https://doi.org/10.5194/egusphere-2024-1008
Preprint. Discussion started: 13 May 2024

Increasing Area and Decreasing Depth: Climate Change Influence on Snow Variations in the Qilian Mountains

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Abstract: The Qilian Mountains serve as a critical water source for the Yellow River and various inland rivers, playing a pivotal role in regulating the regional climate. Given their significance as one of the foremost water resources in the area, the spatial and temporal dynamics of the snow are crucial for understanding potential impacts on regional hydrology and ecology. This study examines the characteristics of spatial and temporal variations in snow-covered extent (SCE), snow depth (SD), snow-covered days (SCD), snow onset date (SOD), and snow end date (SED) within the Qilian Mountains region. We investigate the hydrological and ecological implications utilizing snow area and phenology data, alongside SD data. The findings indicate that:(1) the distribution of snow across the Qilian Mountains mainly splits between the central and western areas, with the central region showing deeper snow than both the eastern and western parts; (2) the area covered by snow in the Qilian Mountains is growing, but the depth of the snow is on a decline, especially in the central area; (3) in terms of snow phenology, most of the region is witnessing an earlier start of SOD , a longer SCD, and an earlier SED.An overall increase in

https://doi.org/10.5194/egusphere-2024-1008
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precipitation is identified as the key factor behind the expanded SCE in the Qilian Mountains, while rising temperatures are pinpointed as the primary cause for the reduction in SD. As global climate change intensifies, the observed alterations in the snow of the Qilian Mountains present emerging challenges for regional water security and ecological equilibrium.

Keywords: Qilian Mountains, snow, water resources, climate change

1. Introduction

Snow constitutes the predominant form of cryospheric moisture (Pulliainen, J., et al. 2020).It is estimated that over one-sixth of the global population relies on glaciers and seasonal snows as a critical water supply (Barnett, J., et al. 2005). Alpine regions play a crucial role in serving as reservoirs for ice and snowmelt recharge. Specifically, the Qilian Mountains capture airborne water vapor, leading to the formation of both permanent glaciers and seasonal snows. This process underpins the watershed of numerous streams that sustain the Hexi Corridor and the Qaidam Basin (Zhu, et al. 2022). Consequently, a comprehensive understanding of the spatial and temporal dynamics of mountain snow, alongside its evolving patterns, is imperative for safeguarding the ecological equilibrium of oasis environments. Furthermore, such knowledge is vital for ensuring the continued sustainable development of both the economy and society within arid regions.

Globally, approximately 78% of mountainous snow exhibits a declining trend, characterized by a reduction in snow duration by up to 43 days in extreme cases and a decrease in snow-covered area by up to 13% (Notarnicola, et al. 2020). Within the highland rangelands of Central Asia, a positive correlation has been observed between the Peak Height of Vegetation (PH) and snow-covered days (SCD), alongside a negative correlation between Thermal Time to Peak (TTP) and SCD. Topographical attributes, particularly slope and orientation, have been identified to significantly influence the snow end date (SED) (Tomaszewska, et al. 2020). Snow phenology parameters such as SCD, snow onset date (SOD), and SED have undergone notable changes in the arid regions of Asia (Tang, et al. 2022). An increasing trend in snow has been documented on the southwestern edge and southeastern part of the Tibetan Plateau (Huang, et al. 2016). Since the turn of the millennium, the consequences of global warming have grown increasingly pronounced, making snow changes in the Northwest a subject of considerable interest in climate change research.

The effects of climate change on the cryosphere have significantly influenced hydrological processes and water resources in mountainous areas, leading to increased runoff due to accelerated glaciation and snowmelt (Dibesh, et al. 2014). Therefore, analyzing the snow depth(SD), along with spatial and temporal variation characteristics of snow in the Qilian Mountains, holds paramount importance for comprehending climate change and ecological evolution in mountainous regions. While previous research has predominantly concentrated on changes in snow-covered extent (SCE) and SD, a comprehensive analysis of the spatio-temporal patterns of snow phenology across the Qilian Mountains is critical for appraising and forecasting future climatic conditions. Furthermore, to gain a more profound understanding of the alterations in snow and snow phenology, along with their driving mechanisms and impacts on the global climate system, it is imperative to conduct analyses on the scale of the entire study area.

Snowmelt water plays a critical role in supporting local agriculture and livestock irrigation; consequently, variations in the SCE can profoundly impact local environmental dynamics and human livelihoods. Situated in the arid region of Central Asia, the Qilian Mountains experience substantial snowfall in winter, whereas summers are characterized by high temperatures and scant rainfall, positioning snowmelt runoff as a pivotal water resource for urban, agricultural, and industrial development within the region (Wu, et al. 2021). Hence, sustained and precise monitoring of the temporal and spatial variations in the SCE of the Qilian Mountains is of both practical and theoretical importance. Such efforts are crucial for advancing our understanding of snowmelt runoff dynamics in mountainous areas, facilitating the effective management and utilization of water resources, and preparing for winter snowstorms and spring and summer floods in pastoral and agricultural regions, respectively.

This study employs snow data spanning from 1980 to 2019 to analyze the spatial and temporal patterns of changes in snow depth and area within the Qilian Mountains, aiming to:(1) delineate the processes underlying spatial and temporal variations in snow accumulation; (2) identify the characteristics of snow volume and snow phenology; and (3) investigate the implications of snow accumulation changes for watershed water resources. The findings of this research offer a scientific foundation for elucidating the impacts of climate change on the Qilian Mountains' snow and for guiding the protective management, rational development, and utilization of snow resources in the area.

2.Data and methods

2.1Study area

The Qilian Mountains, situated in the northeastern segment of the Qinghai-Tibet Plateau, span across Qinghai and Gansu Provinces. Characterized by its complex and varied topography, the region predominantly features altitudes ranging from 3,500 to 5,000 meters. Owing to its positioning within the north temperate zone and the consequential effects of elevation, the Qilian Mountains region records an average annual temperature that generally remains below 4 degrees Celsius.Precipitation patterns within this area are influenced by a myriad of factors, including altitude, geographic location, as well as the slope and orientation of the terrain, resulting in pronounced seasonal and inter-annual variabilities.The Qilian Mountains encompass a diverse snow classification, comprising permanent snow areas, stable seasonal snow areas, annually cyclical unstable seasonal snow areas, and non-annually cyclical unstable seasonal snow areas. This diversity culminates in a multifaceted snow distribution pattern across the region.

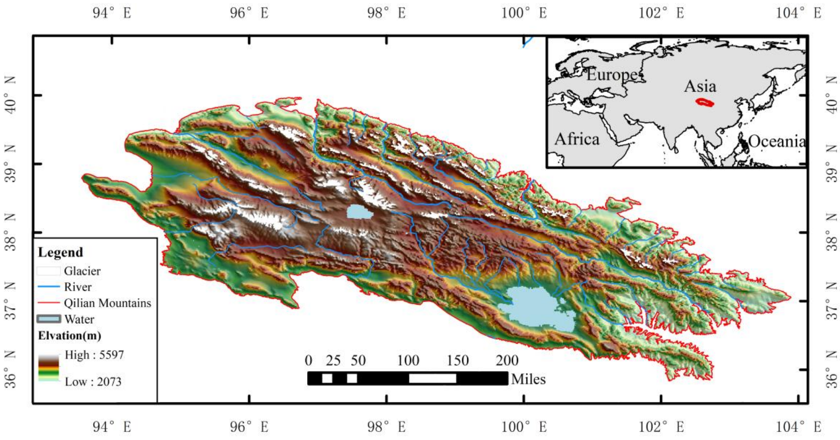

Fig. 1 Study area

2.2Data description

This research leveraged snow data products from the period 2000-2020, obtained from the National Cryosphere Desert Data Center (NCDC), including MODIS (Moderate Resolution Imaging Spectroradiometer) day-by-day clear-sky snow products and phenology dataset products. Furthermore, it utilized the "Big Earth Data" longitudinal snow depth dataset (referenced in Table 1). This dataset elucidates the snow accumulation characteristics across China, employing the MODIS reflectance product MOD/MYD09GA. A novel multi-index combined snow accumulation discrimination algorithm was developed, tailored to different land cover types. This algorithm notably enhances the precision of identifying snow accumulation areas within forested and mountainous regions. Additionally, it implements complete cloud removal using the Hidden Markov Model and integrates multi-source data fusion methodologies.

The data fusion framework integrates various sources, including the Advanced Microwave Scanning Radiometer-2 (AMSR2), Global Snow Monitoring for Climate Research (GlobSnow), Northern Hemisphere Snow Depth (NHSD), ERA-Interim, and the Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2). It incorporates geographic (latitude and longitude) and topographical (elevation) data as input independent variables. Utilizing over 30,000 terrestrial-based observations as dependent variables, the models underwent training and validation across distinct temporal scales. This comprehensive fusion framework yielded a longitudinally continuous daily snow depth dataset for the Northern Hemisphere, featuring a spatial resolution of 0.25°.

Table 1 Data source

Data name	Spatial resolution/m	Temporal resolution	Format	Number of files	Source
A long-term daily gridded snow depth dataset for the Northern Hemisphere from 1980 to 2019 based on machine learning	27000	1day	TIF	10,656	Big Earth Data （https://doi.org/10.1080/20964471.2023.2177435）
China MODIS Daily Cloudless 500m Snow Area Product Dataset	500	1day	HDF5	7,614	National Cryosphere Desert Data Center(www.ncdc.ac.cn)
A dataset of snow phenology in China based on MODIS from 2000 to 2020	500	1year	TIF	60	National Cryosphere Desert Data Center(www.ncdc.ac.cn)
1-km monthly precipitation dataset for China (1901-2022)	1000	1month	NetCDF	1,464	National Tibetan Plateau Data Center （https://data.tpdc.ac.cn/）
CSR GRACE/GRACE-FO RL06.2 Mascon Solutions (RL0602)	27000	1month	NetCDF	255	Gravity Recovery and climate Experiment （http://www2.csr.utexas.edu/grace）

2.2Data processing

2.2.1Snow cover

The presence of extensive cloud cover in snow-covered regions presents a significant challenge to the utilization of MODIS (Moderate Resolution Imaging Spectroradiometer) snow products for snow monitoring. This study has addressed this issue by employing a day-by-day cloud-free dataset, which classifies data as follows:0 for land, 1 for image-recognized snow, 2 for de-clouded interpolated snow, 3 for snow-depth interpolated snow, 4 for water, and 255 for regions that are unrecognizable. Prior to analysis, the snow product undergoes a preprocessing phase. Given that the product is in the HDF5 format, a batch conversion to the GeoTIFF format, which incorporates a geographic coordinate system (GCS), is necessary to facilitate visualization. Subsequent steps involve cropping the data to match the study area and reclassifying snow raster values (where t=1,2,3) to i=1 (indicating snow presence), and no-snow raster values (where t=0,4,255) to i=0 (indicating snow absence). The mean values of these raster datasets within the study area are then calculated using band set statistics to determine the snow-covered extent (SCE).To accurately delineate the snow-covered area, a conversion from the geographic coordinate system (GCS) to a projected coordinate system (PCS) is required. This process, along with operations such as image superimposition and geometric computation, facilitates the determination of the study area's snow-covered area. Data preprocessing is accomplished through the application of Python programming and MODIS-specific software tools, including the MODIS Reprojection Tools (MRT) and the Environment for Visualizing Images (ENVI).

$$SCE（\%）=\frac{Count（i=1）}{Count（i=1，0）}$$

2.2.2Snow depth

Research on SD predominantly concentrates on the snow period, which is characterized by the presence of snow with considerable depth. Defined as the interval during a year when snow is continuous, the snow period generally extends from the occurrence of the first widespread snowfall to the complete melting of spring snow, traditionally spanning from November 1 to March 31 of the subsequent year. In the context of this study, the time series of SD dataset products were reclassified to align with the snow accumulation period, utilizing an extensive data series from 1980 to 2019. This reclassification was further delineated into five-year intervals: 1980-1984, 1985-1989, 1990-1994, 1995-1999, 2000-2004, 2005-2009, 2010-2014, and 2015-2019. The objective of calculating the average SD during the snow period was to facilitate a more intuitive understanding of the overall snow dynamics and its temporal variations.

2.2.3Snow Phenology

Similar to the methodology applied to the analysis of SCE, the study employed a

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Preprint. Discussion started: 13 May 2024

reassignment approach for raster data, subsequently reclassifying the snow phenology dataset in accordance with the hydrological year by segmenting the product time series. The evaluation of SCD、SOD and SED was conducted on an annual basis, per hydrological year and per image element. These calculations derived from the predefined snow-covered climate parameters tailored for China, spanning the years 2000 to 2020, facilitated a nuanced understanding of snow dynamics within the specified period.

3 Results

3.1 Spatial and temporal variation of snow area in the Qilian Mountains

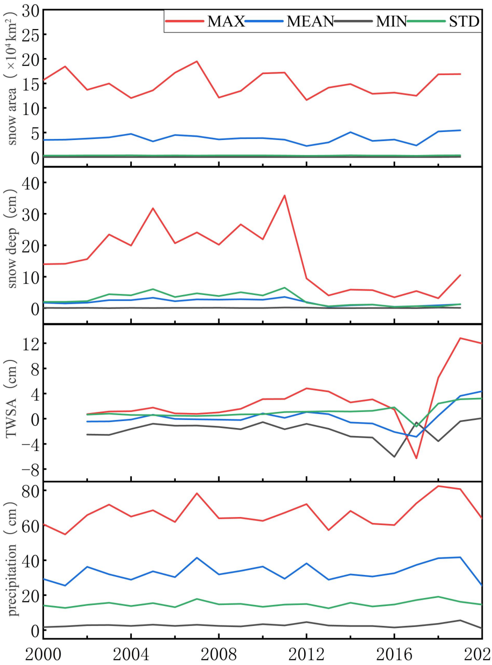

Fig. 2 Interannual Changes in snow area, snow deep, Terrestrial Water Storage Anomaly (TWSA), and precipitation in Qilian Mountains 2000-2020

The analysis of the interannual mean snow in the Qilian Mountains from 2000 to 2020 reveals a generally fluctuating upward trend, characterized by periods of increase and decrease. Specifically, increments were observed during the periods of 2000/2001-2004/2005, 2012/2013-2014/2015, and 2017/2018-2019/2020, while declines were noted in 2006/2007-2012/2013 and again in 2015-2017/2018. The peak of the interannual mean snow-covered area was recorded in 2019/2020, reaching approximately 5.45×10^4km^2,whereas the lowest extent was observed in 2012/2013, at nearly 2.26×10^4km^2. Over the entire study period from 2000/2001 to 2019/2020, the trend of the mean snow-covered area exhibited a growth rate of approximately 0.17×10^4km^2/a per annum.A historical maximum snowage area was noted on January 27, 2008, with an extent of 19.47×10^4km^2, corresponding to a 94.52% snow. In contrast, the year 2012/2013 recorded the lowest maximum snow area within the same timeframe, with a coverage of11.6×10^4km^2 and snow constituting 78.35%. It is notable that during most years, there was at least one day with a complete absence of snow in the ablation period. Exceptions to this pattern were recorded in 2002/2003 and 2019/2020, during which snow persisted throughout the year, maintaining minimal areas of82.4km^2 and 206.01km^2, respectively. Peak snow areas in the Qilian Mountains typically manifested in November and January.The analysis identified four notable peaks in the inter-annual mean snow area, occurring in 2004/2005 (4.72×10^4km^2), 2014/2015 (5.07×10^4km^2), 2018/2019 (5.21×10^4km^2), and 2019/2020 (5.45×10^4km^2). Additionally, the SCE within the Qilian Mountains exhibited significant seasonal variability. December and January witnessed the highest SCE levels, characterized by substantial fluctuations, whereas from June to September, the SCE's standard deviation decreased, often reaching a low value or even zero, as depicted in Figures 2 and 3.

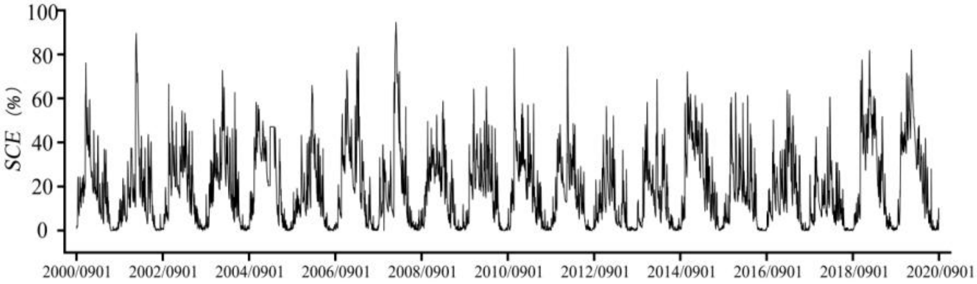

Fig. 3 Changes in SCE (%) of snow in the Qilian Mountains for multi-year days 2000-2020

3.2 Spatial and temporal variations of snow in the Qilian Mountains

SD is widely recognized as a crucial metric for assessing snow conditions. It is defined as the vertical thickness of snow present on the ground. While SD does not provide direct information about the volume or mass of the snow, it serves as a reliable proxy due to the simplicity and immediacy of its measurement. In this research, the multi-year average SD within the Qilian Mountains snow was evaluated using data collected from 1980 to 2019. The analysis of this dataset reveals distinct spatial distribution patterns of snow across the Qilian Mountains, with the highest concentrations of snow predominantly located in the mountain range's central area. These spatial characteristics highlight a notable trend: regions east of 98°E exhibit greater snow accumulations compared to those west of 98°E. Furthermore, regarding elevation distribution, the elevated areas west of 98°E, particularly those with altitudes ranging between 3,500 and 4,000 meters and featuring SDs exceeding 5 cm, serve as the primary zones for substantial snow accumulation. This observation underscores a significant concentration of the densest snow within the central sector of the Qilian Mountains, establishing a demonstrable link between snow accumulation patterns and both geographical positioning (longitude) and elevation (Fig. 5a).

Between 2005 and 2009, the observed spatial distribution of SDs within the region was favorable, especially in zones where SDs ranged from 15 to 20 centimeters. Conversely, the period from 2015 to 2019 marked a significant reduction in the region's SD performance, with average SDs consistently registering between 0 and 5 centimeters across the area. This pattern denotes a marked, initial uptrend in snow within the Qilian Mountains region from 1980 to 1984, progressing through to 2005-2009. Post-2009, however, the trend in snow began to demonstrate a decline, with regions previously averaging more than 5 cm in SD gradually diminishing until such extents were no longer observed (Fig. 3). In synthesizing the SD distribution data across the Qilian Mountains over the past four decades, it becomes evident that the interval from 2005 to 2009 represented a zenith in terms of snow levels within the region, succeeded by a substantial decline between 2015 and 2019. This observed trend underscores the susceptibility of the region's snow distribution to climatic shifts and anthropogenic influences. Consequently, it heralds potential future challenges for climate change mitigation efforts and strategies pertaining to regional water resource management.

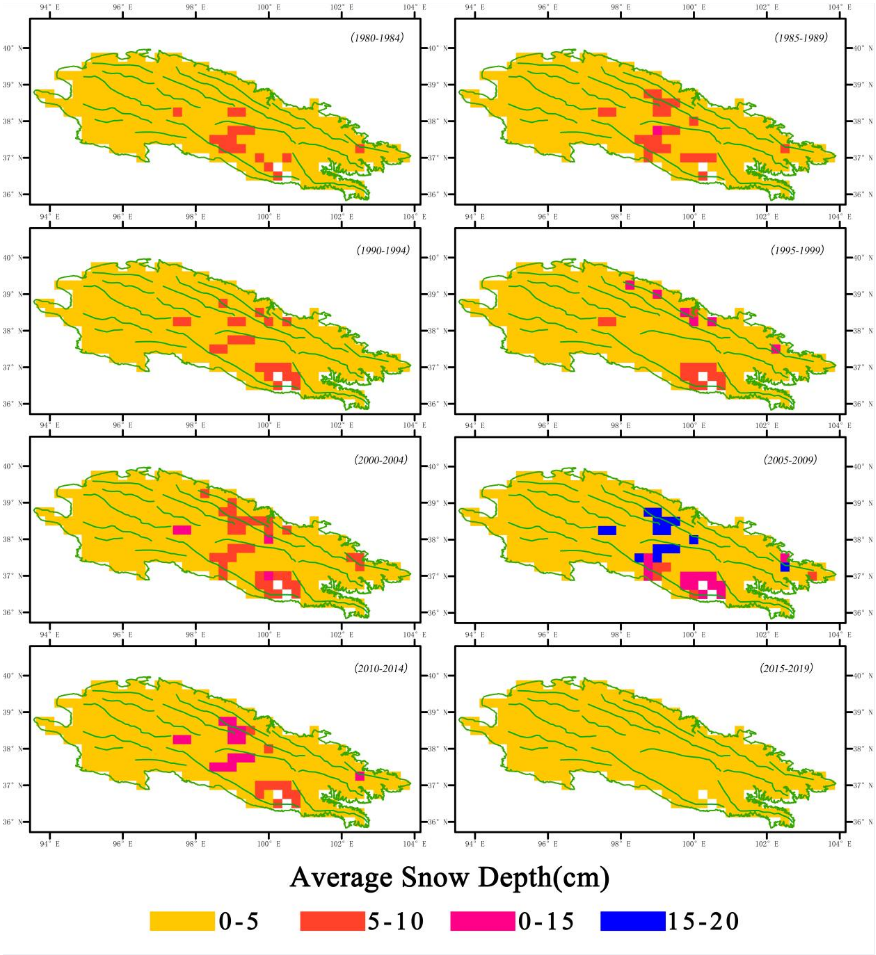

Fig. 4 Changes in the distribution of mean SD in the Qilian mountainous area snow from 1980-2019

The analysis of inter-annual variations in the mean SD in the Qilian Mountains from 1980 to 2019 reveals that the SD exhibited significant volatility up to the 1994/1995 period. Subsequently, a gradual yet steady upward trend in SD was observed until the 2005/2006 period. Despite experiencing some fluctuations within this time frame, the SD consistently increased, culminating in a peak depth of 3.577 cm in the 2011/2012 season. It is critical to underscore that, post-2011, the SDs have undergone a marked decline. Although this decline was interspersed with periodic fluctuations, the overall SD levels have persistently remained low up until 2019. This analysis highlights notable temporal fluctuations in SD within the region, underscoring a period of growth followed by a significant and sustained reduction in depths observed in recent years.

The analysis of the interannual rate of change in mean SD between 1980 and 2019 within the

Qilian Mountains demonstrates a significant decreasing trend in SD to the east of 98°E. This decline is notably acute at elevations around 3,500 meters, where the inter annual rate of change for the majority of this region registers at less than -0.04 cm/year. Historically, this area has been characterized by relatively deeper SDs. In contrast, regions situated to the west of 98°E exhibit a modest increase in SD, with inter annual rates of change varying between 0.04 and 0.08 cm/year (Fig. 5b). These contrasting trends likely underscore the spatial heterogeneity of climate change impacts across different regions and highlight how topographical and elevation gradients influence precipitation and temperature distributions.

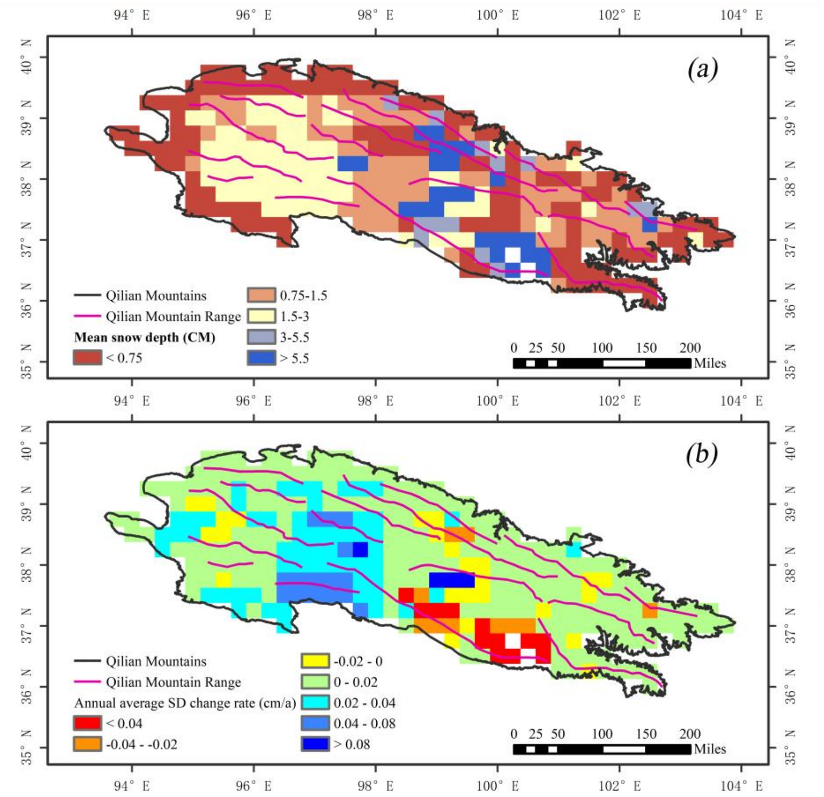

Fig. 5 Mean SD in the snow of the Qilian Mountains, 1980-2019 (a) Distribution of mean SD; (b) Distribution of inter-annual rate of change of mean SD

3.3Alterations in snow Phenology within the Qilian Mountains

The physical characteristics of the snow within the Qilian Mountains exhibit substantial spatial heterogeneity. This study analyzed the spatial distribution characteristics of the SOD、SED and SCD utilizing observational data, which revealed pronounced disparities. Generally, the SOD across the region predominantly occurs post-December, while the SED is chiefly observed before May of the subsequent year, with the SCD primarily spanning 0 to 40 days. However, this broad characterization markedly contrasts with the conditions observed in the High Altitude Mountains.In the higher elevation zones, the climatic attributes of the snow display an earlier SOD and a later SED. Specifically, the SOD typically commences before September 15, and the SED extends beyond June 21st. Furthermore, the SCD in these areas significantly exceeds that of lower elevations, ranging between 220 and 360 days. This pattern is predominantly observed along the major mountain ridges of the Qilian Mountains, underscoring the profound impact of elevation on snow phenology.Conversely, areas of lower altitude situated on the periphery of the Qilian Mountains exhibit an antithetical trend, characterized by later SOD, earlier SED, and consequently, a reduced SCD. These observations highlight the intricate relationship between altitude and snow dynamics within the Qilian Mountains, reflecting the complex interplay of geographical and climatic factors in shaping regional snow phenology.

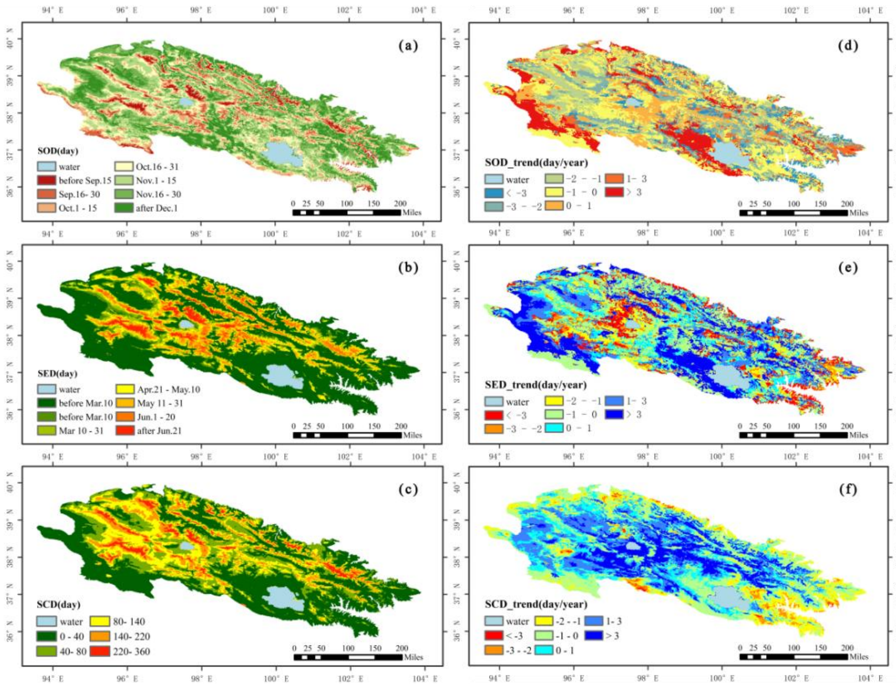

Fig. 6 Spatial distribution of multi-year average snow phenology in Qilian Mountains snow from 2000 to 2020: (a) SOD (b) SED (c) SCD；Spatial distribution of the trend of multi-year snow phenology in the Qilian Mountains from 2000 to 2020: (d) SOD (e) SED (f) SCD

The analysis of changes in snow phenology reveals significant spatial heterogeneity across the Qilian Mountains. Examination of the interannual variation of the SOD indicates that the majority of the area, approximately 68.94%, experienced an advancement in SOD. Conversely, approximately 12.12% of the snow areas within the study region exhibited a noticeable delay in SOD, with a change potential greater than 3 days per annum (d/a). This delay predominantly occurred in the low-altitude areas at the southwestern edge of the Qilian Mountains region and in central-southern mid-altitude areas. A smaller proportion, about 6.8%, of the snow area witnessed a significant advancement in SOD, with a change potential less than -3d/a, and this distribution was more scattered across the region (as shown in Fig. 6d).

Regarding the interannual variation of the SED, the data reveals a roughly equal division between areas experiencing delayed and advanced SED within the Qilian Mountains. Areas with advanced SED accounted for approximately 51.6% and were slightly more prevalent than those with delayed SED. Notably, the area with significantly delayed SED made up 23.15% of the region, exhibiting a trend greater than 3d/a and featuring a wide and sporadic distribution. In contrast, areas with significantly advanced SED constituted 9.09% of the snow, demonstrating a trend of less than -3d/a with a similarly sporadic distribution (as depicted in Fig. 6e).Analysis of the interannual variation of the SCD indicated that the area within the Qilian Mountains experiencing an extension of SCD comprised 54.12% of the total region, which was marginally higher than the area witnessing a reduction in SCD. Importantly, regions with significantly prolonged SCD accounted for 15.06%, featuring a trend of change greater than 3d/a. In stark contrast, regions with a significantly reduced SCD represented a mere 0.3%, with a trend of change less than -3d/a (as illustrated in Fig. 6f).This detailed analysis underscores the complex and varied impact of climate dynamics on snow phenology across different geographical and altitude gradients within the Qilian Mountains.

4.Discussion

4.1 Mechanisms driving snow changes

As a pivotal mountain range in northwestern China, the Qilian Mountains are influenced by an array of potential mechanisms driving changes in snow, shaped by both natural and anthropogenic factors. Observations from 2000 to 2019 indicate a dynamic trend in the snow-covered area within the region, characterized by an initial increase followed by a subsequent decline. Specifically, the period from 2000 to 2005 witnessed an increasing trend in snow-covered area, whereas a pronounced decreasing trend was observed from 2008 to 2013. Further analysis aligns the fluctuations in precipitation within the Qilian Mountains with the observed trends in SCE, strongly indicating that variations in precipitation exert a significant impact on the snow dynamics. This finding underscores the critical role of precipitation as a pivotal climatic determinant in the modulation of snow characteristics.The investigation into the effects of wind speed and temperature on snow variability posits that temperature, despite the global warming phenomenon, exerts a relatively minor influence on the interannual variability of snow area in the Qilian Mountains. This assertion is based on the analysis which demonstrates that the interannual variability in these climatic factors is relatively small, consequently having a limited direct impact on SCE. However, an analysis covering the years 2000 to 2020 revealed a generally fluctuating upward trend in the mean annual SCE within the Qilian Mountains. This observation suggests that the interannual variability of the SCE, even in a global warming context, remains complex and variable(as shown in Fig. 7).

The aforementioned insight does not negate the influence of climate change on the snow in the Qilian Mountains. Instead, it highlights the imperative for further research into the complexity and multifaceted nature of climate change impacts on snow dynamics, aiming for a more precise understanding and prediction of future snow trends. For example, this study’s analysis of spatial and temporal changes in snow over the extensive period of 1980-2019 revealed a significant decline in mean SD values in the Qilian Mountains beginning after a peak in the 2011/2012 season, with no areas recording mean SD values exceeding 5 cm in the period of 2015-2019. This indicates that the trends in snow phenology could be critical for comprehending snow dynamics amid climate change, suggesting shifts towards higher winter temperatures, alterations in snowfall patterns, earlier snowmelt, and shortened snow season durations. Nevertheless, changes observed in the snow phenology of the Qilian Mountains, with a majority of the area experiencing an advance in the SOD (68.94%), a slight predominance of extended SCD over decreased areas (54.12%), and a minor advance in the SED (51.6%), indicate a complex interplay of factors. Furthermore, regions with significantly prolonged SCD and notably delayed SED substantially outnumber those with significantly reduced SCD and notably advanced SED, respectively.

Comparative studies in snow phenology, such as those by C. Notarnicola (2020), reveal that approximately 78% of mountainous regions globally experienced reductions in snow, with durations shortening by 43 days and area decreasing by 13%. Only a few regions exhibited positive changes. Conversely, Wang et al. (2017) found no significant decrease in snow over the last 15 years on the Tibetan Plateau, utilizing MODIS data from 2000 to 2015. This aligns with the observations in the Qilian Mountains, a significant mountain system on the northeastern edge of the Tibetan Plateau, a generally positive trend in snow surface and phenology was identified, with high spatial heterogeneity in snow phenology trends. This reinforces the conclusions drawn in the current study, emphasizing the nuanced impacts of climate dynamics on snow.

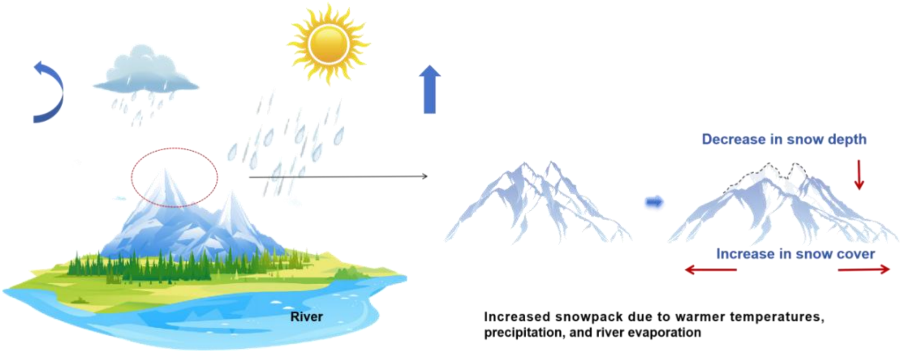

Fig. 7 Conceptual diagram of potential driving mechanisms of snow change in the Qilian Mountains

4.2 Impacts of the Qilian Mountains snow on hydrology and ecosystems

The hydrological dynamics within the Qilian Mountains are profoundly influenced by the snow's intra-annual accumulation and ablation processes, where snowmelt acts as a critical source of freshwater for tens of millions of people. Varied watershed studies within this region illustrate that the contribution of meltwater from snowmelt to total runoff significantly fluctuates across different watersheds. For instance, the Yarlung Tsangpo River and its tributaries derive approximately 9.7% of their runoff from snow and ice melt. Conversely, in the source area of the Yangtze River, characterized by high elevation and the prevalent development of glaciers and permafrost, precipitation stands as the predominant source of recharge. Here, snow, largely occurring as patchy distributions, along with ice meltwater, constitutes about 13.6% of the runoff. Furthermore, the proportion of snow and ice meltwater in the runoff of the upper reaches of the Black River in the Qilian Mountains accounts for roughly 16.1%, a figure that underscores the variance in snow development and hydrothermal conditions across different watersheds.

Although the overall contribution of snowmelt to total runoff might appear modest, its significance cannot be overstated. The peak of snowmelt typically aligns with late spring, a critical juncture for agricultural irrigation needs and the growth phase of natural vegetation. Thus, snowmelt plays an indispensable role in the recharge of soil moisture and river runoff. Climate change introduces notable impacts on the hydrological processes associated with the snow in the Qilian Mountains, with responses varying across different regional watersheds. For example, an increase in snowfall within the eastern watersheds is anticipated to moderate the rate of runoff increase and delay the commencement of peak runoff periods.While snow presently constitutes the primary driver of river flow in these regions, future climate scenarios predict an increase in the frequency and intensity of rainfall events, potentially reducing the relative contribution of snowfall. This shift highlights the evolving dynamics of hydrological processes in the face of climate change, underscoring the need for adaptive water resource management strategies in the Qilian Mountains.

4.3 Impacts of the Qilian Mountains snow on ecosystems

Snow significantly influences the climate system, water resource management, and ecological diversity. It plays a crucial role in regulating ground-level energy absorption, maintaining the water balance, influencing surface temperature, and facilitating gas exchange processes in vegetation. In the Qilian Mountains, variations in snow are directly associated with agricultural productivity and the preservation of biodiversity. snow critically impacts water cycle dynamics by regulating the availability of water resources across different seasons: it limits water resources during the cold season and ensures their abundance during the snowmelt period. Additionally, snow indirectly influences the energy balance at the ground level. The potential heat flow to the atmosphere is reduced, and the heat flow to the soil is altered, as snow impedes groundwater recharge by capturing precipitation and meltwater, and transports substantial volumes of water downstream during melting. Hence, future shifts in snow are poised to significantly transform the hydrology of the Qilian Mountains. Decreases in snow, earlier melting periods, and heightened rates of evapotranspiration and sublimation are likely to affect both seasonal and long-term water and ice storage. Consequently, many areas of temporary and semi-permanent snow in the Qilian Mountains may experience reduction or complete disappearance, impacting the SCE on glaciers and adversely influencing their mass balance. The diminution of snow is also expected to lead to the desiccation of numerous patchy wetlands and deterioration of conditions in other wetlands within the region, which rely on late-season snow to sustain their wet state.

The distribution of snow significantly influences the types of vegetation present in exposed areas, where low-lying plant forms have evolved to withstand the dual stresses of wind erosion and summer drought, demonstrating remarkable adaptation to extreme environmental conditions. Moreover, species of vegetation that remain covered by snow during winter exhibit the capacity to sprout rapidly following snowmelt — capitalizing on the brief growing season in the Qilian Mountains to optimize their growth and reproductive success. Consequently, alterations in snow conditions play a pivotal role in determining vegetation distribution, biodiversity, and ecosystem productivity.In the Qilian Mountains, the intricate and vital interdependence between plant and animal communities and snow conditions cannot be overstated. Changes in snow influence not only the survival of specific species, such as the rock sheep and snow grouse, but also impact the migratory patterns and reproductive behaviors of species that migrate seasonally. For species embarking on long-distance migrations, snow conditions at breeding sites during spring are particularly critical. Therefore, modifications in snow dynamics could lead to significant repercussions for the ecosystem's structure and function, impacting the composition and distribution of species communities within the region.

4.4 Uncertainties and limitations of the study results

The findings of this study are derived from the MODIS snow product and, thus, inherit the limitations associated with it. Despite its lower spatial resolution of 500 meters, inferior to the likes of Landsat and Sentinel-2 data, MODIS remains the most viable data source for monitoring the spatial and temporal dynamics of snow on a large scale over extended time series. Nonetheless, the utility of MODIS snow accumulation products is significantly impeded by cloud contamination.Over the past decades, numerous de-clouding techniques for snow accumulation products have been proposed(Li et al.2019). These include: (1) spatial approaches such as spatial filtering, snowline mapping methods, and locally weighted logistic regression (Gafurov and Bardossy, 2009; Lopez-Burgos et al., 2013; Parajka et al., 2010); (2) temporal strategies, combining Terra and Aqua data, and implementing temporal filters that involve adjacent time inference, multi-day combinations, seasonal filters, and temporal interpolation using mathematical functions (Dozier et al., 2008; Gafurov and Bardossy, 2009; Parajka and Bloschl, 2008; Paudel and Andersen, 2011; Tang et al., 2013); (3) spatio-temporal combination methods (Dariane et al., 2017; Jing et al., 2019; Li et al., 2017);   (4) multi-source fusion methods incorporating optical, microwave, and station observations (Brown et al., 2010; Gafurov et al., 2015; Huang et al., 2016;

https://doi.org/10.5194/egusphere-2024-1008
Preprint. Discussion started: 13 May 2024

Liang et al., 2008).

The de-clouded snow accumulation product employed in this study is developed through a methodology that utilizes high-resolution Landsat TM data as the baseline truth value. It is augmented with MODIS land cover classification products to calibrate index thresholds for discriminating snow accumulation under forested and non-forested categories. These are then integrated with MODIS snow accumulation inversion algorithms to generate the primary dataset, which undergoes further refinement through Hidden Markov de-clouding and snow-depth data interpolation methods to produce a cloud-free, daily snow area product for the study region. However, the employment of spatio-temporal interpolation algorithms and other void-filling techniques may introduce discrepancies due to challenges like prolonged cloud cover and the complexity of terrain and landcover. When quantifying snow area, variations arise from the use of different snow products. Consequently, the calculated snow area over the Qilian Mountains displays slight deviations from values reported by other researchers. However, the overall trend remains consistent, and the margin of error falls within an acceptable range.

5. Conclusion

This study systematically examined the spatial and temporal dynamics of snow accumulation in the Qilian Mountains, analyzing trends in snow area and snow phenology from high-resolution MODIS snow products and snow phenology products spanning 2000-2020, as well as multi-year SD trends derived from long-term SD data covering 1980-2019. The findings revealed several key trends:

(1) The overall snow in the Qilian Mountains exhibited a fluctuating upward trend from the 1980/1981 season until a peak depth of 3.577 cm was reached in the 2011/2012 season, after which a significant decline was observed. The highest SD were located in the central and western regions of the Qilian Mountains, with the central region experiencing the most pronounced reduction in SD, exhibiting an interannual variability of less than -0.04 cm/year.

(2) The snow within the Qilian Mountains demonstrated an overall increasing trend, with peak snow typically occurring in November and January. The study also noted strong seasonal fluctuations in SCE. The seasons of 2002/2003 and 2019/2020 experienced no snow-free days, recording the lowest snow areas of 82.4km^{2}and 206.01km^2, respectively.

(3)In terms of snow phenology, the majority of the Qilian Mountains area experienced an advancement in the SOD, which accounted for 68.94% of the total area studied. There was a marked increase in areas where the SCD was significantly prolonged compared to those where it was significantly reduced. Similarly, areas where the SED was significantly advanced outnumbered those where it was significantly delayed. The overall increase in precipitation was identified as the main driver of these trends, while rising temperatures were pinpointed as the primary cause for the decrease in SD across the Qilian Mountains region.

CRediT authorship contribution statement

Enwei Huang： Conceptualization, Methodology, Formal analysis, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Guofeng Zhu:** Methodology, Validation, Formal analysis, Investigation, Data curation, Software, Writing original draft. **Yuhao Wang:** Writing – review & editing.**Gaojia Meng:** Writing – review & editing. **Ling Zhao:** Writing – review & editing.**Xuan Zhang:** Writing – review & editing. **Xiaoyu Qi：** Writing – review & editing.**Qinqin Wang：** Writing – review & editing.**Yinying Jiao：** Writing – review & editing.**Jiawei Liu：** Writing – review & editing.**Siyu Lu：** Writing – review & editing.**Longhu Chen：** Writing – review & editing.**Rui Li：** Data curation, Software.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was financially supported by the National Natural Science Foundation of China (42371040, 41971036), Key Natural Science Foundation of Gansu Province (23JRRA698), Key Research and Development Program of Gansu Province (22YF7NA122), Cultivation Program of Major key projects of Northwest Normal University (NWNU- LKZD-202302), Oasis Scientific Research achievements Breakthrough Action Plan Project of Northwest Normal University (NWNU-LZKX- 202303).

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