Snow Drought Patterns and Their Spatiotemporal Heterogeneity in China

Yuxin Li, Xiaodong Huang, Ying Ma, Qisheng Feng, and Tiangang Liang

***Abstract*—This study presents a snow drought assessment method using snow water equivalent products to examine the patterns and differences in snow drought events in China from 1980 to 2020. The findings indicate that snow drought changes over the past 40 years can be categorized into three stages: The most severe snow drought occurred in the 1980s, followed by alleviation until 2009, and a subsequent aggravation after 2010. Light snow drought has the widest distribution and shows an increasing trend, whereas medium, heavy, and extreme snow droughts decrease gradually but show a decrease followed by an increasing trend over time. The distribution of snow drought in China displays significant spatial heterogeneity, with areas such as Alxa League in Inner Mongolia, Hami, Turpan, Bayingol, Xinjiang, and the Tibetan Plateau hinterland experiencing frequent snow drought events. Moreover, the low-altitude region has the largest average annual proportion of extreme drought, whereas the high-altitude region has the highest proportion of heavy drought. Among the three snow-dominant areas, Northern Xinjiang has the largest proportion of snow drought areas. The Northeast-Inner Mongolia has the highest proportion of extreme drought while the Tibetan Plateau exhibited abrupt changes in snow drought occurrence. These results contribute to a better understanding of the underlying mechanisms of snow drought changes, as well as serve as a foundation for the protection of the ecological environment.**

***Index Terms*—China, snow drought, snow water equivalent (SWE), spatiotemporal characteristics.**

I. Introduction

SNOW is a crucial component of the cryosphere. It plays a vital role in processes, such as surface energy balance, water fluxes, hydrological cycles, and atmospheric and oceanic circulation. However, due to global climate warming, the spring snow cover area in the Northern Hemisphere has been decreasing, and the distribution of snow in China has also been shrinking with reduced stability [1], [2]. This trend can lead to earlier snowmelt runoff [3], a shorter snow cover period [4], increased frequency of flooding [5], [6], heavy snowstorms, and other extreme climate events, resulting in a range of environmental issues.

Snow drought refers to an abnormal phenomenon where the snowfall is below the climatic average and is considered a precursor to global warming, affecting the timing and volume of snowmelt runoff [7], [8], triggering disruptive warm-season extreme events such as drought [9], [10], heatwaves [11], and wildfires [12], [13], resulting in severe social hazards [14]. Furthermore, the compounded impacts of diminished snowpack, potentially leading to lower water tables or soil moisture, and heightened heat due to climate change, have significant implications for the ecological functioning of mountain forests [15], [16]. Therefore, it is crucial to investigate the spatiotemporal characteristics of snow drought, understand its occurrence locations, and assess its intensity for effective defense and post-disaster management. Previous studies on snow drought have identified two scenarios that contribute to its formation: 1) inadequate winter precipitation and 2) insufficient snow accumulation despite normal winter precipitation levels [17].

In recent years, despite the increasing global interest in snow drought research, there is still no unified standard for determining and assessing snow drought. Currently, the snow water equivalent (SWE) on April 1st is commonly used as an approximation of maximum snow accumulation for a hydrological year [18]. The snow accumulation and melting seasons are separated, and the SWE during this period is compared to the climatic average to identify snow drought [7]. However, this approach does not consider the relationship between peak SWE timing and potential meltwater volume, limiting its ability to provide early warnings for snow drought disasters [19], [14]. In addition, using average SWE as a threshold for determining snow drought can overestimate its frequency [20]. To address these limitations, some studies have suggested comparing peak SWE with the climatic average to identify snow drought, which avoids the uncertainty caused by fixed timeframes [20]. By defining years with peak SWE below the 25th percentile of historical data for more than two years (including 2 years) as consecutive drought years, it becomes feasible to monitor snow droughts changes [21]. However, using peak SWE as a representation of the entire snow season can lead to misdiagnosis due to significant increases in SWE around the peak [22]. Therefore, using peak SWE to characterize the temporal evolution of snow drought also has its flaws [23].

Snow drought is a seasonal phenomenon that can start, enhance, and weaken during the snow season. Monitoring the evolution of snow drought throughout the season using the SWE Index (SWEI) allows for a more accurate determination of the timing of snow drought, a finer analysis of its potential

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impacts, and comparisons between regions [24]. However, SWE varies significantly across regions, and there is substantial spatial heterogeneity in the manifestations of snow drought. Therefore, it is necessary to track changes in SWE throughout the snow season in different regions to study snow drought effectively [21].

The distribution and dynamics of snow in China are influenced by its vast territory, diverse topography, and variable climate, making it a complex system that is sensitive to local climate and topographic conditions. Snow accumulation generally increases gradually from south to north and decreases from west to east, with mountainous areas receiving more snow compared to basins and plains, and snow depth increasing with elevation [25]. However, there are specific regions, such as the vast interior and the northern Tibetan Plateau, where snow cover is rare, thin (less than 5 cm), and short-lived (usually less than 1 day for a single snow event) due to strong solar radiation and wind [26], [27]. In these areas, there is minimal snow accumulation, making it challenging to obtain peak SWE measurements. As a result, the current international assessment methods for snow drought may not be directly applicable to the unique snow conditions in China. Therefore, it is crucial to develop an appropriate snow drought assessment method that considers the complex environmental factors in China.

This study aims to comprehensively assess and analyze snow drought in China through the following objectives:

1) determine the occurrence threshold and levels of snow drought based on historical snow accumulation patterns and establish an appropriate snow drought assessment method for China's complex environment;
2) quantify the historical frequency of each snow drought type and analyze the temporal distribution of snow drought events in China from 1980 to 2020;
3) analyze the spatiotemporal distribution characteristics of snow drought in different regions of China to identify susceptible areas and understand variations in snow drought intensity.

II. Materials and Methods

A. Study Area

In order to avoid the influence of transient snow cover and nonsnowfall areas on the analytical outcomes, this study only considers the areas with annual climatic snow cover duration over 30 days, which span 486.2 $\times$ 10^4 km^2, accounting for about one-half of China's total area, and represent the primary reservoirs for China's seasonal snow water resources (see Fig. 1). Within this expanse are three stable snow-dominant areas: *Tibetan Plateau*, covering an area of about 250.2 $\times$ 10^4 km^2. The distribution of snow in this area has obvious vertical zonation, which is mainly dominated by thin, patchy, and discontinuous snow cover. *Northeast-Inner Mongolia*, covering an area of about 172.3 $\times$ 10^4 km^2, where has prolonged snow duration and considerable snow depth, with an average annual snowfall exceeding 60 mm [28]. *Northern Xinjiang*, covering an area of about 87.7 $\times$ 10^4 km^2. The snowmelt water is a vital source for river replenishment, which is conducive to the successful plant overwintering, alleviates spring droughts, and of great positive significance to the local livelihood and production [29], [30].

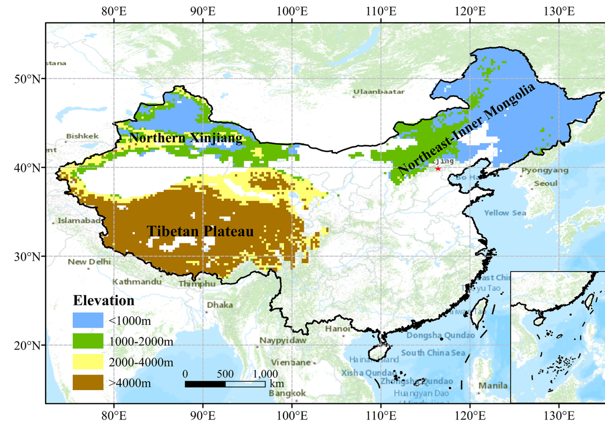

Fig. 1. Areas with annual climatic snow cover duration over 30 days with their elevations of three snow-dominant areas: Tibetan Plateau, Northeast-Inner Mongolia, and Northern Xinjiang in China.

B. Passive Microwave SWE Remote Sensing Data

In this study, we used the SWE satellite remote sensing dataset in China from 1980 to 2020 [31]. Specifically designed for China's snow-covered areas, this dataset produces a daily SWE and snow depth dataset with a spatial resolution of 25 km based on the mixed-pixel SWE inversion algorithm and satellite-based passive microwave remote sensing brightness temperature data. The data adopts the EASE-GRID projection and is stored in the HDF5 file format, encompassing five data elements: snow depth (in centimeter), SWE (in millimeter), latitude, longitude, and quality indicators. The dataset accounts for factors influencing SWE extraction and inversion, such as mixed pixels, topography, atmospheric conditions, and land cover types. The validation results indicates that this product, with an unbiased root mean square error of approximately 10 mm and a correlation coefficient of 0.7 for overall SWE in China, is the highest-accuracy long-term SWE product produced for the Chinese region [32], [33].

C. Definition and Classification of Snow Drought

A hydrological year is defined from July 1st of each year to June 30th of the following year, based on the snow change pattern in the study area. From January 1, 1980, to January 1, 2020, there are a total of 39 hydrological years considered in this study. Instead of solely relying on peak snow accumulation, this study introduces a new indicator to characterize snow drought intensity. The ratio of the total snow accumulation for the hydrological year to the climatic median on a pixel scale is used as the primary indicator. To calculate the snow accumulation, SWE values are extracted at a 25-km resolution using the SWE satellite remote sensing dataset for China from 1980 to 2020. The snow accumulation data is generated by combining the SWE values

TABLE I
CLASSIFICATION CRITERIA FOR SNOW DROUGHT IN CHINA

Snow mass	Classification
50th – 25th percentile	Light drought
25th – 15th percentile	Medium drought
15th – 5th percentile	Heavy drought
< 5th percentile	Extreme drought

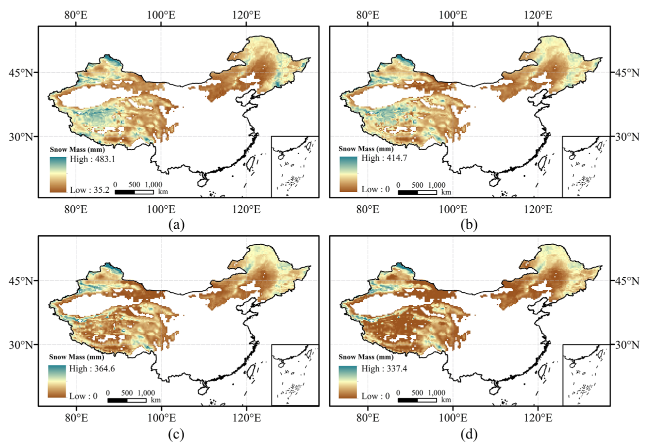

Fig. 2. Spatial distribution of (a) 50%, (b) 25%, (c) 15%, and (d) 5% quartiles of snow mass accumulation in China.

with

$$\text{Snow Mass}_{\text{year}} = \sum_{i=1}^{\text{days}-1} (\Delta \text{SWE}_i) \tag{1}$$

where $\text{Snow Mass}_{\text{year}}$ is the annual accumulated SWE (millimeter); *days* represents the total number of days in the hydrological year; i is the number of days; ΔSWE_i is the increment of SWE relative to the previous day, when $\Delta\text{SWE}_i < 0$, the accumulation is not counted.

Using the snow accumulation data, each grid is defined as follows: A snow drought occurs when the snow accumulation is below the 25th percentile (or the first quartile) of historical climate [14], [21], [24]. To assess the intensity of snow drought, the snow drought assessment indicator is categorized into four classes, as shown in Table I. This classification system is similar to probabilistic climate classification, which determines the severity of snow drought based on historical climatic characteristics. The resulting classification layer is depicted in Fig. 2. These layers are used as classification criteria layers for the calculation of snow drought classes, and the distribution of snow accumulation on the maps can also be used as a reference for the distribution of snow drought.

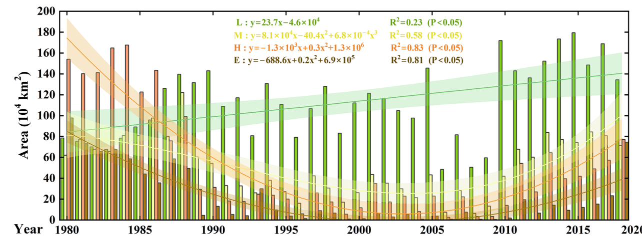

Fig. 3. Histogram of the area of each snow drought category in China from 1980 to 2018 hydrological years. The colored solid line represents the trend fitting line, the light-colored wide band represents the 95% confidence band, and the trend fitting equations, correlation coefficients and significance test results are labeled (L: Light drought, M: Medium drought, H: Heavy drought, E: Extreme drought).

III. RESULTS

A. Changes in Snow Drought Extent

During the period from 1980 to 2020, the most extensive areas affected by snow drought were classified as light drought, with an annual average area of 112.4×10^4 km^2. The occurrence of light drought showed a significant increasing trend over the years ($p < 0.05$) (see Fig. 3). The areas covered by medium drought and heavy drought were comparable, with annual average areas of 51.5×10^4 km^2 and 51.3×10^4 km^2, respectively. Both categories exhibited a trend of initially declining before rising in terms of affected areas. The areas affected by extreme drought were relatively smaller, with an annual average area of 21.6×10^4 km^2, and also followed the trend of first declining and then rising.

Based on the spatiotemporal distribution map of snow drought in China (see Fig. 4), the study identified three distinct phases of snow drought development from 1980 to 2020. During the period of 1980–1989, the study observed the most severe snow drought conditions, with an average snow drought area of 354.0×10^4 km^2. The primary type of snow drought during this phase was heavy drought, mainly affecting the Tibetan Plateau, Northern Xinjiang, and Northeast-Inner-Mongolia regions.

In the period of 1990–2009, the snow drought conditions were relatively lighter, with an average snow drought area of 152.5×10^4 km^2. Light drought was the primary type during this phase. There were localized large-scale extreme drought areas occurring only from 1990 to 1993 hydrological years, mainly in the Lesser Khingan of Heilongjiang and the eastern mountainous regions of the Tibetan Plateau. Compared with the 1980s, the snow drought classification of Tibetan Plateau changed significantly, which suggested that the snow accumulation on the Tibetan Plateau continued to increase, resulting in a decrease in the occurrence of severe snow drought events. This situation persisted until 2010, after which the frequency of severe snow drought events began to gradually increase.

After the 2010 hydrological year, the snow drought situation worsened, with an average drought area of 294.3×10^4 km^2. Light drought became the primary type, and there was a trend of increasing snow drought intensity from west to east. In 2018, the El Niño phenomenon influenced the region, leading to reduced snowfall and a warm winter, resulting in exceptional drought

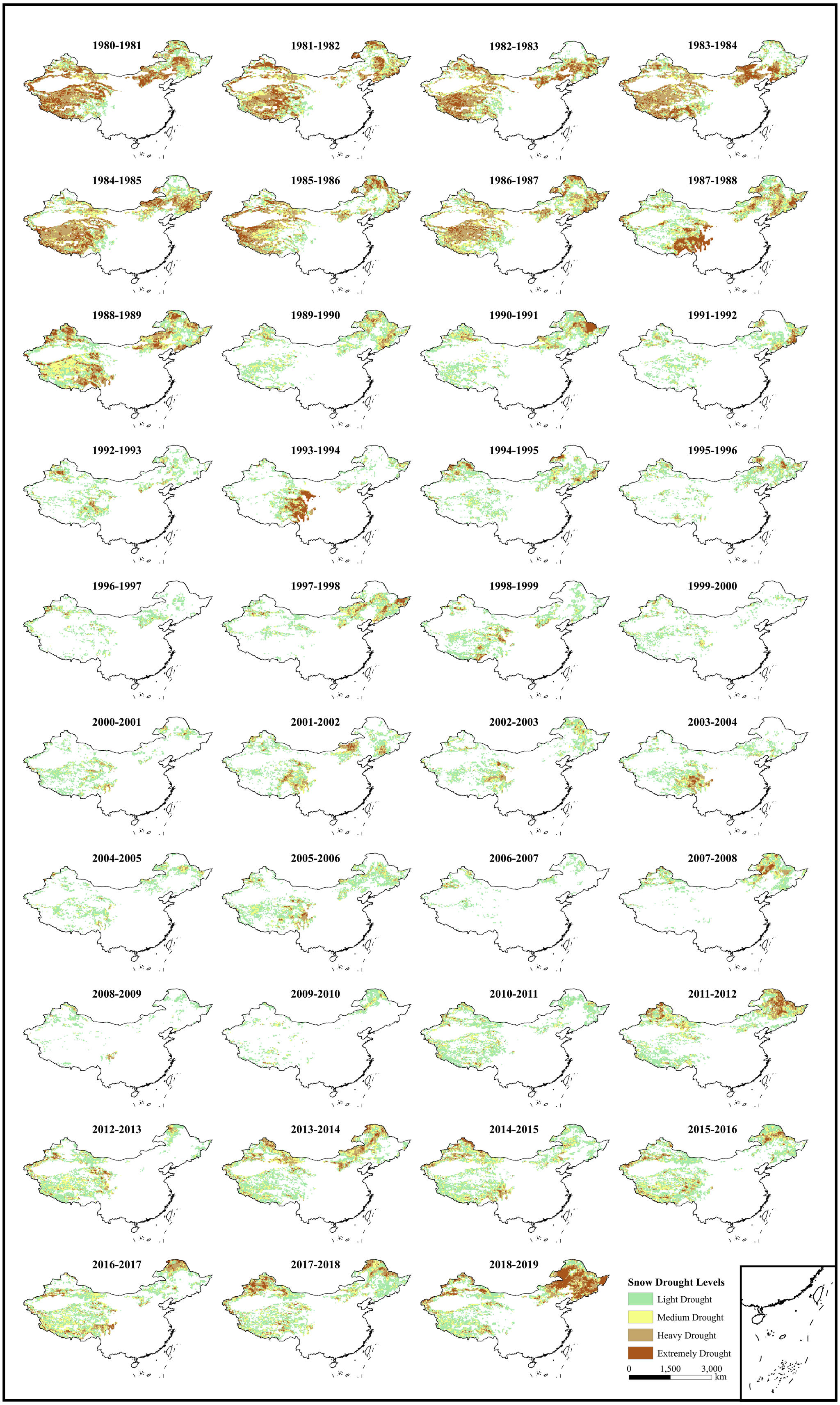

Fig. 4. Spatiotemporal distribution of snow drought categories in China's snow-covered areas.

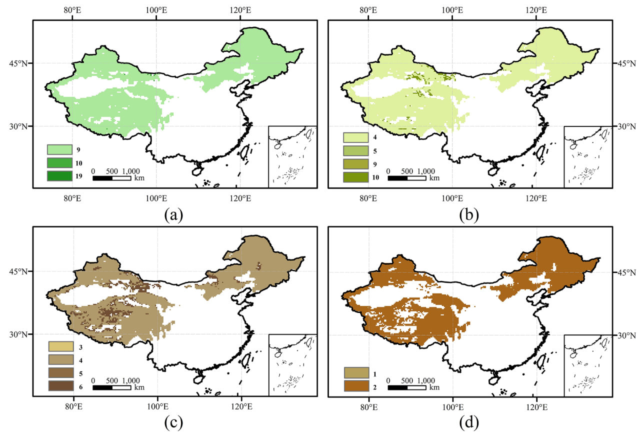

Fig. 5. Frequency of (a) light drought, (b) medium drought, (c) heavy drought, and (d) extreme drought in China from 1980 to 2020 hydrological year.

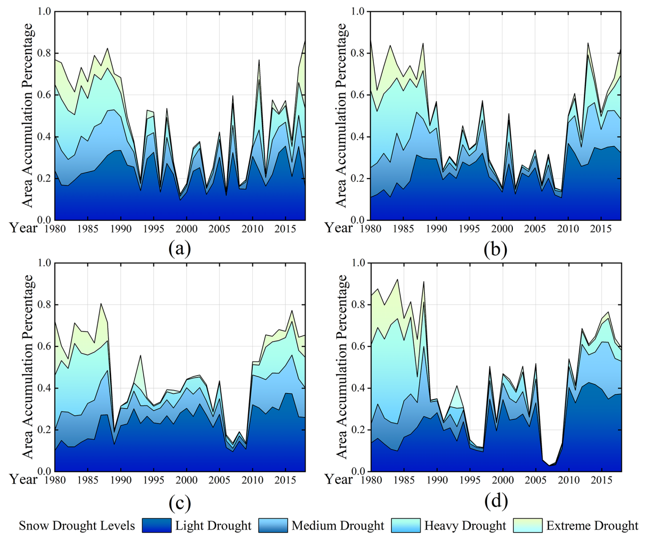

Fig. 6. Stacked plot of the area proportion of each snow drought type within the snow-covered zones at elevations of (a) <1000 m, (b) 1000–2000 m, (c) 2000–4000 m, and (d) >4000 m.

conditions [34]. The analysis indicated that the area affected by extreme drought reached approximately 34.9% of the total snow-covered area in Northeast-Inner Mongolia (see Fig. 4).

B. Snow Drought Frequency

Fig. 5 presents the frequencies of different snow drought types in China's snow-covered areas from 1980 to 2020 hydrological years. Throughout the study period, all snow-covered areas experienced at least 9 instances of light drought, with the western region of Alxa League in Inner Mongolia being affected the most, experiencing light drought 19 times. Medium drought occurred at least four times in 99.8% of the snow-covered areas. Specifically, regions such as Golmud City in Qinghai Province, Dunhuang City in Gansu Province, Hami and Turpan Cities in Xinjiang, and Alxa League in Inner Mongolia had medium drought occurrences 10 times.

Furthermore, 97.5% of the snow-covered areas experienced heavy drought at least four times. The regions with a high frequency of heavy drought were mainly concentrated in the Tibetan Autonomous Region in the hinterland of the Tibetan Plateau and the southeastern part of the Northern Xinjiang snow area. In addition, the border region between the northeastern plains and the Lesser Khingan Mountains, as well as the Xilingol League in the central part of the Inner Mongolian Plateau, also had high frequencies of heavy drought.

Approximately 86.9% of the snow-covered areas experienced extreme drought. The regions experiencing twice accounting for 86.7% of the total snow-covered areas. The spatial distribution map of snow drought frequency highlighted the Alxa League in western Inner Mongolia, Hami, Turpan, and the Bayingolin Mongol Autonomous Prefecture in the southeastern parts of Northern Xinjiang, as well as the hinterland of the Tibetan Plateau, as the most frequently affected areas in China's snow-covered regions. These areas also represented the primary regions facing snow drought risks. Notably, the western part of Alxa League has experienced light drought 19 times, medium drought 10 times, and heavy drought 6 times, making it the region with the highest frequency for all types of snow drought.

C. Elevation Effect on Snow Drought

According to the division of elevation zones in snow-covered areas of China (see Fig. 1), this study analyzed the distribution of different types of snow drought within each elevation zone and examined the influence of elevation on the occurrence of snow drought (see Fig. 6). The findings revealed that light drought was the dominant type of snow drought in all elevation zones, with the range of snow drought decreasing and then increasing over time.

In the elevation zone below 1000 m, the average annual total snow drought area was 79.9×10^4 km^2, accounting for 16.4% of the regional area. This zone had the highest proportion of extreme drought, averaging 4.8% annually, compared to other elevation zones.

In the 1000–2000 m elevation zone, the average annual total snow drought area was 42.4×10^4 km^2, making up 8.7% of the regional area. This zone had the largest proportions of light and medium snow droughts, at 23.3% and 11.1%, respectively, among all elevation zones. Extreme drought accounted for the smallest proportion, averaging 3.9%.

For the 2000–4000 m elevation zone, the average annual total snow drought area was 32.5×10^4 km^2, accounting for 6.7% of the regional area. This was the smallest average annual total area proportion compared to other zones, and the average annual proportions of each type of snow drought were in the middle range. The most severe snow drought occurred in the 1987–1988 hydrological year, with a proportion of 80.6% of the snow-covered areas, whereas the least severe was observed in 2007–2008, at 13.7%.

In the zone above 4000-m elevation, the average annual total snow drought area was 82.1×10^4 km^2, accounting for 16.9% of the zone. The average annual proportion of heavy drought was 10.9%. The most severe drought occurred in the 1984–1985 hydrological year, with the snow drought area amounting to 92.2% of the snow-covered areas. In contrast, the lightest

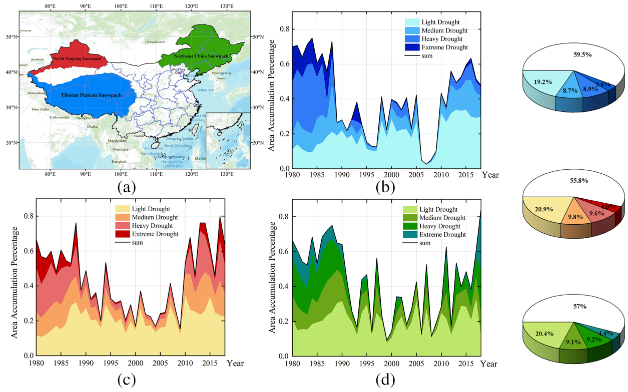

Fig. 7. (a) Distribution of the three snow-dominant areas. Stacked and pie charts of the area proportion of each snow drought type in (b) Tibetan Plateau, (c) Northern Xinjiang, and (d) Northeastern-Inner Mongolia.

drought was observed in the 2007–2008 hydrological year, with the area accounting for only 2.9%. This region had the highest fluctuation of snow drought area, the largest average annual total area proportion of snow drought, and the widest range of heavy drought among all elevation zones.

Overall, the high-elevation zone had the highest proportion of heavy drought, whereas the low-elevation zone had the highest proportion of extreme drought. Both zones had an average annual snow drought area of over 16.0%, indicating severe impacts. The mid-elevation zones had a larger proportion of light and medium droughts, with an average annual snow drought area of less than 9%, suggesting milder snow drought conditions.

D. Regional Difference

The overall trend in the three snow-dominant areas showed a pattern of initially mitigating and subsequently intensifying snow drought, particularly after the hydrological year of 2010–2011, where the increase became significant. The proportions of different types of snow drought were similar in all regions, with the largest proportion being light drought, followed by comparable proportions for medium and heavy droughts, and the least for extreme drought (see Fig. 7).

In the high-latitude regions of Northern Xinjiang and Northeastern-Inner Mongolia, the snow-covered areas experienced similar snow drought situations, with temporal fluctuations in the area under snow drought. The peaks of the snow drought area were observed in the hydrological years of 2013–2014 and 2018–2019, respectively. However, compared to Northern Xinjiang, the Northeast-Inner Mongolia snow-covered area exhibited more pronounced fluctuations in snow drought.

The Tibetan Plateau snow-covered area differed from the other two regions in that the fluctuation pattern of snow drought extent was not obvious. Due to its unique topographic and climatic conditions, the snow accumulation process and occurrence of snow drought are highly variable. In the hydrological years of 1995–1998 and 2006–2010, the area of snow drought decreased sharply and was mostly light drought, corresponding to years with high snow accumulation on the Tibetan Plateau (see Fig. 4). However, in the subsequent hydrological years of 1998–1999 and 2010–2011, there was a sudden increase in the area of snow drought, which then stabilized. The previous studies suggested that the snow-covered area and snow depth over the Tibetan Plateau increased over the latter half of the 20th century, but decreased significantly during the early part of the 21st century [35], [36].

Among the three snow-dominant areas, the Northern Xinjiang snow-covered area exhibited the largest average annual total snow drought area proportion, at 44.2%. In addition, all types of droughts except extreme drought (light, medium, and heavy) had the largest occurrence area in this region. The Northeastern-Inner Mongolia snow-covered area recorded an annual total area proportion of 43.0%, with the highest proportion of extreme drought. The Tibetan Plateau snow-covered area had an annual total area proportion of 40.5% and showcased more volatile patterns in its snow drought occurrences.

Overall, the Northern Xinjiang snow-covered area experienced the most extensive occurrence of light, medium, and heavy droughts among the three snow-dominant regions. The Northeastern-Inner Mongolia snow-covered area was most heavily affected by extreme drought, whereas the Tibetan Plateau snow-covered area exhibited more variable patterns in its snow drought occurrences.

IV. Discussion

The analysis of snow drought area statistics shows that the most severe snow drought in China's snow areas occurred during the hydrological years of 1980–1989, with a decline in snow drought area and intensity after the 1990 hydrological year, which is consistent with the findings of Huning and AghaKouchak [24]. The conclusion by Liu et al. [37] that snow resources decreased from 1980 to 1995, increased from 1995 to 2010, and then declined again from 2010 to 2020 indirectly validates the three-phase change of snow drought in this study. Moreover, statistics indicate that over the past 50 years, 80% of El Niño years have been accompanied by warm winters in China. The severe snow drought in China during the 1980s was attributed to a strong El Niño event and a decline in snow resources [34]. However, in the 1990s, despite frequent El Niño events leading to increased temperatures, abundant winter precipitation alleviated the snow drought, limiting its extent and preventing severe snow drought conditions. The El Niño event in 2018 influenced the Northeast region, which experienced severe snow drought during the hydrological year of 2018–2019, resulting in insufficient snowmelt in spring and inadequate irrigation water. The Chinese Disaster Report indicated that the Northeast region suffered a spring drought from February to May 2019, with precipitation 48% below the same period of normal years, the lowest since 1961, and an average temperature 2.4 °C higher than the same period of normal years, the second-highest since 1961. This had a certain impact on the sowing and growth of new crops in provinces such as Inner Mongolia, Heilongjiang, and Jilin. However, compared to the previous five years, the Northeast region experienced significantly lighter low-temperature freezing and snow disasters in 2019, according to the Emergency Management website [38]. The semiarid Andes of central Chile typically had absent snow at low elevations [39]. High-elevation mountain areas typically accumulate more snow and are, therefore, more affected by climate change, leading to dramatic snow drought events [26], [40], [41].

With global temperatures on the rise and the frequency of extreme weather events increasing, the impact of snow drought is becoming more evident in many snow-covered regions. Studies have shown that the snow season has been shortened, and the area covered by snow has significantly decreased in these areas [42]. This trend is also observed in mountain ecosystems in the western United States, Europe, and other parts of North America, where winter snow volume has declined [43], [8]. In China's Sanjiang Plain, snow droughts have become more frequent and severe, affecting the growth of forests and grasses in mid-high latitude areas [44]. On the other hand, temperature is considered a major factor in the occurrence of snow drought, and warm winters have become more common since the 21st century. Further research should focus on identifying the driving factors of snow drought and their interactions.

V. Conclusion

In this study, we constructed a snow drought assessment method suitable for China's complex environment. We analyzed the spatiotemporal distribution characteristics and regional differences of snow drought in China from 1980 to 2020. Our research conclusions are as follows.

1) From 1980 to 2020 hydrological years, the distribution area of light drought was the widest and showed an increasing trend, whereas the distributions of medium, heavy, and extreme droughts decreased and then increased in sequence. The 1980–1989 hydrological years were the period with the most serious snow drought, mainly dominated by heavy drought. From 1989 to 2009 hydrological years, the snow drought was lighter, with light drought as the main type, and the drought fluctuated significantly. After the 2010 hydrological year, the snow drought area continued to increase.
2) The Alxa League in western Inner Mongolia, the Hami, Turpan, and Bayingolin Mongol Autonomous Prefecture in southeastern Northern Xinjiang, and the hinterland of the Tibetan Plateau were the regions in the snow-covered areas of China where snow drought was frequent.
3) Among the three snow-dominant areas, the Northern Xinjiang snow-covered area had the widest occurrence areas of light, medium, and heavy drought types. The Northeast-Inner Mongolia snow-covered area had the highest average annual proportion of extreme drought, where the regions most exposed to the risk of snow drought.

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