A Methodological Framework for Harmonized Comparison of Model-Based and Satellite-Derived Snow Cover Products in Data-Sparse Mountain Regions of Kyrgyzstan

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Abstract QR

This presentation participates in OSPP

Outstanding Student & PhD candidate Presentation contest

MOTIVATION

- ~1.9 billion people depend on High Mountain Asia water systems & >1/6 of global population relies on snowmelt.
- Kyrgyzstan's water resources are largely driven by seasonal snow and glacier melt & is highly climate-vulnerable.
- Accurate cryosphere monitoring is essential for water resources management and hydrological forecasting.

(Harpold et al., 2017; Huning & AghaKouchak, 2020; Qin et al., 2020; Wieder et al., 2022)

- Sparse uneven in-situ observations (declining since 1990s)
- Existing snow products differ in physics, mechanisms, inputs, resolutions and assumptions:

  Satellite products → cloud, terrain, spectral limitations
  Models → forcing, parameterization uncertainties

OBJECTIVES & POSTER SCOPE

The project evaluates three operational cryosphere monitoring tools (MODSNOW, SnowMapper and GlacierMapper) across Kyrgyzstan (2000–2024) with three objectives.

i. Inter-product agreement & divergence across seasonal, interannual and basin scales;
ii. Topographic dependence by assessing classification skill variation as a function of elevation, slope, aspect and glacierized terrains;
iii. Snow process representation by characterizing systematic discrepancies in snow persistence, melt timing, transitions and snowline altitude.

This poster focuses on the prerequisite methodology: The harmonization framework that makes the snow produces comparable to achieve objectives i-iii.

Snow Products

Attribute	MODSNOW *(Gafurov et al, 2016)*	SnowMapper *(Fiddes & Gruber, 2012)*	GlacierMapper *(Ragettli, 2025)*
Core Approach	MODIS Terra+Aqua; multi step cloud removal	FSM energy balance + ERA5/ECMWF + TopoPyScale downscaling	MODIS NDSI, decadal compositing in GEE
Output Variables	Daily binary snow cover + snow statistics	Continuous SWE, snow depth (Daily + 10 day forecast)	Decadal Fractional snow cover (FSC) + Snow Line Altitude (SLA)
Cloud Physics	8step cloud cover removal *(Gafurov & Bárdossy, 2009)*	Not needed	Temporal gap filling + compositing
Key Limitation	Cloud/ water body misclassification	High elevation negative bias; no glacier physics	10 day temporal coarsening
Spatial Resolution	500 m (0.0058926°)	500 m (0.0056534°)	500 m (0.0044916°)

Fundamentally different products ⟶ Need Harmonization before comparison

METHODOLOGICAL FRAMEWORK

1. Study Area Selection

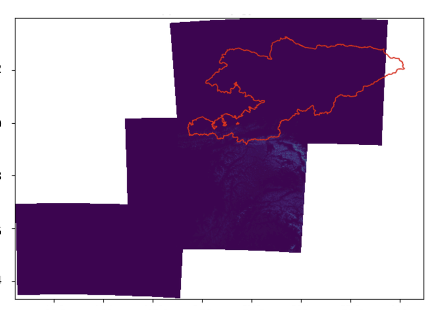


Fig 1. SnowMapper Spatial Coverage

Missing Eastermost part of Kyrgyzstan

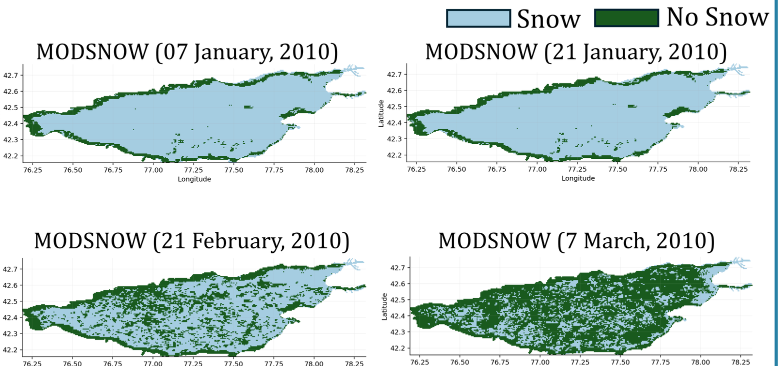


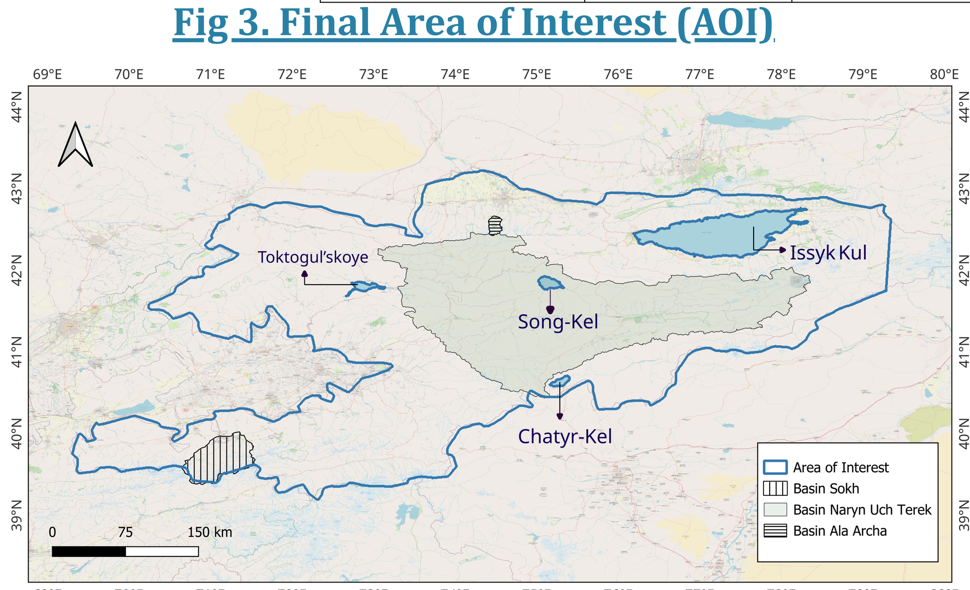
Fig 2. MODSNOW Misclassification over Lake Issyk-Kul

Lake Issyk-Kul remains largely ice-free in winter, so detected snow cover indicates misclassification *(Benson et al., 2012; Peeters et al., 2003).*

Table 1. Major inland water bodies excluded

Lake Names	Lake Area (sqkm)	Lake Names	Lake Area (sqkm)
Issyk Kul	6195	Toktogul'skoye	223.44
Song Kel	274.73	Chatyr-Kel	151.84

Fig 3. Final Area of Interest (AOI)



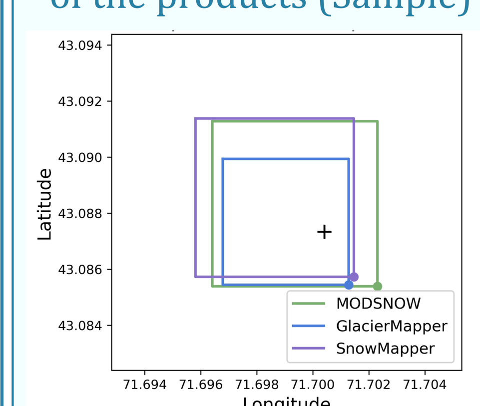
Three basins were selected to capture contrasting hydro-climatic and topographic conditions:

- **Ala Archa ($273\ km^2$)**
- **Naryn–Uch-Terek ($46{,}734\ km^2$)**
- **Sokh ($5{,}292\ km^2$)**

2. Data Harmonization

Spatial co-registration

Fig 4. Native Grid Footprints of the products (Sample)



Independent Grid Creation
(0.005653°)

Nearest Neighbor Resampling

Preserves discrete categorial values, Minimizes changes to pixel values
(Qiao et al., 2022; Cui et al., 2023; Dawson et al., 2018; Nkiaka et al., 2022; Wu et al., 2022)

Resampled NetCDF

Variable Transformation (SnowMapper SWE → Binary)

Randomized dates - SWE (Oct-May) → Candidate threshold values *T(m,m) = {1,3,5,10,20,50}* *(Brown et al., 2010; Dawson et al., 2018; Hofmeister et al., 2022; Ray et al., 2017)*

$$\text{Snow}(i,j) = \begin{cases} 1, \text{ if } SWE(i,j) \geq T \\ 0, \text{ if } SWE(i,j) \leq T \end{cases}$$

Confusion Matrix	MODSNOW snow	MODSNOW no snow
SnowMapper snow	True positive	False Positive
SnowMapper no snow	False Negative	True Negative

Precision, Recall, F1 score, Balanced Accuracy, Mattews Correlation Coefficient (MCC) | FSCA

1 mm SWE (~1cm snow depth) identified as optimal threshold & applied to full record

Performance Evaluation

Fig 5. F1-score across multiple thresholds

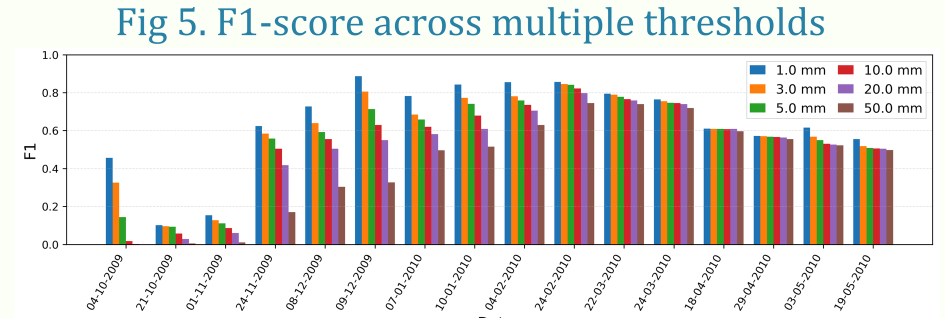
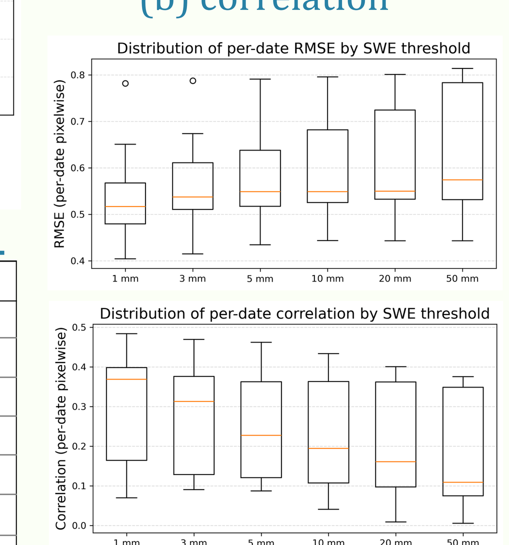


Table 2. Overall FSCA and Classification metrics

SWE Threshold (mm)	F1	BA	MCC	FSCA		
				Mean Bias (%)	RMSE (%)	Corr.
1	0.72	0.72	0.43	-9.47	20.56	0.75
3	0.67	0.69	0.38	-15.63	24.42	0.71
5	0.65	0.68	0.36	-18.34	26.7	0.68
10	0.62	0.66	0.33	-21.3	29.7	0.63
20	0.58	0.64	0.3	-24.15	33	0.55
50	0.5	0.61	0.25	-30.09	40.19	0.34

Fig 6. FSCA error metrics (a) RMSE & (b) correlation



Temporal Alignment

MODSNOW & SnowMapper →≥5 Valid days ← Reference Calendar (GlacierMapper)

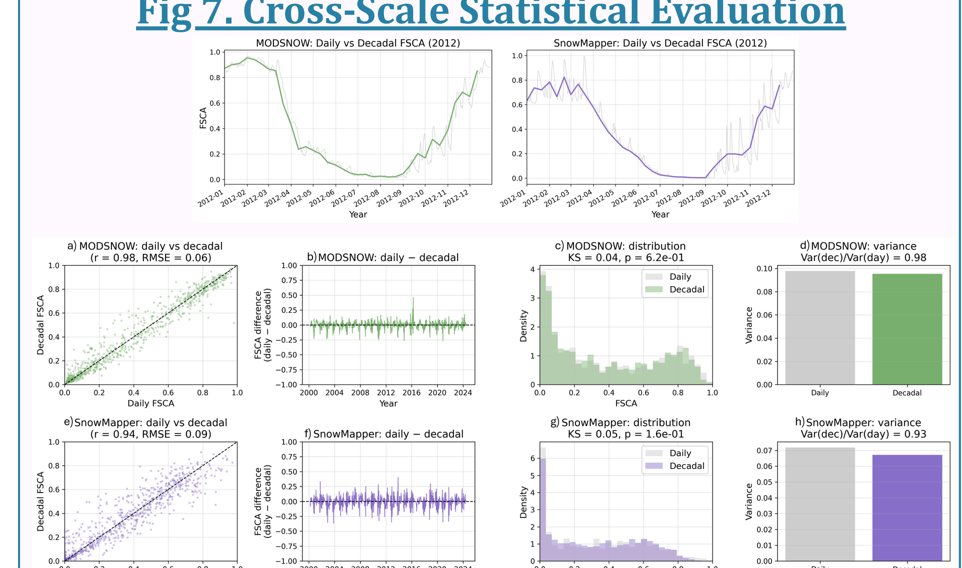
Valid decades

Majority Rule
≥50% Snow ⟶ Pixel assigned Snow, otherwise no snow

Decadal NetCDF → **Statistical Analyses** (Daily vs Decadal)

Statistical Evaluation

Fig 7. Cross-Scale Statistical Evaluation



(FSCA difference, Seasonal distribution, RMSE, Correlation, Kolmogorov-Smirnov test, p-value, variance ratio)

Negligible information loss confirmed.

3. Evaluation Metrics Suite

Multi Scale Analysis	Evaluation Metrics
Pixelwise agreement & divergence	Fractional Snow Cover (FSCA)
Daily, Seasonal & Basin scale	Classification Metrics (F1, BA, MCC)
Process-based (Hydrological Indicators)	Three product Consensus Patterns
Topographic functions (Elevation, slope, aspect, glacierized regions)	Outlier Fractions
	Cohen's Kappa (κ), Critical Success Index (CSI)
	Snow Depletion Curves (SDCs) per 500m elevation band
	Snow line Altitudes (SLA) Canny edge detection

Elevation · Slope · Aspect

Fig 8. Pixel wise Spatial Comparison Workflow

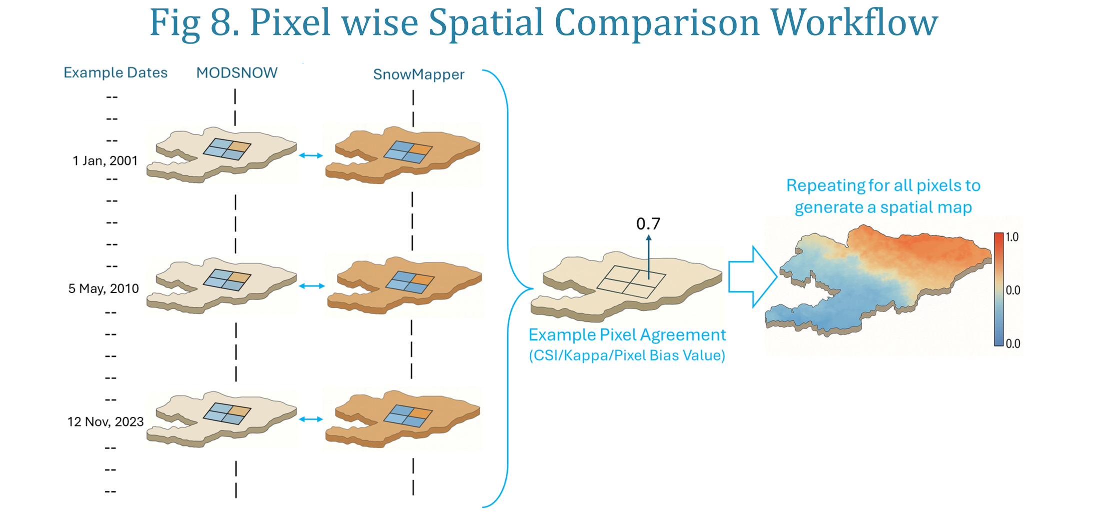
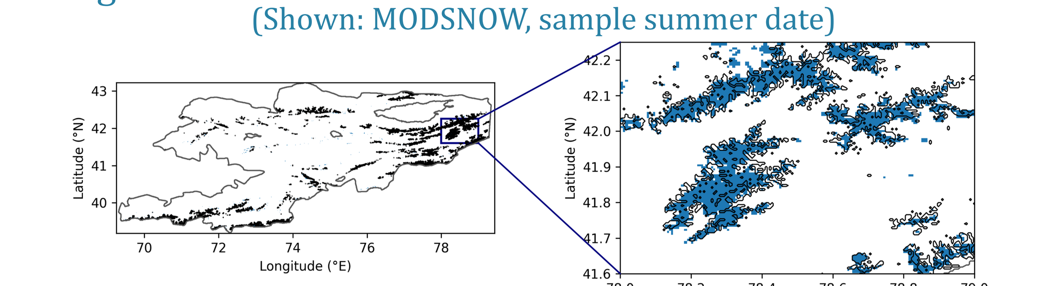


Fig 9. Glacier outlines ⟶ to partition glacierized and non-glacierized regions ⟶ to assess differences in snow cover behavior (Shown: MODSNOW, sample summer date)



Framework is sensor-agnostic and transferable to other data-sparse mountain regions (product heterogeneity and variable incompatibility)

INSIGHTS & TRANSFERABILITY

- Framework can apply beyond Kyrgyzstan. The 3 step harmonization (spatial co-registration, variable transformation, temporal alignment) addresses issues common to any multi-product snow intercomparison in data-scarce mountain regions.
- Apparent product discrepancies arise not only from physical inconsistencies but also from methodological treatment. Hence, the two must be disentangled before any performance judgment is made.
- The framework can be further improved by spatially adaptive SWE thresholds, allowing threshold values to vary with elevation, climate or terrain instead of using a single uniform value. Incorporating in situ observations, even if limited, would further strengthen the framework by enabling validation against ground-based reality (For this project, MODSNOW provides a validated reference (~93–94% accuracy) against in situ observations).

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