Retrieving, validating, and assimilating fractional snow-covered area from emerging optical satellites for snow reanalysis

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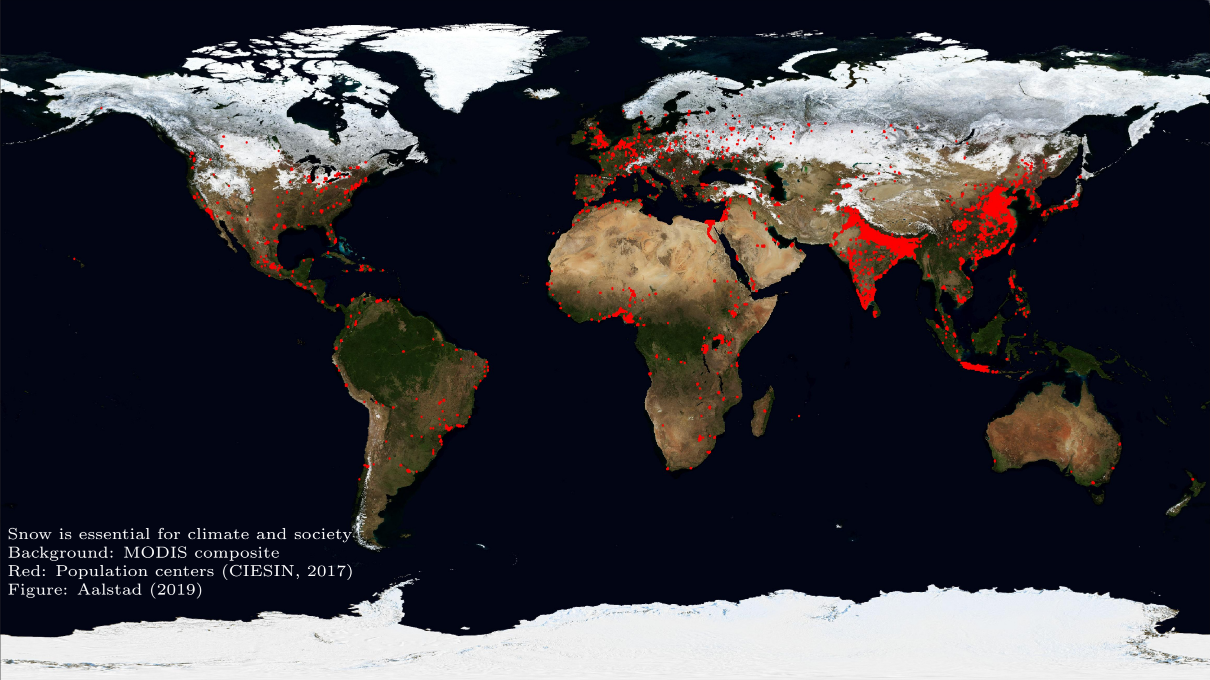
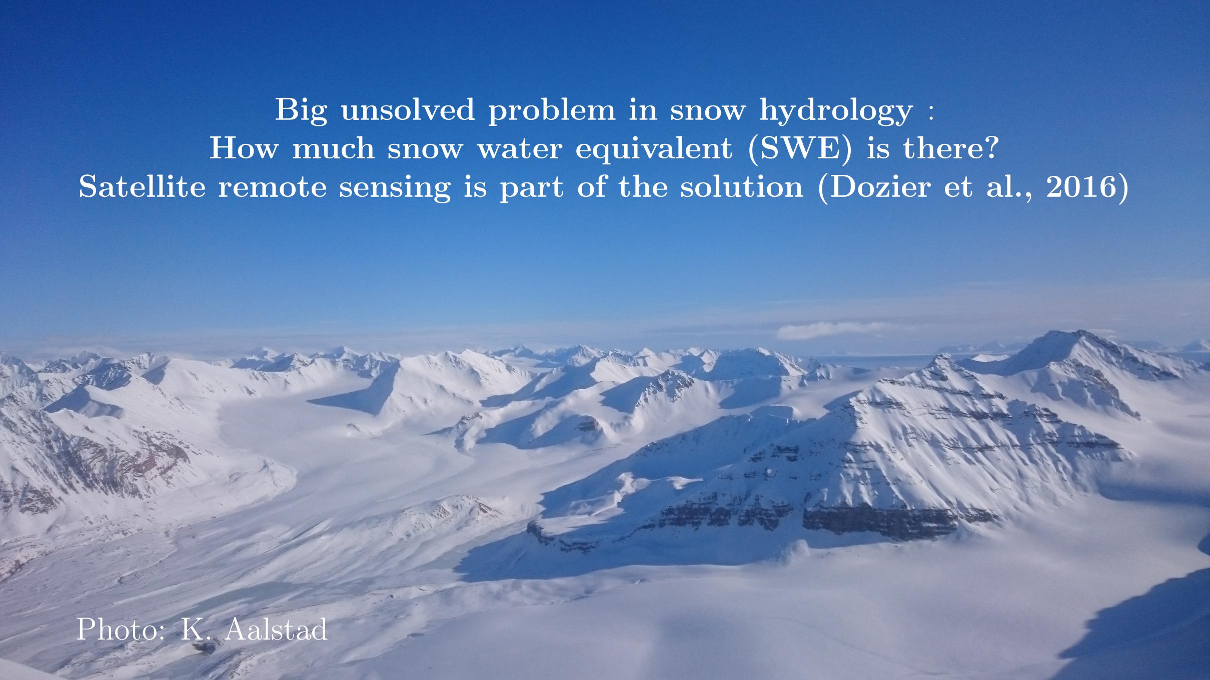

Snow is essential for climate and society
Background: MODIS composite
Red: Population centers (CIESIN, 2017)
Figure: Aalstad (2019)


Big unsolved problem in snow hydrology :
How much snow water equivalent (SWE) is there?
Satellite remote sensing is part of the solution (Dozier et al., 2016)
Photo: K. Aalstad

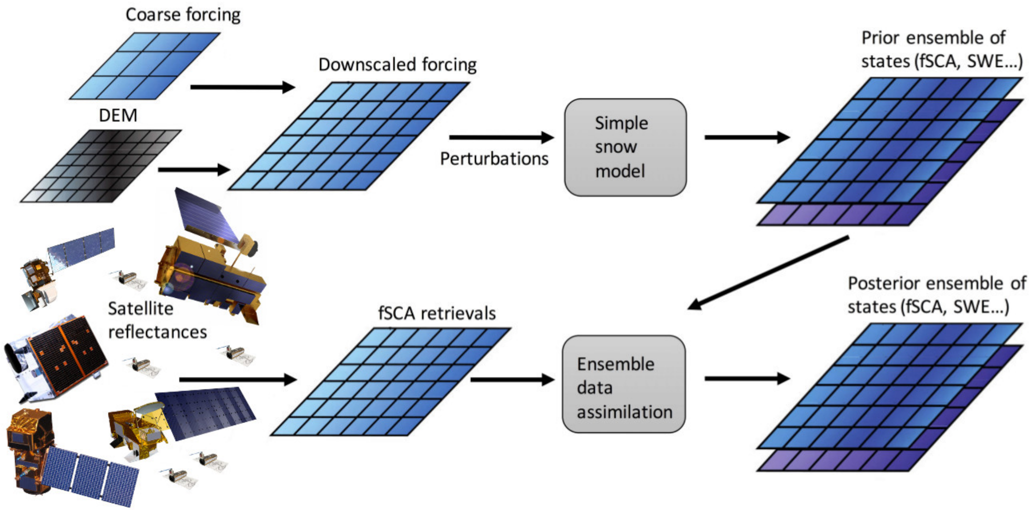


Figure: The ensemble-based snow reanalysis method (Durand et al., 2008; Aalstad et al., 2018; Fiddes et al., 2019; Aalstad, 2019), where we mainly use an iterative ensemble smoother (Emerick and Reynolds, 2013) (related to the ensemble Kalman filter) to solve a Bayesian inverse problem (Stuart, 2010).

Part I: Validating satellite retrieved fractional snow-covered area using a terrestrial automatic camera system (Aalstad et al., 2020)

Photo: K. Aalstad

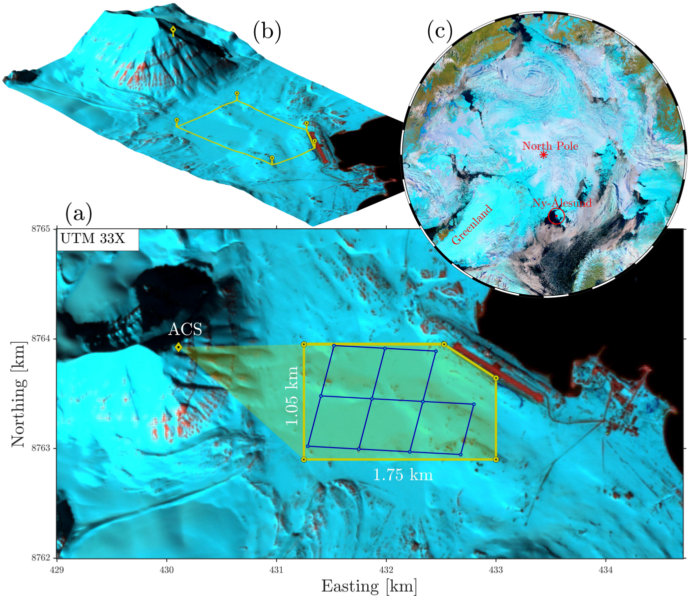


Figure: Panels **(a)&(b)**: Enhanced Sentinel-2 false color images showing the location of the camera (yellow diamond) on Scheteligfjellet and the relevant footprint (yellow polygon) at Bayelva near Ny-Ålesund.

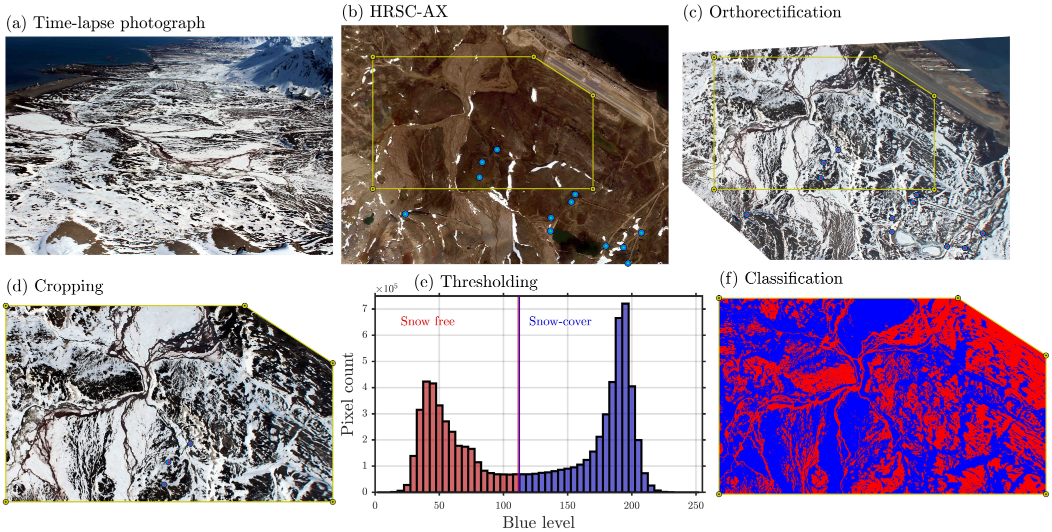


Figure: Workflow for generating daily high quality 0.5 m resolution reference snow-cover maps from a terrestrial automatic camera system.

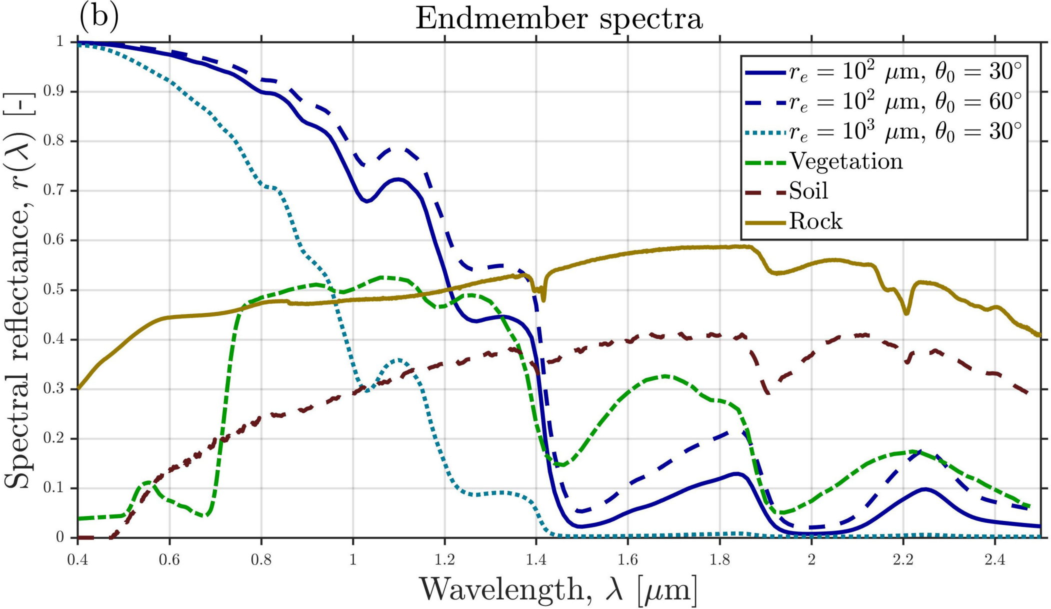


Figure: Reflectance spectra for snow (in blue, from the SNICAR radiative transfer model) and typical snow-free (from the JPL spectral library) surfaces at Bayelva.

S2B 11-Jun-2018 12:46:59Z

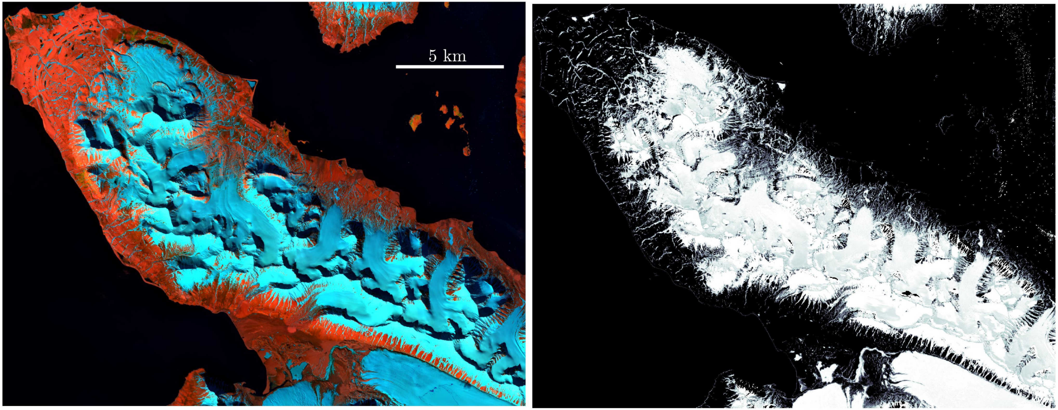


Figure: **Left**: Sentinel-2B MSI L2A false color (RGB=[SWIR1,NIR,R]) image of the Brøgger peninsula sensed 11.06.2018 at 12:46:59Z. Snow appears turquoise in this band combination. **Right**: Fractional snow-covered area (fSCA, white is 100% black is 0% fSCA) obtained through fully constrained linear spectral unmixing applied to the same scene.

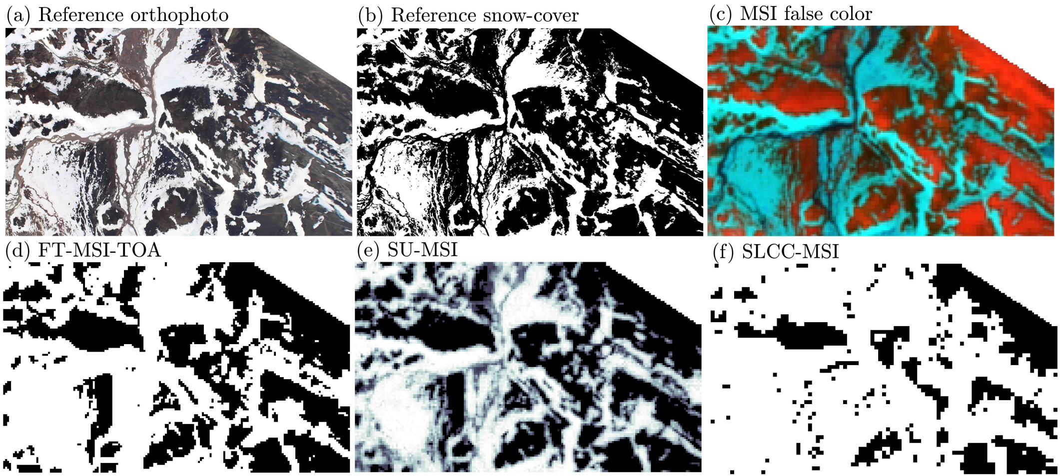


Figure: Different estimates of snow-covered area at Bayelva. **Top left**: Reference orthophoto (noon 21.06.2017) of the 2 km^2 AOI. **Top middle**: Binary snow-cover derived from the reference orthophoto (white is snow, black is bare). **Top right**: Sentinel-2 MSI false color image for the same day, snow is turquoise in this band combination. **Bottom left**: Binary snow-cover retrieved from MSI using a fixed threshold on the NDSI. **Middle right**: Fractional snow-covered area (fSCA, gray is partial) retrieved from MSI using spectral unmixing. **Bottom right**: Native scene land cover classification from MSI.

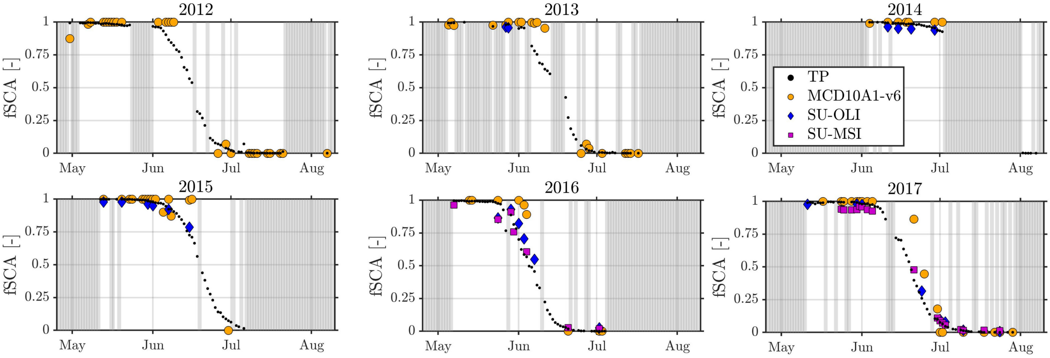


Figure: Depletion of fractional snow-covered area (fSCA) as retrieved from time-lapse photography (black dots) for 6 melt seasons at Bayelva. The available fSCA retrievals from satellites for days where camera images exist are shown for comparison: a merged MOD10A1/MYD10A1 (MODIS) product is shown as orange circles, Landsat spectral unmixing retrievals are shown as blue diamonds, and Sentinel-2 spectral unmixing retrievals are shown as purple squares. The camera malfunctioned during 2014.

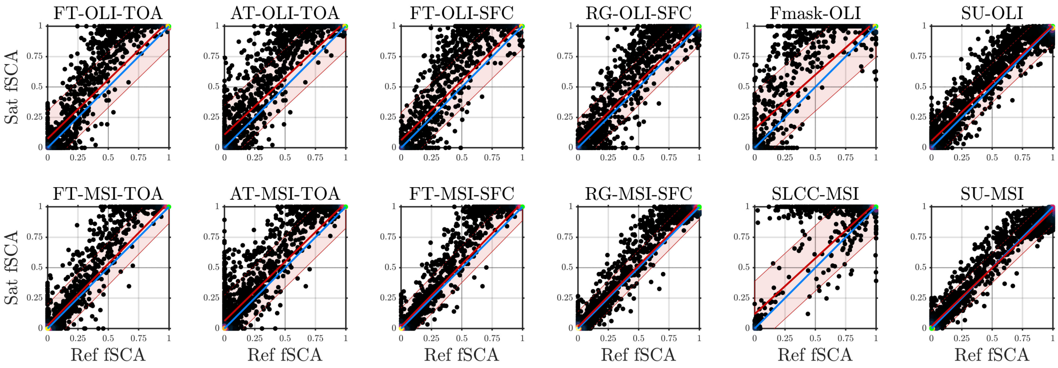


Figure: Evaluation of satellite retrieved fSCA at 100 m resolution; x-axis: reference fSCA from the terrestrial automatic camera system; y-axis satellite retrieved fSCA; blue line: identity (1:1) line; red line: linear best fit line with 95% prediction intervals in red shading. **Top**: Landsat 8 OLI retrievals. **Bottom**: Sentinel-2 MSI retrievals. **Key**: FT=fixed NDSI threshold, AT=adaptive NDSI threshold, TOA=top of the atmosphere reflectance, SFC=surface reflectance, Fmask=Landsat 8 native scene classification, SLCC=Sentinel-2 native scene classification, SU=spectral unmixing.

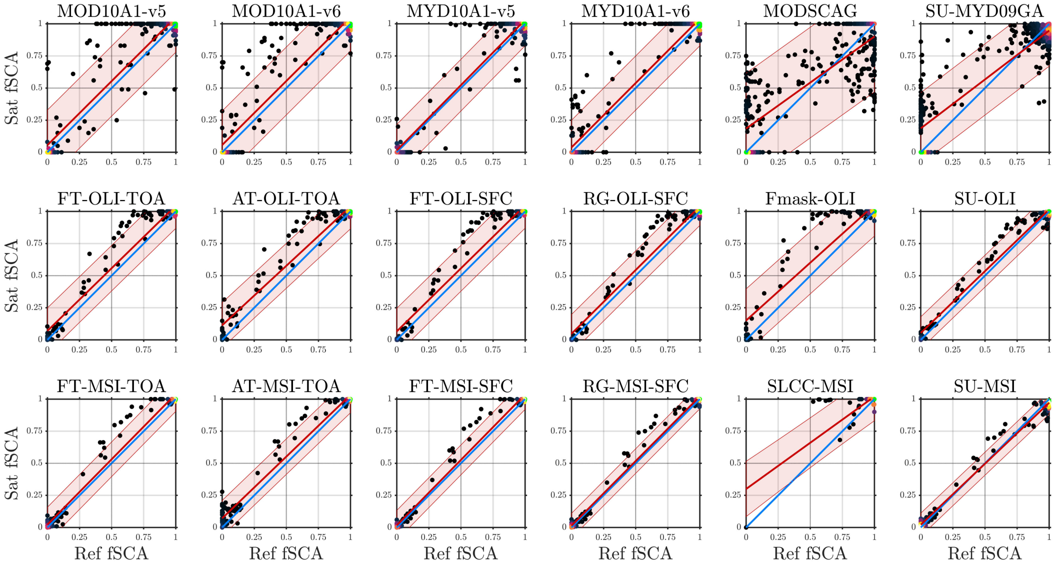


Figure: Evaluation of satellite retrieved fSCA at 500 m resolution. Top row shows MODIS retrievals.

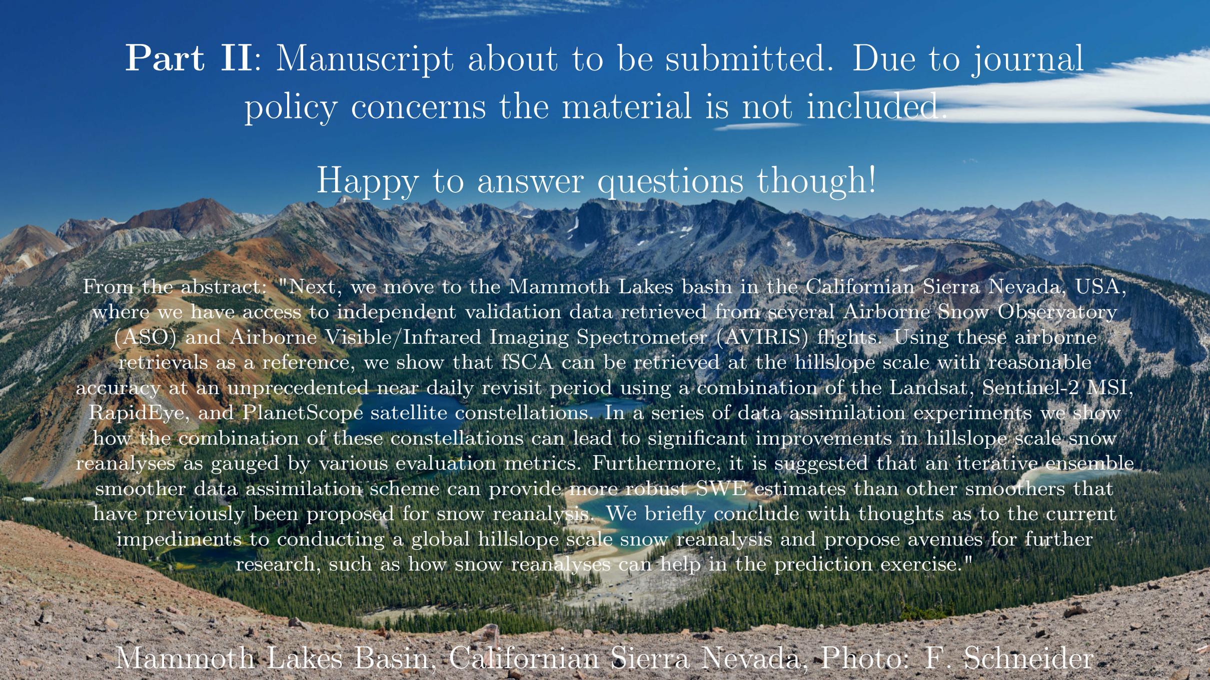
Main conclusions in Aalstad et al. (2020):

1. fSCA retrieved by spatially aggregating NDSI-derived binary snow-cover maps from Sentinel-2 MSI and Landsat 8 OLI is inherently biased due to the mixed pixel problem.
2. Spectral unmixing with the same sensors can explicitly account for this problem, leading to near unbiased estimates with lower error variance.
3. NDSI-regression based fSCA retrievals implicitly account for the mixed pixel problem and can thus provide satisfactory results.
4. The Fmask-OLI and SLCC-MSI native scene classifications overestimate both cloud and snow-cover.
5. Unsupervised adaptive NDSI threshold selection does not necessarily outperform a fixed threshold of 0.4.
6. Atmospheric correction has little impact on fSCA retrieved using NDSI thresholding and regression.

Part II: Manuscript about to be submitted. Due to journal policy concerns the material is not included.

Happy to answer questions though!

From the abstract: "Next, we move to the Mammoth Lakes basin in the Californian Sierra Nevada, USA, where we have access to independent validation data retrieved from several Airborne Snow Observatory (ASO) and Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) flights. Using these airborne retrievals as a reference, we show that fSCA can be retrieved at the hillslope scale with reasonable accuracy at an unprecedented near daily revisit period using a combination of the Landsat, Sentinel-2 MSI, RapidEye, and PlanetScope satellite constellations. In a series of data assimilation experiments we show how the combination of these constellations can lead to significant improvements in hillslope scale snow reanalyses as gauged by various evaluation metrics. Furthermore, it is suggested that an iterative ensemble smoother data assimilation scheme can provide more robust SWE estimates than other smoothers that have previously been proposed for snow reanalysis. We briefly conclude with thoughts as to the current impediments to conducting a global hillslope scale snow reanalysis and propose avenues for further research, such as how snow reanalyses can help in the prediction exercise."



Mammoth Lakes Basin, Californian Sierra Nevada, Photo: F. Schneider

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Thanks!