International Journal of Scientific Trends- (IJST)
ISSN: 2980-4299
Volume 5, Issue 9, September - 2026
Website: https://scientifictrends.org/index.php/ijst
Open Access, Peer Reviewed, Scientific Journal

Snow Cover Climate Sensitivity and Glacier Indicators in the Tupalang River Basin from 2001 to 2025

Abror Lolaev
TIIAME National Research University, Tashkent, Uzbekistan
lolayevabror119@gmail.com
Research area: Environmental Protection and Rational Use of Natural Resources

Abstract
Reliable cryosphere information is limited in many mountain catchments of Central Asia. This paper develops a basin-scale evidence base for the Tupalang River Basin by combining MODIS snow observations, climate reanalysis, gridded water-balance products, a glacier inventory, and a 2025 Sentinel-2 snow and ice classification. Daily MODIS records for 2001 to 2025 were summarized as annual, winter, spring, and persistent-snow areas. Trend magnitude was estimated with the Sen slope, statistical significance was assessed with the Mann-Kendall test, and climate controls were examined through correlation analysis. Mean annual snow area was 1397.85 km2, whereas winter and spring means were 2182.48 and 1434.75 km2. The four snow indicators declined in slope terms, but none passed the 0.05 significance threshold. Annual mean air temperature increased by 0.041 degrees C per year and was the only significant monotonic climate trend reported in the study. Warmer conditions coincided with smaller snow areas in the annual, winter, and spring series. The GLIMS layer contained 618 mapped glacier polygons covering 78.61 km2. A Sentinel-2 classification for 2025 identified 526.35 km2 of snow and ice, of which 23.16 km2 intersected the mapped glacier layer. Tests with MODIS NDSI thresholds of 20, 30, and 40 produced different area totals but similar negative trend estimates. Comparisons with Landsat and Sentinel-2 showed that seasonal aggregation, image date, cloud screening, and spatial resolution materially affect area estimates. The results define a transparent monitoring baseline, while observed discharge and station measurements remain necessary for hydrological attribution.

Keywords: Tupalang River Basin; seasonal snow; climate sensitivity; glacier inventory; MODIS; Sentinel-2; uncertainty

International Journal of Scientific Trends- (IJST)
ISSN: 2980-4299
Volume 5, Issue 9, September - 2026
Website: https://scientifictrends.org/index.php/ijst
Open Access, Peer Reviewed, Scientific Journal

Introduction

1 Research Problem and Objectives

Snow stored in mountain terrain delays part of the cold-season water supply and influences the timing of meltwater reaching downstream areas. Monitoring this storage is difficult in the Tupalang River Basin because continuous field observations are limited and the basin contains a strong elevation gradient. Satellite products offer consistent spatial coverage, but their estimates depend on sensor characteristics, classification rules, and the period represented by each image.

The study evaluates four linked questions. It measures the year-to-year behavior of seasonal snow area, describes the elevation position of spring snow, summarizes mapped glacier indicators, and tests how the snow record relates to temperature and moisture variables. A separate sensitivity analysis examines whether the principal MODIS finding changes when the NDSI threshold is adjusted. Cross-sensor results are reported as comparability evidence rather than ground-truth accuracy.

2 Basin Characteristics

The Tupalang catchment covers 2750.81 km2. Elevation was divided into six classes so that changes in valley areas could be distinguished from changes in the upper mountain belt. The same basin boundary was applied to the snow, climate, terrain, and glacier summaries.

Basin attribute	Value used in the study	Analytical purpose
Total basin area	2750.81 km2	Common denominator for area percentages
Elevation classes	<1500; 1500 to 2000; 2000 to 2500; 2500 to 3000; 3000 to 3500; >3500 m	Comparison of snow behavior along the elevation gradient
Analysis period	2001 to 2025	Long-term MODIS and climate summaries
Primary snow threshold	NDSI 30	Baseline snow classification
Seasonal frequency rule	0.20	Annual, winter, and spring snow extent
Persistent-snow rule	0.60	Frequently snow-covered surface

Table 1. Basin definition and classification rules used consistently across the analysis.

3 Data and Analytical Design

3.1 Data sources

Each dataset was assigned a specific role. MODIS supplied the temporal record, Sentinel-2 and Landsat supported spatial comparison, GLIMS represented mapped glacier units, and three climate products were used to examine possible controls on snow variability. The products were not treated as interchangeable measurements.

International Journal of Scientific Trends- (IJST)
ISSN: 2980-4299
Volume 5, Issue 9, September - 2026
Website: https://scientifictrends.org/index.php/ijst
Open Access, Peer Reviewed, Scientific Journal

Source	Variable	Coverage	Use
MODIS MOD10A1 Version 6.1	Daily NDSI snow cover	2001 to 2025	Seasonal frequency and area time series
ERA5-Land	Temperature and precipitation	2001 to 2025	Climate trend and correlation tests
TerraClimate	Precipitation, maximum SWE, P-AET, runoff	2001 to 2025	Water-balance indicators and runoff proxy
CHIRPS	Precipitation	2001 to 2025	Independent precipitation comparison
GLIMS	Glacier polygons	Inventory snapshot	Number, area, and basin share of mapped glaciers
Sentinel-2	NDSI snow and ice mask	2025	High-resolution area and glacier overlap
Landsat	Snow or ice mask	Four comparison years	Cross-sensor area comparison

Table 2. Data sources and their assigned analytical functions.

3.2 Statistical treatment

The Mann-Kendall test was used to evaluate monotonic change, and the Sen estimator quantified the annual rate of change (Mann, 1945; Sen, 1968). Results with p below 0.05 were classed as statistically significant. Pearson coefficients describe linear association between paired annual series. These coefficients indicate co-variation and do not establish a causal mechanism.

Analysis component	Reported statistic	Interpretation rule
Temporal trend	Sen slope	Direction and annual rate of change
Trend significance	Mann-Kendall p value	Significant when $p < 0.05$
Climate association	Pearson r and p value	Strength and direction of linear co-variation
Threshold sensitivity	Means and slopes at NDSI 20, 30, and 40	Stability of the result under alternative classification rules
Cross-sensor comparison	Relative area, mean bias, and RMSE	Consistency between unlike observation designs

Table 3. Statistical outputs and the limits placed on their interpretation.

4 Results

4.1 Seasonal snow area

Winter produced the largest basin-scale snow extent. The annual and spring indicators were similar in average area, whereas persistent snow represented a much smaller surface. Every Sen slope was negative. The p values, however, ranged from 0.1682 to 0.5593, so the record does not demonstrate a significant monotonic reduction in any of the four area indicators.

Snow indicator	Mean km2	Minimum km2	Maximum km2	Sen slope km2 per year	p value
Annual	1397.85	908.90	1661.23	-6.01	0.3153
Spring	1434.75	1164.89	1723.07	-6.26	0.1990
Winter	2182.48	1857.83	2751.97	-7.78	0.1682
Persistent	144.10	19.97	333.14	-1.54	0.5593

Table 4. Snow-area statistics for 2001 to 2025. All four trends are non-significant at the 0.05 level.

4.2 Spring snow elevation

Both elevation indicators moved upward in slope terms. The mean elevation of the detected spring snow surface increased by 3.85 m per year, and its minimum elevation increased by 6.21 m per year. Neither change was statistically significant. These variables describe the MODIS-derived spring snow mask and should not be interpreted as glacier equilibrium-line altitude.

Elevation indicator	Mean m	Observed range m	Sen slope m per year	p value	Result
Mean spring snow elevation	3059.30	2896.72 to 3219.87	+3.85	0.1682	Upward but non-significant
Minimum spring snow elevation	1767.12	1454 to 2053	+6.21	0.3037	Upward but non-significant

Table 5. Elevation statistics derived from the annual spring snow masks.

4.3 Glacier and snow ice indicators

The glacier inventory and the Sentinel-2 classification represent different dates and surface definitions. Their intersection therefore measures spatial agreement for the selected 2025 image; it does not quantify glacier retreat. The GLIMS polygons occupy 2.86 percent of the basin, while the broader Sentinel-2 snow and ice class covers 19.13 percent.

Indicator	Value	Share or comparison
Mapped GLIMS polygons	618 polygons	Inventory units
Total mapped glacier area	78.61 km2	2.86 percent of basin area
Sentinel-2 snow and ice area in 2025	526.35 km2	19.13 percent of basin area
Sentinel-2 overlap with GLIMS	23.16 km2	29.46 percent of mapped glacier area

Table 6. Glacier inventory and 2025 Sentinel-2 indicators.

4.4 Climate trends

Annual mean temperature showed the clearest monotonic change. Its increase of 0.041 degrees C per year was significant at p equal to 0.0265. The spring temperature, maximum SWE, and runoff-

International Journal of Scientific Trends- (IJST)
ISSN: 2980-4299
Volume 5, Issue 9, September - 2026
Website: https://scientifictrends.org/index.php/ijst
Open Access, Peer Reviewed, Scientific Journal

proxy trends did not reach the significance threshold. The runoff series remains a gridded proxy because measured discharge was unavailable.

Variable	Mean	Range when available	Sen slope per year	p value	Assessment
Annual mean temperature	4.72 degrees C	3.44 to 6.24 degrees C	+0.041 degrees C	0.0265	Significant increase
Spring mean temperature	4.26 degrees C	Not reported	+0.040 degrees C	0.2525	Non-significant increase
Maximum SWE	181.30 mm	Not reported	-1.59 mm	0.1886	Non-significant decrease
Runoff proxy	196.01 mm	Not reported	-4.92 mm	0.1303	Non-significant decrease

Table 7. Climate and water-balance trends used to interpret the snow record.

4.5 Climate snow relationships

Temperature had the strongest and most consistent relationship with snow area. Annual, spring, and winter coefficients were negative and statistically significant. Precipitation measures showed smaller positive coefficients, while maximum SWE had a moderate positive association with spring snow area. The near-perfect relation between mean spring snow elevation and spring snow area is partly mathematical because both measures come from the same classified mask.

Paired variables	r	p value	Reading of the result
Annual temperature and annual snow area	-0.6899	0.0001	Warmer years coincide with smaller annual snow area
Spring temperature and spring snow area	-0.7631	<0.001	Strong negative seasonal association
Winter temperature and winter snow area	-0.7614	<0.001	Strong negative seasonal association
CHIRPS precipitation and annual snow area	+0.4127	0.0403	Moderate positive association
ERA5-Land precipitation and annual snow area	+0.4341	0.0301	Moderate positive association
Maximum SWE and spring snow area	+0.6513	0.0006	Larger SWE coincides with larger spring area
Runoff proxy and spring snow area	+0.6016	0.0019	Positive association based on a proxy
Spring temperature and mean spring snow elevation	+0.7567	<0.001	Warmer springs coincide with higher detected snow

Table 8. Selected climate and snow correlations. Association does not establish causation.

International Journal of Scientific Trends- (IJST)
ISSN: 2980-4299
Volume 5, Issue 9, September - 2026
Website: https://scientifictrends.org/index.php/ijst
Open Access, Peer Reviewed, Scientific Journal

4.6 Threshold and sensor sensitivity

A lower NDSI threshold classified more of the basin as snow. Raising the threshold from 20 to 40 reduced the mean annual area by 90.08 km2 and the mean spring area by 96.01 km2. The three trend slopes remained close, and all were negative and non-significant. Threshold choice therefore affects magnitude more than trend direction in this record.

NDSI threshold	Annual mean km2	Annual slope km2 per year	Spring mean km2	Spring slope km2 per year
20	1441.75	-5.16	1483.38	-6.42
30 baselines	1397.85	-6.01	1434.75	-6.26
40	1351.67	-5.79	1387.37	-6.13

Table 9. Sensitivity of MODIS snow statistics to the NDSI classification threshold.

High-resolution product	Mean area relative to MODIS	Mean bias km2	RMSE km2	Scope of comparison
Landsat	71.8 percent	-387.17	442.15	Four validation years
Sentinel-2	20.5 percent	-1097.58	1117.17	Four validation years

Table 10. Cross-sensor area comparison. Negative bias indicates a smaller high-resolution estimate than the MODIS seasonal metric.

5 Interpretation

The record contains evidence of climatic pressure without a statistically confirmed basin-wide decline in snow area. Significant annual warming and strong negative temperature-snow coefficients show that warm conditions reduce the observed extent of seasonal snow. Large interannual fluctuations, precipitation differences, and elevation-dependent persistence can nevertheless mask a simple monotonic response over twenty-five years.

For water-resource assessment, spring snow area and its elevation provide useful indicators of the amount and location of melt-season storage. They cannot by themselves predict discharge. Melt rate, soil storage, groundwater exchange, reservoir operation, and abstraction determine how much water eventually reaches downstream users and ecosystems. The satellite record is therefore best used as one component of a broader monitoring system.

The sensor comparison also changes how the area values should be used. MODIS represents repeated observations summarized over a season, whereas a Landsat or Sentinel-2 mask may represent one clear image acquired during a particular stage of melt. The difference between those products is methodological as well as spatial. Future comparisons should use matched observation windows and identical cloud, terrain, and classification rules.

6 Study Limitations and Research Priorities

Limitation	Effect on interpretation	Priority for the next stage
No observed discharge series	Runoff response cannot be calibrated or attributed	Obtain gauge records and compare seasonal snow with measured flow
Cloud, shadow, and mixed MODIS pixels	Area may vary with valid observation coverage	Archive annual quality masks and test cloud-gap procedures
Single-date high-resolution classifications	Results depend on acquisition date and melt stage	Use several Landsat and Sentinel-2 dates in a fixed seasonal window
Inventory and image dates differ	GLIMS overlap is not a glacier-change measurement	Compile date-matched glacier outlines and assess debris-covered ice
Twenty-five-year trend period	Low power for detecting gradual or non-linear change	Extend the time series and apply change-point and elevation-specific tests

Table 11. Main limitations and the corresponding research response.

7 Conclusions

The 2001 to 2025 assessment yields four main findings. Snow area declined in slope terms across all seasonal definitions, but the changes were not statistically significant. Annual mean temperature increased significantly and showed a clear negative relationship with snow extent. Mapped glacier polygons covered 78.61 km2, while the 2025 Sentinel-2 snow and ice class covered a substantially larger and methodologically different surface. Finally, alternative MODIS thresholds preserved the direction of the trend, whereas cross-sensor differences were large. These results provide a defensible remote-sensing baseline for the Tupalang Basin, but hydrological conclusions require measured discharge and coordinated field observations.

References

1. Abatzoglou, J. T., Dobrowski, S. Z., Parks, S. A., and Hegewisch, K. C. (2018). TerraClimate, a high-resolution global dataset of monthly climate and climatic water balance. Scientific Data, 5, 170191. https://doi.org/10.1038/sdata.2017.191
2. Funk, C., Peterson, P., Landsfeld, M., et al. (2015). The Climate Hazards Infrared Precipitation with Stations dataset. Scientific Data, 2, 150066. https://doi.org/10.1038/sdata.2015.66
3. Hall, D. K., Riggs, G. A., Salomonson, V. V., DiGirolamo, N. E., and Bayr, K. J. (2002). MODIS snow-cover products. Remote Sensing of Environment, 83, 181 to 194. https://doi.org/10.1016/S0034-4257(02)00095-0
4. Kendall, M. G. (1975). Rank Correlation Methods. 4th ed. Charles Griffin, London.
5. Mann, H. B. (1945). Nonparametric tests against trend. Econometrica, 13(3), 245 to 259. https://doi.org/10.2307/1907187
6. Muñoz Sabater, J., et al. (2021). ERA5-Land: a state-of-the-art global reanalysis dataset for land applications. Earth System Science Data, 13, 4349 to 4383. https://doi.org/10.5194/essd-13-4349-2021

7. Raup, B. H., et al. (2007). The GLIMS geospatial glacier database: a new tool for studying glacier change. Global and Planetary Change, 56, 101 to 110. https://doi.org/10.1016/j.gloplacha.2006.07.018
8. Sen, P. K. (1968). Estimates of the regression coefficient based on Kendall's tau. Journal of the American Statistical Association, 63(324), 1379 to 1389. https://doi.org/10.1080/01621459.1968.10480934
9. NASA LP DAAC. (2021). MODIS Terra Snow Cover Daily Global 500 m, Version 6.1. https://doi.org/10.5067/MODIS/MOD10A1.061