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Changes in snow depth under elevation-dependent warming over the Tibetan Plateau

Liucheng Shen[1] | **Yuqing Zhang**[2,3] | **Safi Ullah**[2] | **Nick Pepin**[4] | **Qianrong Ma**[5]

[1]School of Environmental and Geographical Sciences, Shanghai Normal University, Shanghai, China
[2]Department of Atmospheric and Oceanic Sciences, Institute of Atmospheric Sciences, Fudan University, Shanghai, China
[3]School of Urban and Environmental Sciences, Huaiyin Normal University, Huai'an, China
[4]School of Environment, Geography and Geosciences, University of Portsmouth, Portsmouth, UK
[5]Key Laboratory of Meteorological Disaster, Ministry of Education (KLME)/Joint International Research Laboratory of Climate and Environment Change (ILCEC)/Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters (CIC-FEMD), Nanjing University of Information Science & Technology, Nanjing, China

Correspondence
Yuqing Zhang, Department of Atmospheric and Oceanic Sciences, Institute of Atmospheric Sciences, Fudan University, Shanghai 200438, China.
Email: geonuist@foxmail.com

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Abstract

Snow plays an essential role in regulating climate change, the hydrological cycle, and various biological processes. Passive microwave snow depth data and gridded data from the Climate Research Unit (CRU_TS4.04) are utilized in this study to investigate spatiotemporal variations of snow depth over the Tibetan Plateau (TP), with special focus on the vertical dimension. The response of snow to elevation-dependent warming (EDW) is determined accordingly. High mountains experience more rapid warming than lower elevations. During 1980–2014, the total snow depth over the TP decreased; areas with the most significant decreasing trends are mainly concentrated in the northwestern and southwestern parts of the TP. The plateau-wide decrease in snow depth (−0.24 cm/decade) is mainly affected by increasing temperature (0.30°C/decade). The reduction in snow depth trend intensifies as sub-regional mean elevation increases from 3,332 m (IID2) to 5,074 m (ID1). A stronger snow depth decrease in high-elevation sub-regions generally corresponds to higher warming rates, which demonstrates EDW. The most pronounced correlation between snow depth decrease rate and elevation occurs in the southeastern TP, which covers the largest elevation range on the plateau (from 2,000 to 6,000 m).

KEYWORDS
climate zone, elevation-dependent warming, snow depth, Tibetan Plateau

1 | INTRODUCTION

Snow plays an essential role in the global land surface energy balance, water cycle, and soil moisture/temperature relationships owing to its high albedo, the hydrological effects of melting, and its low thermal conductivity (Barnett *et al.*, 1988; Zheng, 1996; Kang *et al.*, 2010; Ghatak *et al.*, 2014; Song *et al.*, 2019;

Immerzeel *et al.*, 2020; You *et al.*, 2020b). Snow depth is an indispensable indicator of climate change, water resource storage, and the relationships between atmospheric and oceanic circulations (Xu *et al.*, 2017; Zhong *et al.*, 2018; Bao and You, 2019). Changes in snow depth can dramatically influence local or even global weather and climatic conditions (Zhang, 2005). The distribution of snow depends strongly on latitude and altitude (Zhong *et al.*, 2018). There are large amounts of snow in alpine regions around the world, such as the Rocky Mountains in North America, the Caucasus Mountains in Western Asia, and High Mountain Asia (e.g., the Tibetan Plateau) (Bormann *et al.*, 2018); snow conditions in these areas are extremely dynamic and can change very rapidly.

With an approximate coverage of over 2.5 million km^2 and an average elevation of 4,000 m above sea level, the Tibetan Plateau (TP) contains the largest snow-covered areas in the northern hemispheric mid-latitudes (Qin *et al.*, 2006; Zheng and Zhao, 2017). The TP is also known as the “Asian water tower” (Xu *et al.*, 2008; Immerzeel *et al.*, 2020), as it provides abundant freshwater resources for downstream regions (Immerzeel *et al.*, 2010). Therefore, the spatiotemporal characteristics of snow depth over the TP and its associated mechanisms have considerable research significance. Xu *et al.* (2017) suggested that the annual mean snow depth increased from 1960 to 1982, then decreased from 1983 to 2010 based on 103 surface meteorological stations across the TP. Wei and Dong (2015) pointed out that the snow depth simulated by most Coupled Model Inter-Comparison Project (CMIP5) models shows a decreasing trend, though surface observations of snow depth show an increasing trend from 1960 to 1996 and decreasing trend from 1996 to 2005. There were slight differences in interannual snow depth variations between the two datasets. Smith and Bookhagen (2018) examined the trend of snow water equivalent (SWE) based on passive microwave data from 1987 to 2009 to find a decrease in SWE in High Mountain Asia, which encompasses the TP.

There have been many studies to date on snow depth variations over the TP at local or regional scales. However, conclusions concerning interannual variations in snow depth are not always in agreement due to differences in study periods and datasets. It is yet necessary to adopt a snow depth dataset with a sufficiently lengthy study period, wide coverage area, and high accuracy to comprehensively understand the characteristics of snow depth variations in this region. Moreover, there is still a lack of understanding of snow depth changes in the vertical dimension (Xu *et al.*, 2017; Smith and Bookhagen, 2018). Both SWE (Smith and - Bookhagen, 2018) and snow depth (Xu *et al.*, 2017) are strongly related to elevation, but the relationships are nonlinear. There is no consensus regarding whether snow depth trends over the TP have a clear elevation-dependent variation or not (You *et al.*, 2020b), and detailed vertical variations remain unclear.

Snow depth is anticipated to be extremely sensitive to global warming (Qin *et al.*, 2006; IPCC, 2013; Freychet *et al.*, 2017; Su *et al.*, 2017; Thakuri *et al.*, 2019; Duan *et al.*, 2020). The warming rate over the TP is significantly faster than that in the surrounding lower elevation areas and even exceeds the global mean (Rangwala *et al.*, 2013; You *et al.*, 2020a), second only to the rate of warming in the Arctic (Screen and Simmonds, 2010). This is referred to as “elevation-dependent warming” (EDW): high mountains experience contrasting warming rates to lower elevations (Pepin and Lundquist, 2008; Rangwala *et al.*, 2013; Pepin *et al.*, 2015). There is consensus regarding the overall enhanced warming of the TP, but the exact elevation profile of EDW is still controversial (You *et al.*, 2008; Rangwala *et al.*, 2009; Kang *et al.*, 2010; You *et al.*, 2010; Guo and Wang, 2012; Gao *et al.*, 2018). For example, Li *et al.* (2020) suggested that EDW has only occurred in specific mountainous ranges on the TP. It is expected that such regional EDW differences across the plateau could significantly impact the spatiotemporal characteristics of snow depth. It is not clear which areas of TP have the strongest EDWs, in turn affecting the snow depth significantly, in those particular regions.

The objectives of the study are two-fold. (a) We examine the spatiotemporal variations in snow depth over the TP and identify regions where the snow depth trends change significantly with elevations. (b) We identify regions with contrasting EDW profiles and reveal the effect of warming rates on snow depth at different elevations. A detailed description of our data and methods is given in Section 2, including the division of climate zones. Section 3 investigates the spatiotemporal characteristics of snow depth over the TP and the elevation-dependent variation of snow depth under the effects of EDW. The discussion and conclusions are presented in Section 4.

2 | DATA AND METHODS

2.1 | Climate zones

Snow depth, temperature, and precipitation over the TP exhibit high variability both in space and time (Ghatak *et al.*, 2014; Wang *et al.*, 2017b; Wang *et al.*, 2018) due to the complex topography and contrasting atmospheric circulation systems over the TP (Figure 1) (Smith and Bookhagen, 2018; Yao *et al.*, 2019; You *et al.*, 2020b). A combination of different hydrothermal conditions creates

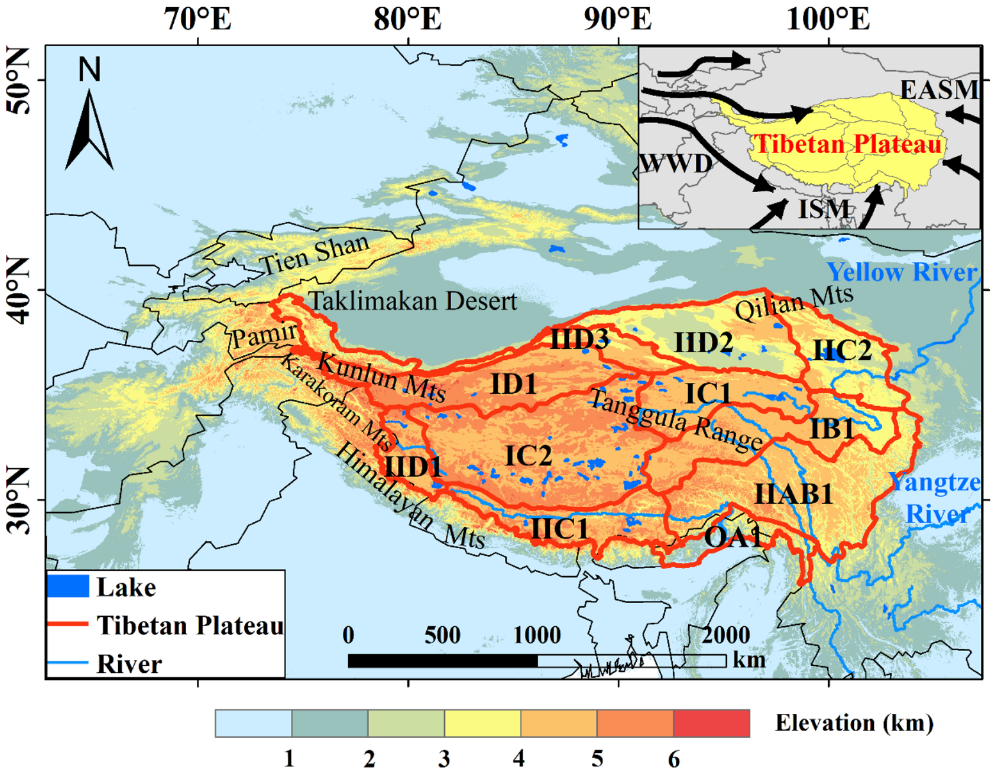

FIGURE 1 Study area. Topographic map of TP derived from SRTM DEM data (Lehner *et al*., 2008) with the classification of 11 climatic sub-regions marked by a red solid line (Zheng, 1996; Chen *et al*., 2018). Inset map shows three major atmospheric circulation system wind directions: Winter westerly disturbances (WWD), Indian summer monsoon (ISM), and East Asia summer monsoon (EASM). (IB1: Golog-Nagqu high-cold shrub-meadow zone, IC1: Southern Qinghai high-cold meadow steppe zone, IC2: Qiangtang high-cold steppe zone, ID1: Kunlun high-cold desert zone, IIAB1: Western Sichuan-eastern Xizang montane coniferous forest zone, IIC1: Southern Xizang montane shrub-steppe zone, IIC2: Eastern Qinghai-Qilian montane steppe zone, IID1: Ngari montane desert-steppe and desert zone, IID2: Qaidam montane desert zone, IID3: Northern slopes of Himalaya montane evergreen broad-leaved forest zone, OA1: Southern slopes of Himalaya montane evergreen broad-leaved forest zone)

diverse climate systems (Zheng, 1996; Zheng and Zhao, 2017), which affect the distribution of snow depth differently in individual climatic regions. Therefore, it is necessary to investigate the changes in snow depth at the regional scale. We use the climate zoning approach introduced by Zheng (1996) here to divide the entire TP into 11 sub-regions (Figure 1), in which the climate (hydrothermal) conditions are as similar as possible (Zheng, 1996; Chen *et al*., 2018). We further investigated snow depth and its elevation-dependent variations in different climate regions accordingly.

2.2 | Dataset and methodology

Three datasets were used in this study:

1. Passive microwave snow depth data spanning the years 1980–2014, derived from microwave brightness temperature measured via scanning multichannel microwave radiometry with a spatial resolution of 0.25° × 0.25°. This dataset has been widely used to study snow characteristics in China, especially across the TP (Ji and Kang, 2013; Song *et al*., 2014; Wang *et al*., 2017a; Bao and You, 2019). Its quality was enhanced and calibrated with surface observations as well as Moderate Resolution Imaging Spectroradiometer (MODIS) data (Che *et al*., 2008) prior to its release by National Tibetan Plateau Data Center in China (https://data.tpdc.ac.cn/zh-hans/data/df40346a-0202-4ed2-bb07-b65dfcda9368).
2. Monthly observed gridded land surface air temperature and precipitation from the Climate Research Unit (CRU) of the University of East Anglia (Harris *et al*., 2020). This dataset has a spatial resolution of 0.5° × 0.5° and temporal coverage of 1980–2014 (https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.04). CRU temperature data can reasonably reflect the interannual temperature variation over the TP (Figures S1–S6). The temperature trend of the CRU

data is consistent with the surface observation data (Figures S1, S2, and Table S1) and the ERA5 reanalysis dataset (Figures S3, S4, and Table S2), even in the northwestern TP (Figures S5, S6, and Table S3).

3. The digital elevation model (DEM) product is derived from the Shuttle Radar Topographic Mission (SRTM) (Lehner *et al.*, 2008) with a horizontal spatial resolution of 90 m × 90 m. This set is available from http://srtm.csi.cgiar.org/srtmdata.

Years were classified into four seasons (Xu *et al.*, 2017): spring (March–May), summer (June–August), autumn (September–November), and winter (December–February). We also calculated the linear trends for each grid point of

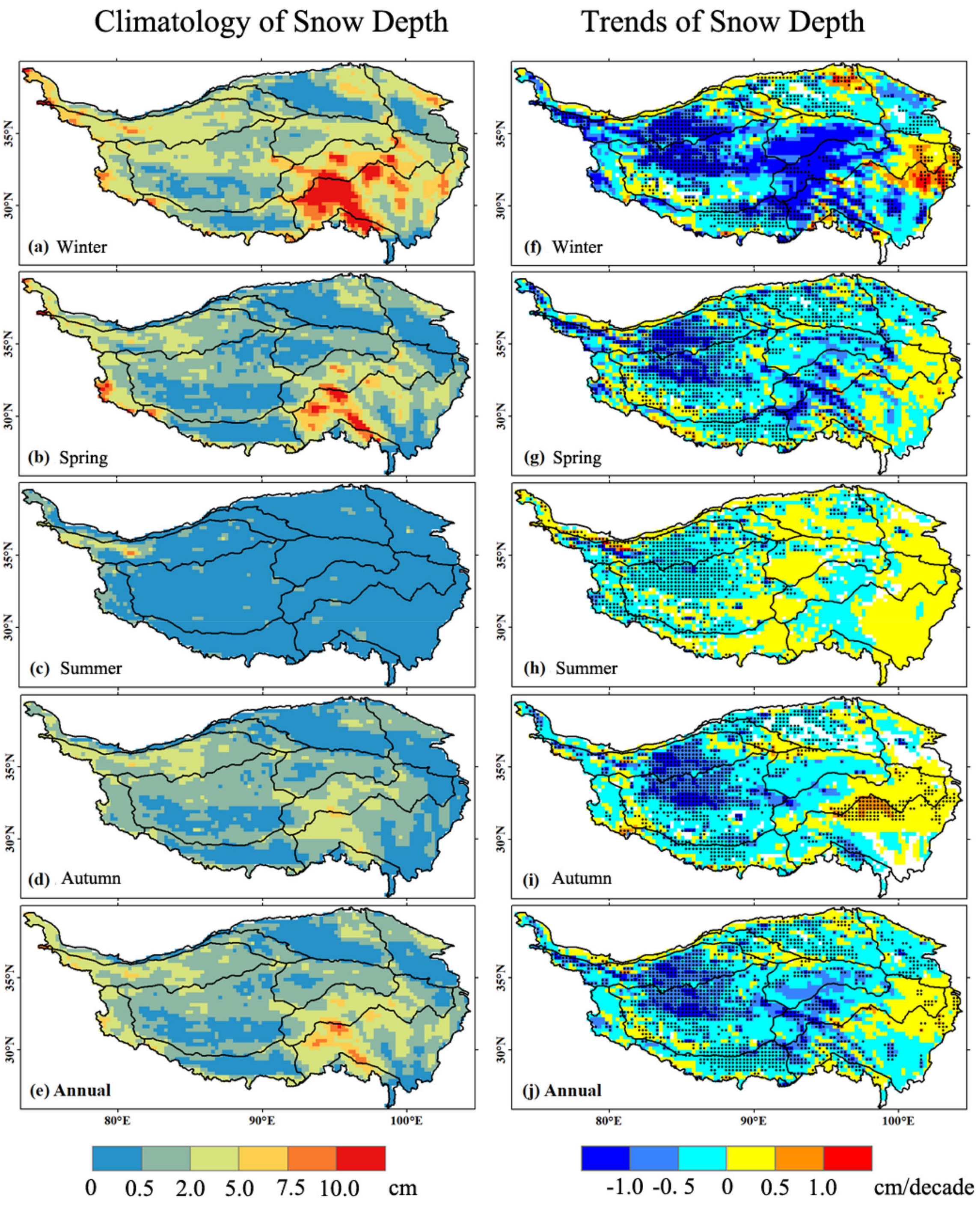

FIGURE 2 Climatology (a–e, left panel) and trends (f–j, right panel) of snow depth on annual and seasonal timescales, 1980–2014. Dotted regions mark trends significant at $p < .05$

all climatic variables and applied a two-tailed student *t*-test to determine significance at $p < .05$.

3 | RESULTS

3.1 | Spatiotemporal variation of snow depth

Large spatial heterogeneity in snow depth is observed over the TP for the years 1980–2014 (Figure 2). In general, the snow depth is highest in winter (Figure 2a). Areas with thicker snow depth in winter are mainly distributed in the southeastern TP (sub-regions IB1, IIAB1, and OA1), the Qilian Mountains in the northeastern TP, and the western edge of the TP, where westerlies are dominant. The maximum snow depth in winter is ≥10 cm in the southeastern TP (i.e., western parts of HAB1 and some parts of OA1), while much shallower snow is distributed in the Qaidam Basin and southwestern TP. The spatial patterns in whole year, spring (Figure 2b), and autumn (Figure 2d) are broadly similar to those in winter. The snow depth in summer (Figure 2c) is far lower than any other season (≤0.5 cm), during which time snow is only recorded at high elevations.

Snow depth at most grid points decreases during 1980–2014 (Figure 2f–j). On average, the annual mean snow depth over the TP is decreasing (74.27% of the entire TP) while the remainder shows positive trends, especially in the eastern TP (Figure 2f). On a seasonal scale, the percentage of the TP showing negative trends is 75% (winter), 72.23% (spring), 52.34% (summer), and 64.87% (autumn) of grid points. The fastest decline can be found in winter, where the rate of decrease is −1.0 cm/decade and centered mainly in the hinterland (northwestern) TP and the Nyainqentanggula Mountains-Tanggula Range. The only weak positive trend of snow depth across the region falls into the eastern TP and is especially pronounced in winter. The mean plateau-wide change of snow depth is decreasing at a rate of −0.24 cm/decade, which can be attributed to both temperature warming and precipitation variability (Duan and Xiao, 2015; Wang *et al.*, 2018).

There are subtle variations in trends in different sub-regions (Figures 3 and 4). All 11 sub-regions show decreasing trends, but the trends are more intense in regions IC2 (−0.38 cm/decade), ID1 (−0.49 cm/decade), and IIC1 (−0.18 cm/decade). Increases in temperature appear to markedly influence snow depth reductions, as most parts of the TP experienced significant warming over the same period (Figure 4c) and especially the

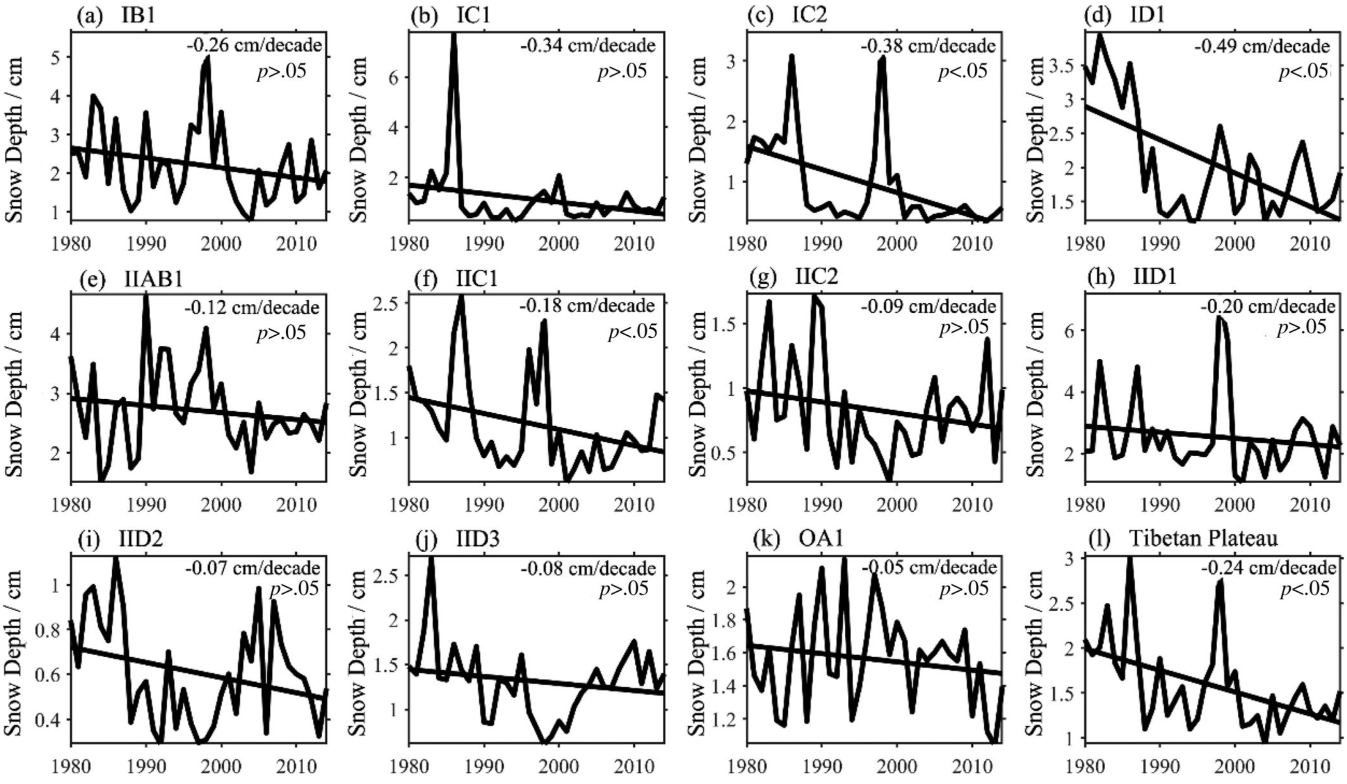

FIGURE 3 Time series and linear trends of annual mean snow depth for different sub-regions (a–k) and whole study area (l) from 1980 to 2014 over TP. Inset numbers show trend magnitudes; $p < .05$ indicates statistically significant trend

northwest. Previous researchers have made similar observations (Duan *et al.*, 2015; Duan and Xiao, 2015; You *et al.*, 2016). In addition, the western, northern, and eastern parts of TP have experienced a decline trend (−50 to 0 mm/decade) in precipitation (Figure 4d), which may have significantly affected snow depth in these regions. Upon first glance, it may appear that temperature plays a more prominent role than precipitation in snow depth reductions over different parts of the TP. Compared to the low correlation between snow depth and precipitation, however, the correlation coefficients between the time series of snow depth and air temperature at annual and seasonal scales are higher and statistically significant. This further indicates that air temperature has a stronger regulatory effect on snow depth (Figure S7).

3.2 | Elevation-dependent variation of snow depth and temperature/precipitation

Table 1 shows annual and seasonal trends of snow depth in different sub-regions ordered by mean elevation. The strongest decreasing trends can be found in higher sub-regions (sub-regions IC2 and ID1 ≥5,000 m a.s.l). Annual snow depth at high elevations decreases significantly; this phenomenon is most obvious in the colder seasons (Table 1). An increase in snow reduction at higher elevations appears to be more closely related to elevational patterns of temperature change (Table 2) than of precipitation change (Table 3). For example, the trend magnitude in the highest sub-region ID1 (average elevation: 5074 m) ranges from −0.74 to −0.18 cm/decade, which in all cases is more rapid than the rate in the lowest sub-region IID2 (average elevation: 3332 m) from −0.16 to 0 cm/decade.

Snow depth is sensitive to changes in air temperature and changes in snow depth can, in turn, affect air temperature via the snow albedo feedback mechanism (You *et al.*, 2016; Guo *et al.*, 2019b). Our observations suggest that EDW over the TP (faster-rising temperatures at higher elevations) exacerbates a reduction in snow depth at higher elevations. This is consistent with the positive feedback effect between snow depth and temperature. A recent study (Guo *et al.*, 2021) puts forward that large-scale atmospheric forcing first causes regional mean warming over the TP, then this warming causes an elevation-dependent decrease in snow depth, which is especially pronounced at higher elevations. The elevation-dependent decrease in snow depth trend may further cause EDW by reducing the snow/ice albedo and increasing the surface absorption of solar radiation (You *et al.*, 2016). Finally, EDW causes an elevation-dependent decrease in snow depth that forms a positive feedback loop (Guo *et al.*, 2021).

To further identify regions where the elevation-dependent variations of snow depth, temperature, and precipitation are related, we calculated trend magnitudes for all grid points at the annual scale for each sub-region

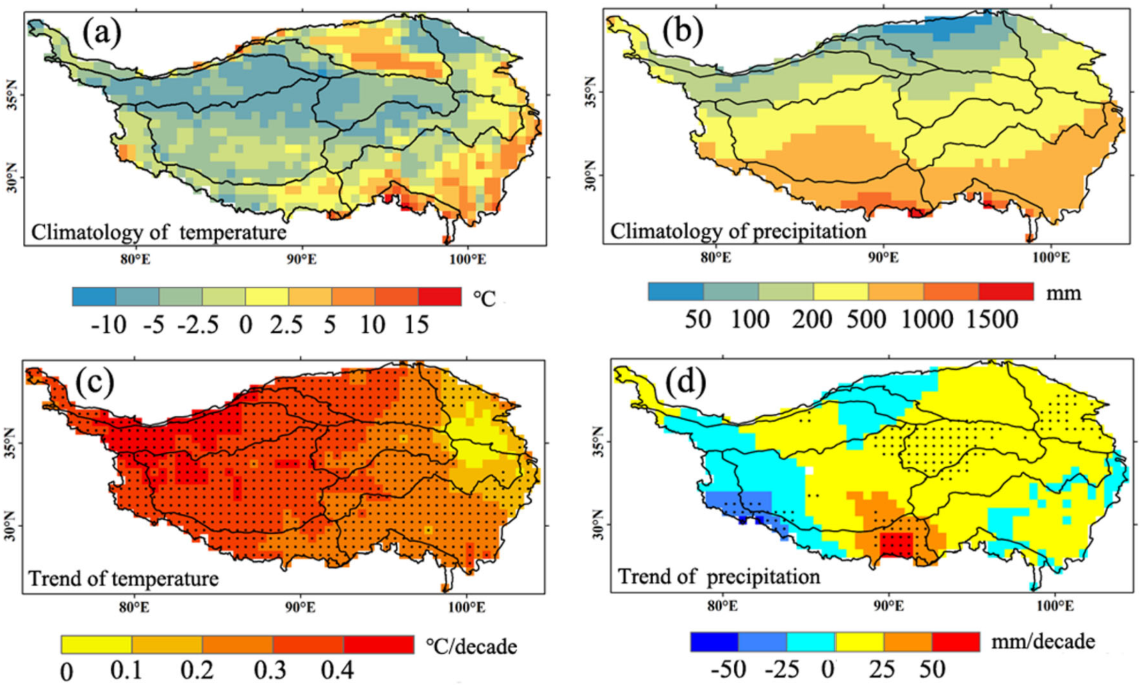

FIGURE 4 Annual mean (a) temperature and (b) precipitation over TP during 1980–2014. Linear trends of (c) temperature and (d) precipitation for each grid point in every sub-region. Dotted regions show trend magnitudes significant at $p < .05$

TABLE 1 Annual and seasonal trends (cm/decade) of snow depth in 11 sub-regions during 1980–2014 over TP

Region Elevation (m)	IID2 3,332	OA1 3,523	IIC2 3,538	IIAB1 4,151	IID3 4,248	IB1 4,474	IC1 4,625	IIC1 4,853	IID1 4,936	IC2 5,035	ID1 5,074	TP 4,447
DJF	0.00	−0.13	−0.17	−0.36	−0.08	−0.72	−0.83	**−0.49**	−0.40	**−0.67**	**−0.74**	**−0.48**
MAM	**−0.16**	0.03	**−0.14**	−0.15	**−0.17**	−0.30	**−0.33**	−0.12	−0.19	**−0.36**	**−0.6**	**−0.27**
JJA	**−0.02**	−0.01	**−0.03**	−0.01	0.04	−0.02	**−0.02**	**−0.02**	**−0.18**	**−0.09**	**−0.18**	**−0.05**
SON	**−0.08**	**−0.10**	−0.01	0.05	−0.10	0.00	−0.19	−0.09	−0.02	**−0.41**	**−0.44**	**−0.16**
Annual	−0.07	−0.05	−0.09	−0.12	−0.08	−0.26	−0.34	**−0.18**	−0.20	**−0.38**	**−0.49**	**−0.24**

Note: Bold trends indicate values significant at the 95% confidence level.

TABLE 2 Annual and seasonal trends (°C/decade) of temperature in 11 sub-regions during 1980–2014 over TP

Region Elevation (m)	IID2 3,332	OA1 3,523	IIC2 3,538	IIAB1 4,151	IID3 4,248	IB1 4,474	IC1 4,625	IIC1 4,853	IID1 4,936	IC2 5,035	ID1 5,074	TP 4,447
DJF	0.22	**0.42**	0.07	**0.43**	0.23	**0.42**	**0.45**	**0.44**	**0.24**	**0.47**	**0.31**	**0.36**
MAM	**0.39**	**0.28**	**0.27**	**0.23**	**0.51**	**0.20**	**0.26**	**0.35**	**0.54**	**0.39**	**0.48**	**0.34**
JJA	**0.40**	**0.14**	**0.27**	**0.19**	**0.38**	**0.20**	**0.28**	**0.18**	**0.30**	**0.26**	**0.37**	**0.27**
SON	0.18	**0.17**	−0.03	0.11	**0.41**	0.04	0.11	**0.26**	**0.45**	**0.33**	**0.43**	**0.22**
Annual	**0.30**	**0.25**	**0.15**	**0.24**	**0.38**	**0.21**	**0.28**	**0.31**	**0.38**	**0.36**	**0.40**	**0.30**

Note: Bold trends indicate values significant at the 95% confidence level.

TABLE 3 Annual and seasonal trends (mm/decade) of total precipitation in 11 sub-regions during 1980–2014 over TP

Region Elevation (m)	IID2 3,332	OA1 3,523	IIC2 3,538	IIAB1 4,151	IID3 4,248	IB1 4,474	IC1 4,625	IIC1 4,853	IID1 4,936	IC2 5,035	ID1 5,074	TP 4,447
DJF	0.13	**−3.72**	0.21	−0.79	2.98	−0.09	−0.11	−4.34	−0.68	−2.03	3.34	−0.43
MAM	−0.26	11.38	−0.16	5.61	−0.61	**2.92**	0.69	4.93	−10.75	1.81	0.32	1.8
JJA	1.16	2.77	4.51	1.42	−1.89	4.42	**8.19**	16.07	−7.82	7.24	−2.11	3.87
SON	1.91	−2.54	**5.69**	−1.97	0.00	0.96	3.49	2.08	−2.13	−0.31	0.10	0.53
Annual	2.95	7.88	**10.25**	4.27	0.48	8.22	**12.26**	18.75	−21.38	6.70	1.66	5.77

Note: Bold trends indicate values significant at the 95% confidence level.

and investigated their distribution with elevation. Not all sub-regions show remarkable elevation-dependent variations but some do (Figure 5). For example, significant decreases in snow depth in sub-regions IB1, IIAB1, and OA1 are strongly related to elevation. Southeastern parts of the TP in general show an accelerating reduction in snow depth with increasing elevation and positive EDW (Figure 5). At the seasonal scale, the characteristics of climatic factors (snow depth, air temperature, and precipitation) versus rising elevation in various sub-regions are similar to those at the annual scale (Figures S8, S10, and S11), except in summer (Figure S9). The trend magnitudes of snow depth and precipitation in winter are both largest among all seasons and thus may dominate the annual variations.

Figure 6 shows a schematic diagram of interannual variations in snow depth, temperature, and precipitation as well as the elevation-dependent variation characteristics based on the results shown in Figure 5. Snow depth over the TP appears to have considerable spatial heterogeneity, which may be attributed to the different climate circulation systems covering the region. In areas dominated by westerlies, rapid warming and significant snow reduction are observable. However, the decreases in snow depth over the central and eastern TP are relatively weak. On the whole, the TP is mainly

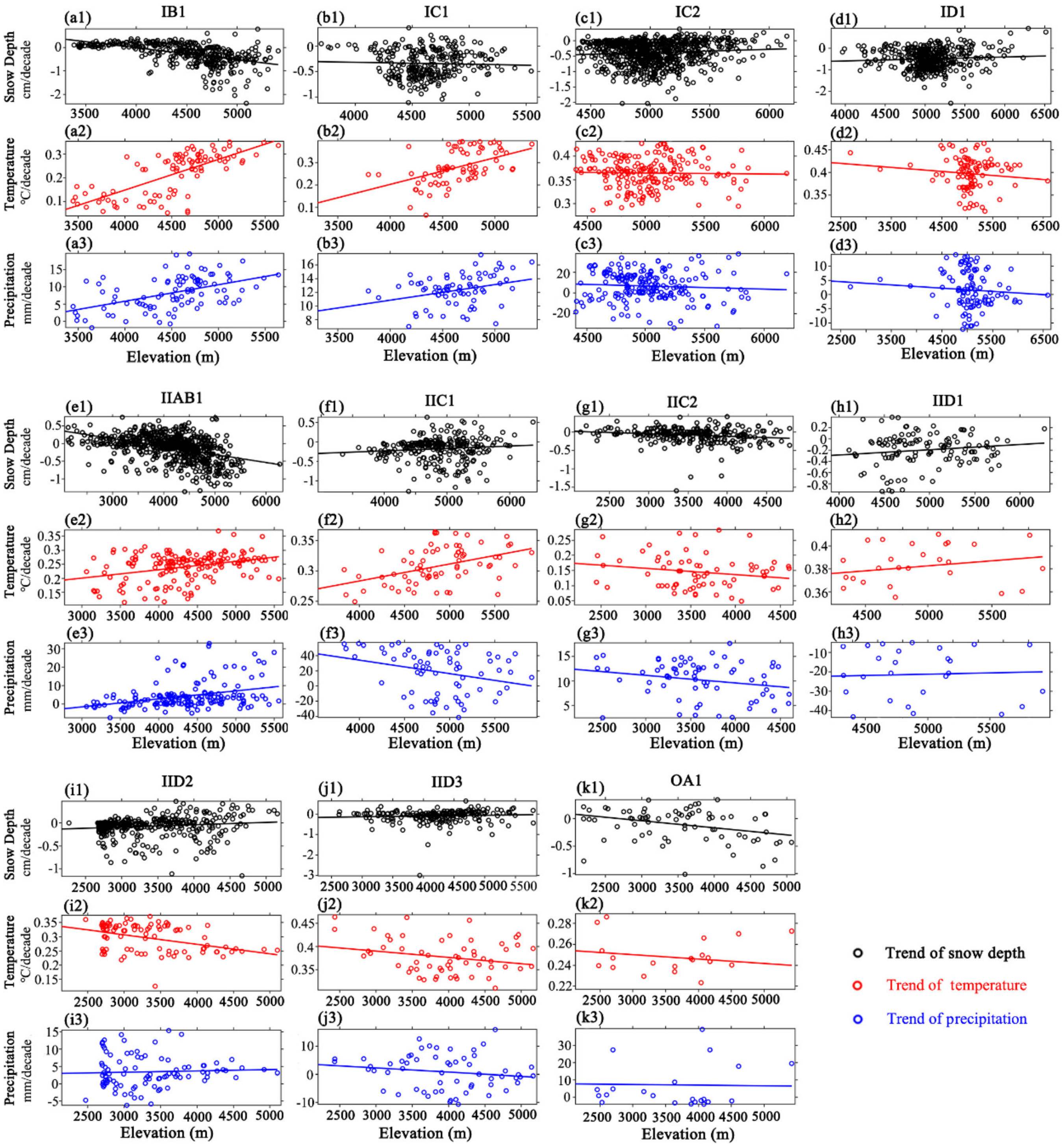

FIGURE 5 Trends of snow depth (a1–k1), temperature (a2–k2), and precipitation (a3–k3) versus elevation based on all pixels for each sub-region (1980–2014)

characterized by warming and wetting trends during 1980–2014 accompanied by an overall decrease in snow depth (Figure 6). The most pronounced EDW and elevation-dependent variations of snow depth trends simultaneously occur in the southeastern TP, where the largest difference in elevation (from 2,000 to 6,000 m) is located.

We also found some slight spatial heterogeneity in the seasonal patterns. For example, the temperature in the northern TP increases significantly in spring, summer, and autumn (Figures S12–S14) but not in winter (Figure S15). At the overall seasonal scale, the above-mentioned elevation-dependent variation of temperature and snow depth trend also occurs in the southeastern TP.

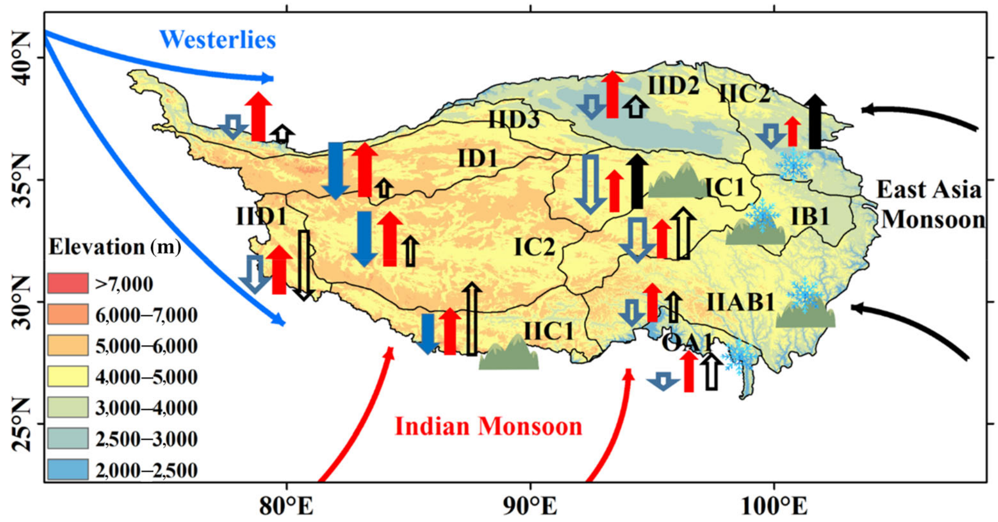

FIGURE 6 Schematic diagram of snow depth (blue arrow), temperature (red arrow), and precipitation (black arrow) trends with characteristics of elevation-dependent variations (based on Figure 5) at annual scale during 1980–2014 over TP. Arrow sizes represent trend magnitudes; solid arrows indicate statistical significance. Mountain illustrations represent areas with distinct positive EDW and snowflakes indicate sub-regions characterized by increasing snow trend reduction versus rising elevation (also shown in Figure 5)

4 | DISCUSSION AND CONCLUSIONS

In the context of the rapid warming of the TP (Pepin *et al*., 2015; You *et al*., 2016; Pepin *et al*., 2019), as well as glaciers (Yao, 2004) and permafrost (Guo and Wang, 2016), snow has undergone significant variation and plays an important role in global climate change (Kang *et al*., 2010). In this study, we assessed the spatio-temporal characteristics of snow depth over the TP, with special focus on its vertical variations and relationship with elevation-dependent changes in temperature.

In contrast to the watershed boundaries or north–south divisions made by some scholars (Smith and Bookhagen, 2018; Li *et al*., 2020), we adopt a climate zoning approach based on hydrothermal conditions (Zheng, 1996) and similar climatic conditions within the same sub-region. Rather than limited surface in situ observations and MODIS data, which can easily be disturbed by cloud cover (Tang *et al*., 2013; Huang *et al*., 2016; Xu *et al*., 2017; Xuejin *et al*., 2019), we use passive microwave data which has an extended time series, wider spatial coverage, and is not affected by inclement weather (Che *et al*., 2008).

Our results indicate a significant decreasing trend in snow depth in the central and western parts of the TP and an increasing trend in the eastern parts of the TP. This is consistent with the findings of Wang *et al.* (2018), who used a snow dataset from the National Snow and Ice Data Center (NSIDC) for the period 1979–2006, and with Smith and Bookhagen (2018), who used SWE data. Wang *et al.* (2018) pointed out that increased snowmelt following warming temperatures may be responsible for the decrease in snow cover across western and southern parts of the TP, whereas increased snowfall (due to increased atmospheric moisture and enhanced upward motion under rapid warming, which offset some of the melting) may contribute to the increasing trend in snow depth in central-eastern TP (Wang *et al*., 2018). The overall annual mean snow depth over the TP, especially in western sub-regions IC2, ID1, and IIC1, decreases significantly over the period 1980–2014. This highlights the urgent need for a scientific and reasonable socioeconomic development roadmap, as well as the implementation of climate change mitigation and adaptation measures.

Snow depth tends to decrease faster at higher elevations ($p < .05$) than at lower elevations (Table 1). We also found faster warming rates at higher elevations, especially at the annual scale (Table 2), which is consistent with previous studies (Rangwala *et al*., 2009; You *et al*., 2020b). There are slight differences among sub-regions and seasons, but positive EDW (enhanced warming rates at higher elevations) appears to greatly contribute to the strong decrease in snow depth in general; positive EDW also may accelerate the reduction in snow depth at higher elevations over the TP across our observation period. However, EDW is not present in all sub-regions. Li *et al.* (2020) similarly suggested that EDW only occurs in certain areas, which is consistent with our results (Figure 6). The most pronounced EDW and elevation-dependent variations of snow depth simultaneously occur in the southeastern TP, where the largest difference in elevation from 2,000 to 6,000 m is located. Previous work in this region has revealed a decrease in lower-level and total cloud cover during daytime hours and vice versa during nighttime, which brings more solar radiation to the ground at higher elevations (Duan and Wu, 2006).

One question which cannot easily be answered due to a lack of sufficient data is whether the elevation-dependent profiles in snow decline extend to extremely high elevations above 5,000 m. Gao *et al.* (2018) suggested that neither ERA-Interim data nor Weather Research and Forecasting (WRF) data indicate EDW above 5,000 m despite some differences in details. Within the sub-regions, those grid points above 5,000 m also show insignificant temperature increases with rising elevation (Figure 5) corresponding to an insignificant snow depth reduction, which is consistent with the findings of Gao *et al.* (2018). Ultra-high elevation mountain regions may be more strongly influenced by tropospheric and stratospheric atmospheric circulations (Nan *et al.*, 2009; Zhu *et al.*, 2018) than mountain surface features. Pepin *et al.* (2019) pointed out that maximum warming exists around 4,500–5,500 m in the Nyenchen Tanglha Mountains, and that warming stabilizes at extremely high elevations in the Himalayas – including absolute cooling above 6,000 m. A previous study also showed that the rate of warming in the TP reverses above 4,500 m (Guo *et al.*, 2019a). Smith and Bookhagen (2018) found that maximum snow depth occurs below the highest elevation peaks in a given area, which suggests that the highest elevations may actually have less snow than lower elevations –particularly in windy locations. At extremely high elevations (above 5,000 m), there may cease to be any elevation-dependent variation of snow depth (Smith and Bookhagen, 2018).

In this study, we used a linear method to detect TP sub-regions wherein snow depth, temperature, and precipitation changes with elevation are most pronounced. Previous researchers have pointed out that elevation-dependent characteristics may be nonlinear (Xu *et al.*, 2017; Smith and Bookhagen, 2018). It is only necessary to satisfy that rates of changes in climatic factors vary systematically with elevation to attribute this to EDW (Pepin *et al.*, 2015). More accurate identification methods are still needed to precisely quantify the exact form of elevation-dependent features over the TP and other elevated regions.

Snow depth over the TP is influenced by many factors including temperature, precipitation, topography, and wind-induced snow redistribution. The elevation-dependent variations in snow depth, in addition to being influenced by EDW (temperature), may also be influenced by snow/ice-albedo feedback, water vapor feedback, cloud radiation feedback, aerosol changes, land-use changes, and vegetation cover (Cui *et al.*, 2006; Duan and Wu, 2006; Rangwala *et al.*, 2009; Kang *et al.*, 2010; Tian *et al.*, 2014; Ren *et al.*, 2016; You *et al.*, 2020c; Guo *et al.*, 2021). Among these factors, the positive relationship between EDW and elevation-dependent decrease in snow depth may be the most direct (and important). For instance, large-scale atmospheric forcing causes regional warming over the TP which decreases snow depth, especially at higher elevations. Decreasing snow depth drives down the surface albedo and increases surface solar radiation absorption, which strengthens EDW and in turn affects the extent to which snow depth decreases. In short: these factors form a positive feedback loop (Guo *et al.*, 2021). The relevant mechanisms merit further study, as comprehensively understanding them can positively impact mountain water management and responses to climate change.

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CONFLICT OF INTEREST

The authors declare no competing interest in this work.

ORCID

Liucheng Shen https://orcid.org/0000-0003-1825-5872

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SUPPORTING INFORMATION

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