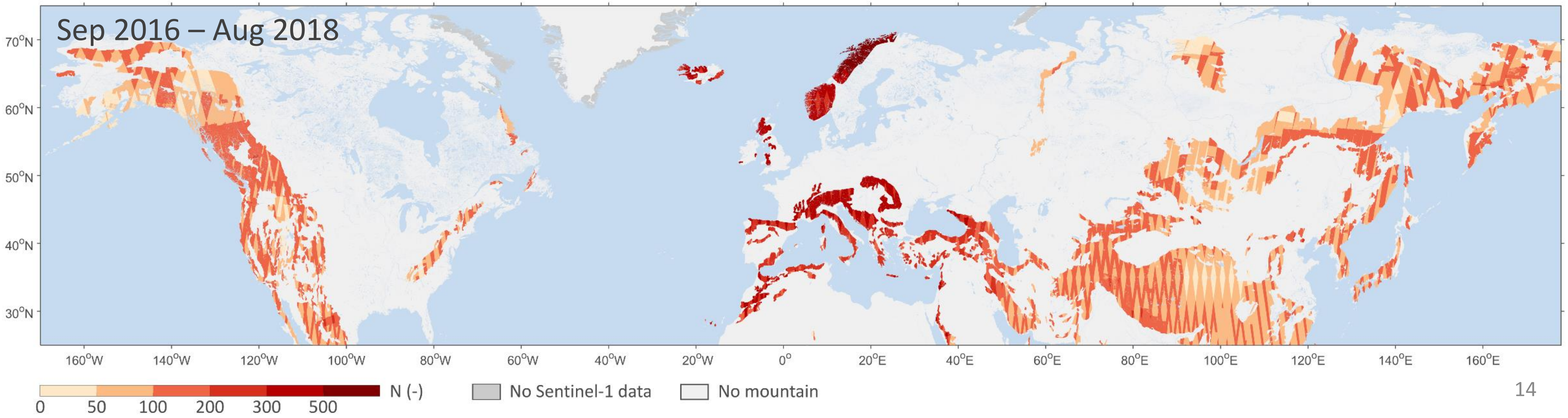
April 1-7, 2018



Snow absent | Snow present | Snowmelt

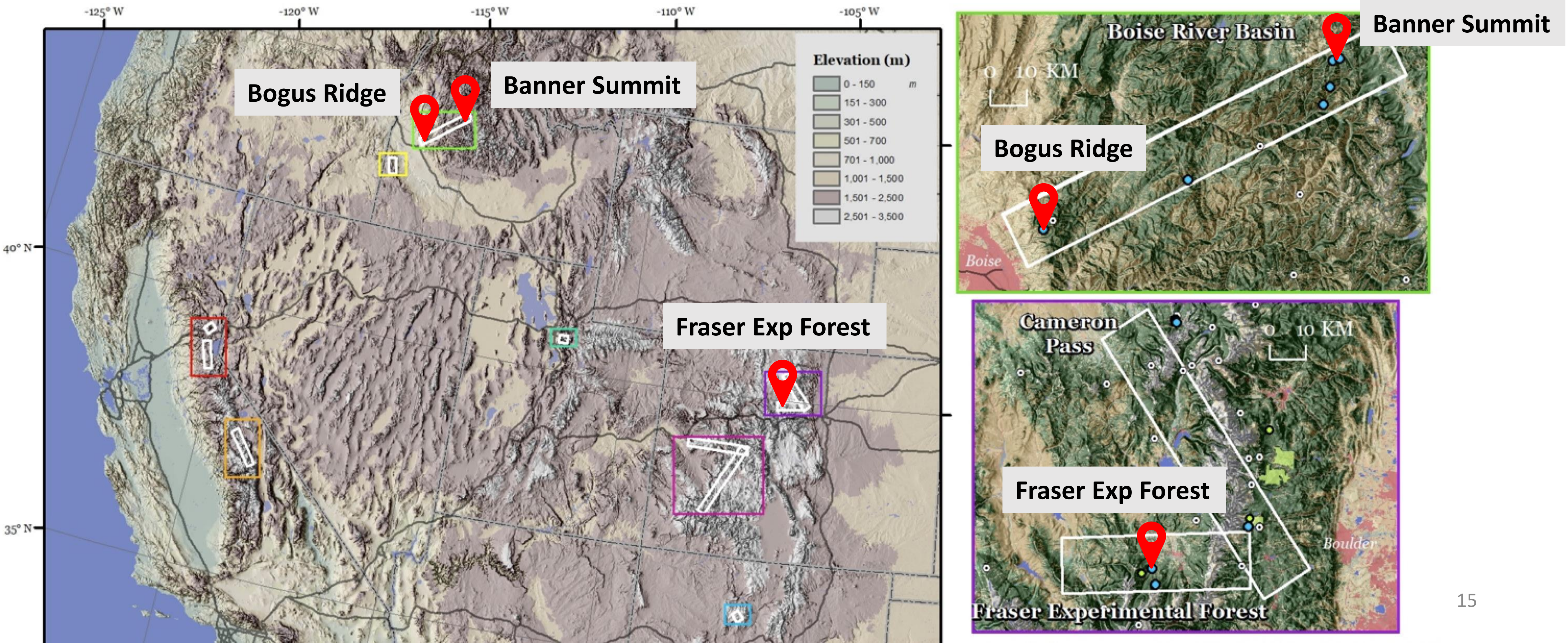
Ongoing activities

- Data assimilation
  - Sentinel-1 snow depth reader implemented in NASA LIS framework
  - Next: Impact of assimilating Sentinel-1 snow depth retrievals on model simulations of snow depth and SWE, discharge, other energy/water balance components
  - Challenges:
    - Bias between modelled and observed snow depth
    - N observations depends on location: unequal updates, unequal observation uncertainties



Ongoing activities

- Field campaigns
  - C-band quad-pol radars (3) deployed in Idaho and Colorado, USA (SnowEx sites)



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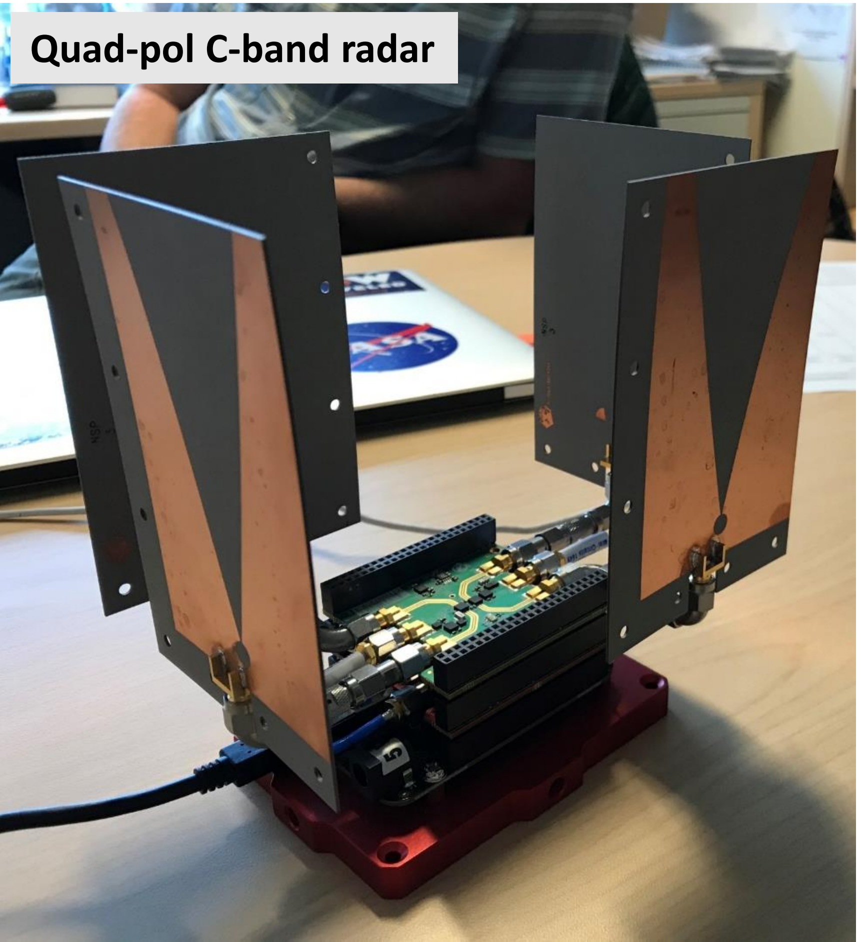

Ongoing activities

- Field campaigns
  - Continuous radar & snow measurements: improved understanding
    - Scattering mechanisms increasing C-band σ^0_{vh}
      - Volume scattering on anisotropic ice crystals?
      - Volume scattering on clusters of ice crystals?
      - Multi-scattering on snow layer interfaces?
      - Diffraction, forward scattering, ground reflection?
    - Scattering impacts from
      - Wet snow
      - Rain on snow
      - Ice lenses
      - Snow microstructure
      - Snow stratigraphy
      - Substrate and vegetation conditions

Conclusions

- First satellite-based snow depth observations in Northern Hemisphere mountains
  - 1-km^2 spatial and ~weekly temporal resolution
  - Reasonably accurate over space and time
  - Data available through https://ees.kuleuven.be/project/c-snow/
- Ongoing activities
  - Potential for data assimilation
  - Algorithm improvements
    - Wet snow detection
    - Field-campaigns with tower-based radar sensors in US Rocky Mountains
- More info
  - Lievens, H., Demuzere, M., Marshall, H.-P., Reichle, R.H., Brucker, L., Brangers, I., de Rosnay, P., Dumont, M., Girotto, M., Immerzeel, W.W., Jonas, T., Kim, E.J., Koch, I., Marty, C., Saloranta, T., Schöber J., and De Lannoy, G.J.M., Snow depth variability in the Northern Hemisphere mountains observed from space, *Nature Communications*, 10, 2019
  - Website: https://ees.kuleuven.be/project/c-snow/
  - Email: hans.lievens@kuleuven.be