SNOW COVER TRENDS OVER HIGH MOUNTAIN ASIA FROM MODSCAG

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EXTENDED ABSTRACT

Snow from the Hindu Kush Himalaya (HKH) significantly contributes to the water resources that millions depend upon downstream (Immerzeel et al., 2010). Several countries, including Bhutan and Pakistan, depend on snowmelt for agriculture and energy-generating purposes, both of which are main components of these local economies (Sharma et al., 2014; Atif et al., 2018). In addition to its socioeconomic impacts, snow cover in this region also contributes to Earth's intricate feedback systems. A decrease in snow lowers the surface albedo and increases the energy absorbed, known as the snow albedo feedback; a highly effective radiative forcing mechanism that contributes to climate change (Hall and Qu, 2006). As the HKH encompasses more snow and ice than anywhere else in the world outside of the polar regions (Panday et al., 2011), a decline in snow would alter the earth's energy budget. Therefore, it is important to understand how snow patterns are changing over time in this region.

Current studies agree that there is a general decline in snow covered area (SCA) across the HKH region (Immerzeel et al., 2009; Menon et al., 2010), although results vary depending on the regional scale, study period, and data used (Hasson et al., 2014; Singh et al., 2018). We use a metric, defined here as snow covered days (SCD) and fractional snow-covered days (fSCD), to assess annual trends in snow frequency over the MODIS record. Although others have used some variation of snow-covered days to monitor snow frequency in the region (Paudel and Andersen, 2011; Dedieu et al., 2014), our method is the first to use daily, gap-filled spatially and temporally complete (STC) MODSCAG data (Rittger 2012). Likewise, trends in snow cover duration are observed on an annual basis from 2002 to 2017, a relatively longer data record when compared to previous studies. Thus, this new data product may satisfy the need for a more spatially and temporally complete dataset for snow trend analysis within this region of the world that is particularly sensitive to changes in climate.

Both SCD and fSCD are used to observe trends in annual snow cover duration for the HKH as a whole, as well as for each study basin and elevation band. The study area includes five major river basins, namely: Syr Darya, Amu Darya, Indus, Ganges, and Brahmaputra. The 30-meter ASTER GDEM V2 dataset, a product of METI and NASA, is used to select and compile data within specific elevation bands, an approach that has also been used by other studies in this region (Tahir et al., 2016; Singh et al., 2018). By doing so, trends in SCA are assessed across varying elevations within each of the five study basins.

The binary analysis (SCD) identifies a pixel value greater than 15% as "snow" and a pixel value less than 15% as "no snow". The 15% cutoff is based on the algorithm detection limit (Painter et al., 2009). Each pixel is then summed to determine annual snow cover trends for each year from 2002 to 2017, such that a pixel value of 365 would indicate persistent snow cover within a specific pixel for a given year. To evaluate fractional snow-covered days (fSCD), the sum of each pixel for a given year is calculated with the 15% threshold applied. A pixel value of 365, in this regard, indicates 100% snow cover within a pixel for each day of the year. Leveraging MODSCAG's capability to map fractional snow cover allows us to assess whether or not trends in snow cover vary when the analysis is carried out at the pixel or subpixel level.

The Mann-Kendall test is used to determine interannual trends (Mann, 1945; Kendall, 1975), while Sen's slope is applied to assess the magnitude of the trend (Sen, 1968). The Mann-Kendall test is a robust, non-parametric test that is often used to detect monotonic trends within a time series, particularly when the sample size is small. To account for autocorrelation within the time series, Hamed and Rao's modified Mann-Kendall test was used in which a variance correction approach is applied to the data, which has been noted as one of the preferred methods for correcting autocorrelation with this type of data (Hamed and Rao, 1998; Bayazit and Önöz, 2007). The annual median SCD and fSCD values are determined for each basin and elevation band. The p-value is then used to determine significant interannual snow cover trends per basin, per elevation band, and for the HKH region.

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Results include significant negative trends in snow cover duration and snow cover extent across the entire HKH region with the highest rate of decline in the most eastern basin, the Brahmaputra (Figure 1; Tables 1 and 2). Similarly, significant negative trends in both SCD and fSCD are found across some of the highest elevations in the Syr Darya and Brahmaputra basins. The longest duration of snow cover persists among the western basins, specifically the Syr Darya, Amu Darya, and Indus basins, with the shortest duration in the Ganges and Brahmaputra basins. The Indus is the only basin to display an increasing tendency, which may reflect anomalies in this region, including the positive trends in the Karakoram. Overall, the general trends across the HKH indicate shorter snow cover persistency and lower snow cover extent, which reflect previous conclusions that SCA is declining in the HKH (Gurung et al., 2017; Singh et al., 2018). The frequency of snow across each basin also reflects the differences between the westerly-influenced basins and the monsoon-influenced basins, where the westerly-influenced basins tend to have longer periods of snow cover (Singh et al., 2014) compared to the monsoon-influenced basins that tend to have shorter snow cover durations (Gurung et al., 2017). Because each statistically significant trend indicates a decline in snow cover duration, snow accumulation and snowmelt patterns should continue to be monitored in this region as millions of people continue to depend on these water resources.

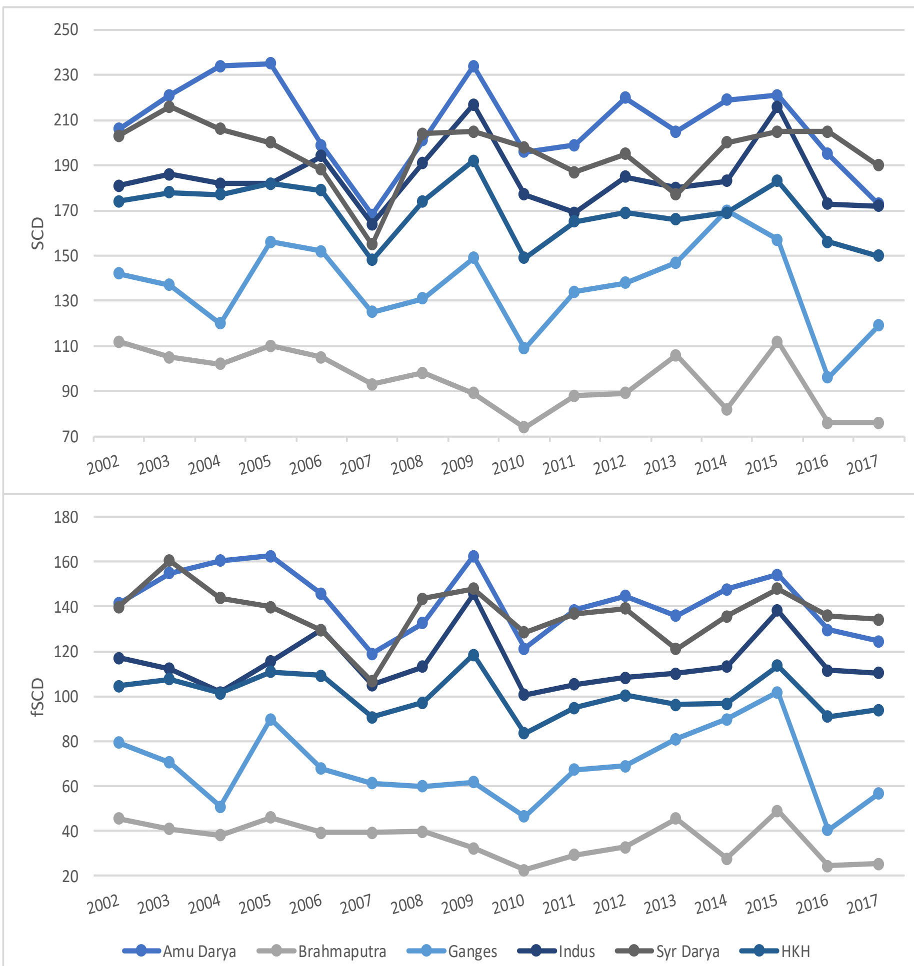

Figure 1. Snow-covered days and fractional snow-covered days per basin from 2002 to 2017

Table 1. Slope of SCD per elevation band for each basin and the total HKH region.

One asterisk represents p-value < 0.05; two asterisks represents p-value < 0.01.

	Sen's Slope					
Elevation Bands (m)	Syr Darya	Amu Darya	Indus	Ganges	Brahmaputra	Total HKH
1,000-2,000	-0.696	-1.481	0.000	0.000	-0.250	-0.267
2,000-3,000	-0.583	-1.036	0.000	-0.279	0.000	-0.780
3,000-4,000	-0.183	-0.819	-0.063	-0.292	-0.835	-0.847
4,000-5,000	-1.202*	-1.139	0.258	-0.929	-1.321**	-1.261**
5,000-6,000	-0.033	-0.840	-1.875	-2.464*	-3.333*	-2.450**
6,000-7,000		0	0	0	-0.545**	0
7,000-8,000		0	0	0	0	0
Above 8,000			0	-0.268*	0	0

Table 2. Slope of fSCD per elevation band for each basin and the total HKH region.

One asterisk represents p-value < 0.05; two asterisks represents p-value < 0.01.

	Sen's Slope					
Elevation Bands (m)	Syr Darya	Amu Darya	Indus	Ganges	Brahmaputra	Total HKH
1,000-2,000	-0.293	-0.715	-0.241	-0.011	-0.047	-0.207
2,000-3,000	-0.454	-0.879	0.159	-0.175	-0.057	-0.326
3,000-4,000	-0.459	-0.753	0.132	-0.237	-0.463	-0.904
4,000-5,000	-0.969*	-1.175	0.453	-0.471	-0.584	-0.488
5,000-6,000	-1.203	-0.816	-0.935	-0.957	-1.781*	-1.428
6,000-7,000		0.012	-0.427	-0.446	-2.534**	-0.497
7,000-8,000		-0.519	-0.120	-0.345	-2.492**	-0.165
Above 8,000			0.473	-0.988	-9.581	-1.289

Ideally, this analysis would include a longer time series, but for a daily analysis at a scale that is relevant for processes in complex terrain, MODIS remains the best option. This study could be extended as the MODIS record becomes longer, and it could also be supplemented by other optical platforms like VIIRS and Sentinel. Comparing these results to datasets with relatively longer records, including passive microwave data, may also be worth considering. A similar approach to monitoring snow cover duration could also be applied to other study areas, including the western United States. (KEYWORDS: snow cover duration, snow covered area, MODSCAG, climate change)

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