Response to Reviewer 3

Reviewer 3.

This study comprehensively investigates snow and glacier dynamics in the Upper Karnali Basin (UKB), integrating multi-source remote sensing data (e.g., MODIS and Landsat) to address critical knowledge gaps in the mid-western Himalayas. The methodology is rigorous, employing NDSI thresholds and Google Earth Engine to mitigate cloud cover challenges, ensuring robust results. Overall, the research reveals significant climate change impacts and provides key evidence for regional resource management, representing a valuable contribution to cryosphere science. However, several improvements are warranted:

1. The study depends solely on remote sensing data (e.g., MODIS LST, ERA5) without incorporating ground observations such as weather stations or glacier mass balance measurements. This omission introduces uncertainty, and the absence of validation protocols (e.g., cross-referencing with DHM station data mentioned in Section 3) weakens methodological credibility.

Response:

We acknowledge the reviewer's concerns regarding the exclusive use of MODIS Land Surface Temperature (LST) data without extensive ground-based validation. Prior studies have demonstrated the reliability of MODIS LST measurements in alpine regions of the Himalayas. For instance, Duan et al. (2019) validated MODIS LST against in situ observations, reporting a mean bias below 1.5 K. Similarly, Yu et al. (2011) observed a strong correlation ($R^2 > 0.9$) between MODIS LST and ground measurements in the Heihe River Basin, an area characterized by comparable topographic complexity. Zhao et al. (2019) employed MODIS LST to analyze warming trends in the central Himalayas, confirming consistency with elevation-dependent climatic patterns despite limited ground data. Furthermore, Hall et al. (2008) demonstrated the reliability of MODIS LST retrievals over snow-covered surfaces, attributing this to snow's high and stable emissivity (~0.99), which reduces errors in thermal infrared sensing. In a similar vein, Hori et al. (2006) validated MODIS-derived LST over snow in Arctic and alpine environments, finding good agreement with ground observations when appropriate atmospheric corrections were applied. Collectively, these findings substantiate the strength of MODIS LST in high-altitude settings, thereby supporting its application in the present study despite the scarcity of ground-based temperature records. We have addressed and incorporated in the revised version of the manuscript.

2. While the fusion of MODIS (500 m) and Landsat (30 m) data is mentioned (Section 3), the spatial scaling approach remains unclear. The paper fails to specify how resolution discrepancies were reconciled or the final output resolution of integrated analyses (e.g., SCA calculations in Section 4.1).

Response:

We agree the reviewer's concerns regarding the reconciliation of spatial resolution differences between MODIS (500 m) and Landsat 8 (30 m) in our integrated analyses. Similar comments have been comprehensively addressed in our response to Reviewer 2, which is summarized as follows: To ensure consistency, Landsat 8 snow cover area (SCA) maps were resampled to 500 m using a majority-aggregation approach (Rittger et al., 2020), aligning them with the MODIS grid. From each resampled scene (185 × 180 km), 10% of pixels (~13,320) were randomly sampled as vector points, representing snow, non-snow, and cloud-covered classes. These points were overlaid on MODIS snow cover extent

(SCE) maps, and MODIS-derived classifications were extracted to construct a composite attribute table for direct comparison.

Accuracy assessments using confusion matrices for six low-cloud (<7%) scenes produced overall accuracies ranging from 77.5% to 94.9%, consistent with previous MODIS validation studies (e.g., Hall & Riggs, 2007; Painter et al., 2009). However, sub-scene comparisons revealed a systematic overestimation of snow cover area (SCA) by MODIS, with values 1.3 to 1.6 times higher than Landsat 8 estimates. This discrepancy is attributable to mixed-pixel effects in heterogeneous terrain (Dozier et al., 2008) and the coarser spatial resolution of MODIS (Gafurov & Bárdossy, 2009). This bias aligns with prior research highlighting MODIS's tendency to overestimate SCA in fragmented landscapes (Rittger et al., 2013; Tang et al., 2017).

While MODIS provides reliable large-scale snow cover area (SCA) estimates (Dietz et al., 2012), our findings emphasize the importance of interpreting trends, especially those related to seasonal monsoon declines, with caution.

Insufficient Mechanistic Analysis

1. Using MODIS to compensate for Landsat cloud gaps (Section 3.2) is noted but lacks uncertainty assessment. The impact of spatial resolution downgrading (30m→500m) on seasonal SCA trends (e.g., monsoon declines in Figure 2) remains unaddressed, directly affecting conclusion reliability.

   Response: Part of the response for comments in the preceding text

We compared MODIS LST with in situ air temperature measurements (at 2 m above ground) from various stations (Table 1). Only high-quality MODIS LST data was used. The relationship between MODIS Terra LST and station air temperature varies significantly by location and season. Jumla shows the strongest correlation, reaching up to 0.85 under optimal conditions, indicating MODIS is quite reliable there on clear, snow-free days. Guthi Chaur exhibits mixed results, with moderate correlations at times but weaker in others. Simkot and Rara generally show low correlations, with Rara even displaying a negative correlation (-0.18), likely due to persistent snow, ice, and high elevation weakening the surface-air temperature link. Overall, MODIS LST performs better in lower, snow-free areas, whereas high-altitude, snow-covered sites require seasonal adjustments. The differences partly stem from measurement methods: ground stations measure air temperature at a single point, 2 m above ground, while MODIS captures the average "skin" temperature over a 1 km^2 pixel, which can include heterogeneous topography, various land covers like vegetation, bare ground, snow, or water, all affecting the reading. Air temperature tends to be cooler than the surface temperature seen by MODIS, especially in sunny or snowy conditions. Factors such as topography, shading, and atmospheric effects also cause discrepancies, often requiring bias correction or filtering. Various studies have established use of MODIS-derived LST can be fruitfully used to measure temperature trend in the snow and glaciers areas where in situ data is very limited, which can be applied to Upper Karnali basin. We have addressed and incorporated this in the revised version of the manuscript.

Table 1. Correlation with MODIS Terra LST and Ground measurement (Air temperature)

Station (m a.s.l)	Correlation				
	Jan-March	April-June	July–Sept	Oct–Dec	Annual average
Jumla (2300)	0.383161	0.85	0.65	0.44	0.3
Simkot (2800)	0.339592	0.23	0.12	0.14	0.18
Guthi Chaur (3080)	0.502245	0.21	0.38	0.46	0.35
Rara (3048)	0.182726	0.22	-0.18	0.07	0.053

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