Spatiotemporal Variations of Warming-Induced Snow(Ice) Melt Flood Frequency and Atmospheric Circulation Pattern Analysis in Xinjiang during the Past Two Decades: A Postprint

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Abstract

Based on snowmelt (ice) flood disaster data from Xinjiang during 2000–2019, this study analyzes the spatiotemporal distribution and regional differences in snowmelt (ice) flood frequency over the past 20 years. The results indicate that snowmelt floods in Northern Xinjiang account for 75% of the total frequency across the region, with the primary flood season occurring in spring and events concentrated in the western and northern parts of Northern Xinjiang, particularly in the Ili Kazakh Autonomous Prefecture (with Xinyuan County being the most affected). In Southern Xinjiang, the primary flood season occurs in summer, with snowmelt (ice) floods mainly appearing on the northern slopes of the Kunlun Mountains; March and July are the high-incidence months for snowmelt floods in Northern Xinjiang and snowmelt (ice) floods in Southern Xinjiang, respectively. Over the past 20 years, the frequency of spring snowmelt floods in both Northern and Southern Xinjiang has exhibited an increasing trend, with snowmelt (ice) flood frequency in the latter decade being approximately 30% higher than in the previous decade. The study elucidates the synoptic classification of snowmelt (ice) floods in Xinjiang, analyzing three atmospheric circulation patterns: the eastward expansion of the Iranian subtropical high, the westward extension of the Western Pacific subtropical high, and the development of the Xinjiang ridge, and presents the upper- and lower-level circulation patterns and weather system configurations for warming-induced snowmelt (ice) floods in Xinjiang. It is found that prior to snowmelt (ice) flood occurrence, the South Asian High at 100 hPa exhibits a monopole pattern, Xinjiang is controlled by a deep high-pressure ridge from 100 to 700 hPa, the height of the 0 °C level in the upper atmosphere is significantly higher than normal, and precipitation in mountainous areas during the preceding period is notably above average. Northern Xinjiang should prioritize prevention of seasonal snowmelt floods in the mid-

and low-altitude mountains of the Ili Prefecture during spring, while Southern Xinjiang should closely monitor two types of snowmelt (ice) floods during summer: high-altitude glacial lake outburst floods and snow- and glacier-melt water floods.

Full Text

Combined Analysis of the Spatiotemporal Variations in Snowmelt (Ice) Flood Frequency in Xinjiang over 20 Years and Atmospheric Circulation Patterns

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Abstract

Using 20 years of data (2000–2019) on snowmelt (ice) flood disasters in Xinjiang, this study analyzes the spatiotemporal distribution and regional differences in snowmelt (ice) flood frequency. The results show that snowmelt floods in northern Xinjiang accounted for 75.8% of the total frequency in Xinjiang, with the main flood season occurring in spring (March), concentrated in the western and northern regions of northern Xinjiang, with the highest frequency in Ili Kazakh Autonomous Prefecture (particularly in Xinyuan County). In southern Xinjiang, the main flood season occurred in summer (July), with snowmelt (ice) floods primarily appearing on the northern slopes of the Kunlun Mountains. Over the past 20 years, the frequency of spring snowmelt floods has shown an increasing trend in both northern and southern Xinjiang, with the frequency in the last 10 years increasing by approximately 30% compared to the first 10 years. This study clarifies the synoptic classification of snowmelt (ice) floods in Xinjiang and analyzes three atmospheric circulation patterns: the eastward expansion of the Iran subtropical high, the westward extension of the West Pacific subtropical high, and the development of the Xinjiang ridge. The high- and low-altitude circulation patterns and weather system configurations for temperature-driven snowmelt (ice) floods in Xinjiang are presented. The analysis reveals that before snowmelt (ice) floods occur, the South Asia high exhibits a single-center pattern, Xinjiang is controlled by a deep high-pressure ridge, the 100 hPa and 700 hPa temperatures are significantly higher than normal, and precipitation in mountainous areas is substantially above average. Flood prevention efforts should focus on seasonal snowmelt floods in the mid- to low-elevation mountains of Ili Prefecture in spring for northern Xinjiang, while southern Xinjiang should closely monitor two types of snowmelt (ice) floods in summer: high-mountain ice lake outburst floods and snow/glacier meltwater floods.

Keywords: snowmelt (ice) flood; atmospheric circulation types; spatiotemporal distribution; Xinjiang

1.1 Study Area Overview

Xinjiang has a vast territory with complex terrain. The Altai Mountains are in the north, the Kunlun Mountains in the south, and the Tianshan Mountains stretch across the central region, representing Xinjiang' s most characteristic mountain range that divides the region into southern and northern parts. The area south of the Tianshan Mountains is southern Xinjiang, while the area north is northern Xinjiang. Northern Xinjiang typically refers to the area north of the Tianshan Mountains, excluding the Turpan and Hami regions. The Junggar Basin lies between the Altai and Tianshan Mountains. Southern Xinjiang refers to the area south of the Tianshan Mountains and north of the Kunlun Mountains, also known as the Tarim Basin, which contains the famous Taklamakan Desert. The geographical features form a "three mountains surrounding two basins" landscape [Figure 1: see original paper]. Xinjiang is an important region in northern China where temperature-driven snowmelt (ice) floods occur. Due to the combined effects of high-mountain snow cover and temperature increases, snowmelt (ice) floods occur frequently and represent a significant meteorological disaster affecting transportation and agricultural and pastoral production.

1.2 Data Sources

Snowmelt (ice) flood disaster data for Xinjiang were obtained from the China Meteorological Disaster Management System, supplemented by research data from Ablimitjan Ablikim et al. [reference]. The study analyzed 20 years (2000-2019) of temperature-driven snowmelt (ice) flood disasters and frequencies in Xinjiang, generating annual, seasonal, and monthly time series and spatial distribution characteristics. Seasons were defined as spring (March–May), summer (June–August), autumn (September–November), and winter (December–February). Atmospheric circulation pattern data were derived from high-altitude observations by C-band radar, obtained from the China Meteorological Information Comprehensive Analysis and Processing System, including 100 hPa geopotential height fields and 500 hPa, 700 hPa, and 850 hPa isobaric temperature data. By analyzing the circulation patterns at different isobaric levels and the 850 hPa field distribution during typical snowmelt (ice) flood processes in Xinjiang, the atmospheric circulation classification for these floods was revealed.

2.1.1 Temporal Variation of Snowmelt (Ice) Floods

From 2000 to 2019, Xinjiang experienced 211 snowmelt (ice) floods, with 160 occurring in northern Xinjiang and 51 in southern Xinjiang, accounting for 75.8% and 24.2% of the total, respectively. The average annual frequencies for Xinjiang, northern Xinjiang, and southern Xinjiang were 10.6, 8.0, and 2.6 times, respectively. Northern Xinjiang experienced significantly more snowmelt floods than southern Xinjiang, with greater interannual variability. The frequency trend in northern Xinjiang was basically consistent with that of Xinjiang as a whole, showing an increasing trend over the 20 years, with the highest frequency in 2010 (18 times in northern Xinjiang) and the lowest in 2001 (2 times, both in northern Xinjiang). The second-highest frequencies occurred in 2005 (17 times) and 2016 (16 times), all in northern Xinjiang. In southern Xinjiang, the highest frequency was 7 times (in 2005 and 2010), and the second-highest was 5 times (in 2002, 2006, and 2016).

Monthly analysis shows that Xinjiang' s snowmelt (ice) floods were concentrated from March to July, with 180 occurrences accounting for 85.1% of the total. March had the highest frequency (76 times, 36.0%), followed by July (41 times, 19.4%) and April (31 times, 14.7%). Winter (December–February) had only 9 occurrences (4.3%), averaging less than 0.5 times per year. The first 10 years (2000–2009) showed 85 occurrences (40.3%), while the last 10 years (2010–2019) had 126 occurrences (59.7%), indicating a significant increase in the latter period, particularly in March, April, and July.

Northern Xinjiang' s snowmelt floods were concentrated in the first half of the year, with 153 occurrences (95.7% of its total), primarily in March (76 times, 47.5%), April (31 times, 19.4%), and May (23 times, 14.4%). The second half of the year had few occurrences (only 7 times, 4.3%). Summer (June–August) had 29 occurrences (18.1%), and winter had 9 occurrences (5.6%). The trend in northern Xinjiang' s snowmelt flood frequency was similar to that of Xinjiang as a whole for the first 10 years, but increased significantly in the last 10 years, particularly in March, April, and July.

Southern Xinjiang' s snowmelt (ice) floods occurred from March to August, with 47 occurrences (92.2% of its total), concentrated in summer (June–August) with 27 occurrences (52.9%). July had the highest frequency (17 times, 33.3%), followed by June (10 times, 19.6%) and August (9 times, 17.6%). No snowmelt (ice) floods occurred from September to February. The last 10 years showed a stable increase in frequency, with July being the most frequent month.

2.1.2 Spatial Distribution of Snowmelt (Ice) Flood Frequency

Analysis of the annual frequency and proportion shows that northern Xinjiang accounted for 160 of the 211 total occurrences (75.8%), more than three times that of southern Xinjiang (51 occurrences, 24.2%). Northern Xinjiang' s snowmelt floods were concentrated in the western and northern regions, accounting for 69.3% of Xinjiang' s total. Among prefectures in northern Xinjiang, Ili had the highest frequency (44.8% of northern Xinjiang' s total), followed by Tacheng (20.0%) and Altay (20.0%). In southern Xinjiang, the distribution was more uniform, with Kizilsu having the highest frequency (26.9%), followed by Hotan (25.0%) and Kashgar and Aksu (both 21.2%). Bayingolin had the lowest frequency (5.8%).

At the county level, Xinyuan County in Ili Prefecture had the highest frequency (17 occurrences), followed by Qapqal and Emin counties. In southern Xinjiang, Aktao County in Kizilsu had the most occurrences (7 times), followed by Hotan City (6 times) and Tashkurgan County in Kashgar (5 times).

The seasonal spatial distribution shows that spring snowmelt floods in northern Xinjiang were concentrated in Ili and Tacheng prefectures, particularly in Xinyuan, Nileke, Emin, and Yumin counties. Summer distribution was more balanced, while winter snowmelt (ice) floods were concentrated in Ili Prefecture (7 occurrences, 77.8% of northern Xinjiang's winter total). In southern Xinjiang, spring snowmelt floods were most frequent in Kizilsu (7 times), with Hotan and Aksu having 4 occurrences each. Summer floods were most common in Hotan (9 times), followed by Kizilsu (8 times) and Aksu (6 times), primarily distributed in Hotan City, Yutian County, and Aktao County.

The monthly spatial distribution reveals distinct differences between northern and southern Xinjiang. Northern Xinjiang' s snowmelt floods were concentrated in the western and northern regions in March, particularly in Xinyuan, Nileke, Emin, and Yumin counties. April showed a similar pattern, while May floods occurred in both eastern and western Altay. July floods were concentrated in Qapqal and Tekes counties. In southern Xinjiang, July floods were most frequent in Aktao County, Kizilsu, while August floods were more common in Shache and Yecheng counties, Kashgar.

2.2 Atmospheric Circulation Classification

The atmospheric circulation pattern during warming periods determines the intensity, location, and timing of snowmelt (ice) floods. Analyzing these patterns enables classification of the circulation types associated with snowmelt floods. During warming events, Xinjiang is controlled by a high-pressure ridge, with sustained warming in the middle and lower troposphere leading to snowmelt (ice) floods. Under the guidance of upper-level airflow, the Iran subtropical high, West Pacific subtropical high, and southern Xinjiang high-pressure ridge all evolve into high-pressure ridges controlling Xinjiang. Based on the position and movement path of the 100 hPa high-pressure ridge, the atmospheric circulation patterns for snowmelt (ice) floods in Xinjiang are classified into three types: Iran subtropical high eastward expansion type, West Pacific subtropical high westward extension type, and Xinjiang ridge development type. Among 211 snowmelt (ice) flood events, the Iran subtropical high eastward expansion type occurred 113 times (53.5%), the West Pacific subtropical high westward extension type occurred 66 times (31.2%), and the Xinjiang ridge development type occurred 32 times (15.3%). The Iran subtropical high eastward expansion type is the dominant circulation pattern for snowmelt (ice) floods in Xinjiang.

2.2.1 West Pacific Subtropical High Westward Extension Type This type is illustrated by a summer case in southern Xinjiang. Before the high temperature event, two high-pressure centers were located over the Iranian Plateau and near the East China Sea. The Iran high weakened and its center disappeared, while the high near the East China Sea gradually moved westward, merging with the high-pressure ridge moving northeastward from the western Tibetan Plateau to form a stronger Xinjiang high, with the center reaching 1688 dagpm at 100 hPa. At 500 hPa, Central Asia was typically a low trough or vortex area, while Xinjiang to Lake Baikal was controlled by a high-pressure ridge. The West Pacific subtropical high developed and extended westward and northward, forming a vigorous system that connected with the high-pressure ridge from Xinjiang to Lake Baikal (ridge line located near 110°E). As the Central Asian low-value system moved eastward to Lake Baikal, the West Pacific subtropical high formed an east-west oriented high-pressure dam controlling the Xinjiang region during its westward extension. In summer, the 500 hPa 588 dagpm line often covered northern Xinjiang, sometimes extending to the Sayan Mountains, while southern Xinjiang was entirely covered by the 588 dagpm line. At 700 hPa and 850 hPa, high-pressure centers around 584 dagpm also appeared over Xinjiang.

In late July 2015, a significant snowmelt (ice) flood occurred in southern Xinjiang. The circulation pattern belonged to the Iran subtropical high eastward expansion type. At 100 hPa, the South Asia high was a single-center type, with the high center located over Xinjiang. At 500 hPa, the Iran high moved eastward and controlled Xinjiang, with the 588 dagpm line' s western boundary reaching near 60°E and its northern boundary extending to 50°N, controlling most of Xinjiang. The 584 dagpm line controlled southern Xinjiang, with closed high centers appearing in the Tarim Basin. At 850 hPa, temperatures could rise above 25°C, with high temperature centers exceeding 25°C [Figure 500: see original paper]. Affected by this sustained high temperature, the northern slopes of the Kunlun Mountains and southern slopes of the Tianshan Mountains experienced successive snowmelt (ice) floods. The Yarkant River, Yulong Kashi River, and Kara Kashi River exceeded warning levels for more than half a month, with the Yulong Kashi River exceeding warnings for 18 days. On July 31, the snowmelt (ice) flood caused the Qilekeya Bridge at K2316+292 on the Southern Xinjiang Railway to be washed away, interrupting traffic. On August 1, a 120 m breach occurred in the flood control dike at Huangyangtan section, Wensu County, and on the same day, a sudden snowmelt debris flow and landslide geological disaster occurred in Baigawule Village, Taheman Township, Tashkurgan County.

2.2.3 Xinjiang Ridge Development Type This type is illustrated by a spring case in northern Xinjiang. At 100 hPa, the South Asia high belt was located on the western side of the Tibetan Plateau, with the ridge line moving northward and the high center strengthening, forming a high-pressure 单体 over the western Tibetan Plateau with the center reaching 1668 dagpm. At 500 hPa, Europe, the Caspian Sea, Aral Sea, and areas west of Lake Baikal were typically low-value regions, while the Tibetan Plateau was controlled by a high-pressure ridge. As the western Xinjiang ridge moved eastward, the Tibetan

Plateau high-pressure ridge also moved eastward and northward, developing and superimposing on the original Xinjiang ridge to form a new, stronger Xinjiang ridge. The ridge top rotated to form a north-south oriented high-pressure belt, with the ridge line generally around 85°E, controlling all of Xinjiang. The 552 dagpm line could control the entire region, with the 556 dagpm line extending northward. At 850 hPa, temperatures in northern Xinjiang could rise to around 15°C, easily causing snowmelt (ice) floods.

In mid-March 2014, sustained warming in northern Xinjiang led to the South Asia high center reaching 1668 dagpm at 100 hPa, with the 560 dagpm line controlling all of Xinjiang. At 850 hPa, temperatures in northern Xinjiang rose to around 15°C. Under this strong warming influence, extensive snowmelt floods occurred in northern Xinjiang. On March 17–18, snowmelt floods affected Ili Prefecture, Tacheng area, and Urumqi, impacting over 1,000 people, with water depths reaching 40 cm in low-lying areas, damaging 500 hm^2 of crops, and causing economic losses of 4.54$×10^{6}$ yuan [Figure 8: see original paper]. In general, the stronger the Xinjiang high-pressure ridge center and the more northward the ridge top, the more severe the snowmelt (ice) flood and the more northward the impact area. Snowmelt (ice) floods occur when 850 hPa temperatures rise above 15°C in spring and above 25°C in summer.

2.3 Upper-Air 0°C Layer Height and Preceding Precipitation

The upper-air 0°C layer height and preceding precipitation directly affect spring snowmelt-type and summer snowmelt (ice)-type floods. Two typical cases were selected to analyze the variation characteristics of the 0°C layer height and preceding precipitation under the three circulation types: Iran subtropical high eastward expansion, West Pacific subtropical high westward extension, and Xinjiang ridge development.

2.3.1 Significantly High Upper-Air 0°C Layer Height In July 2015, rare high temperatures across Xinjiang in the last ten days triggered multiple snowmelt (ice) floods. Xinjiang was controlled by a high-pressure ridge, with the South Asia high showing a single-center pattern and the high-pressure 单体 located over Xinjiang and the Tibetan Plateau. The intensity, position, and duration of this deep high-pressure system determined the severity, location, and timing of snowmelt (ice) floods. Generally, the West Pacific subtropical high westward extension type occurs in midsummer, while the Iran subtropical high eastward expansion type and Xinjiang ridge development type appear throughout the summer half-year. The Iran subtropical high eastward expansion type can cause warming across all of Xinjiang, with more significant warming in the middle and lower layers in southern Xinjiang, resulting in more severe snowmelt (ice) floods.

Analysis of Aksu's July 0°C layer height shows that in 2015, the monthly average height reached 5472.1 m, ranking third highest since 2000 and 381.2 m above the historical average [Figure 9: see original paper]. Daily comparisons show the 0°C layer height was significantly higher than historical values, with the maximum exceeding 610.3 m above average. In March 2014, before snowmelt floods occurred in northern Xinjiang, the 0°C layer height in Yining reached 3528 m, 818.4 m above the historical average, ranking first since 2000 [Figure 10: see original paper]. The 0°C layer height was more than 600 m above historical values, with local mountainous areas exceeding 800 m. In typical years, the 0°C layer height before snowmelt (ice) floods can be more than 600 m higher than normal.

2.3.2 Abundant Preceding Precipitation Analysis of precipitation before the two typical snowmelt (ice) flood events in July 2015 and March 2014 shows that precipitation was significantly above normal. In July 2015, precipitation across Xinjiang was 32% above normal, with the Tianshan Mountains receiving more than 50% above normal. In terms of deviation from historical values, Yining County, Gongliu, Jimsar, Mori, and Qinghe ranked in the top three positions, with Qinghe and Nilka ranking second. In Kashgar, precipitation ranked first historically. Before the March 2014 snowmelt flood in northern Xinjiang, precipitation was significantly above normal, with deviation amplitudes ranking first in Huoerguosi, second in Fuhai, and third in Tuoli. Snow depth in northern Xinjiang was abnormally thick, with Huoerguosi, Huocheng, Paotai, Shihezi, Wulanwusu, Yining City, Yining County, and Urumqi all showing thick snow cover. Precipitation was abundant before the occurrence of snowmelt (ice) floods, with mountainous snow cover being significantly thicker and more extensive.

3 Conclusions

By analyzing the frequency variation patterns of snowmelt (ice) flood disasters in Xinjiang, this study presents the spatiotemporal distribution characteristics of snowmelt (ice) flood frequency over the past 20 years, summarizes the atmospheric circulation patterns and evolution features causing temperature-driven snowmelt (ice) floods in Xinjiang, and briefly describes the impacts of the 0°C layer height and preceding precipitation on these floods. The main conclusions are as follows:

1) From 2000 to 2019, Xinjiang experienced 211 snowmelt (ice) floods, averaging 10.6 times per year. Northern Xinjiang had 160 occurrences (75.8% of the total), significantly more than southern Xinjiang’ s 51 occurrences (24.2%). The annual frequency of snowmelt (ice) floods showed an increasing trend, particularly in the last 10 years, with an increase of about 3 occurrences per year. Both northern and southern Xinjiang showed increasing trends, with northern Xinjiang’ s interannual variability being more pronounced.

2) The spatiotemporal distribution of snowmelt (ice) floods differs significantly between northern and southern Xinjiang. Northern Xinjiang experiences only snowmelt-type floods, mainly in spring, with March being

the peak month, concentrated in the western and northern regions (with Xinyuan County in Ili Prefecture having the highest frequency). Southern Xinjiang experiences both snowmelt- and ice-melt-type floods, mainly in summer, with July being the peak month (with Hotan City in Hotan Prefecture having the highest frequency). Flood prevention should focus on temperature-driven snowmelt floods in northern Xinjiang in March (especially in Ili Prefecture) and two types of snowmelt (ice) floods in southern Xinjiang in July: high-mountain ice lake outburst floods and glacier meltwater floods.

3) The three atmospheric circulation types for snowmelt (ice) floods in Xinjiang are the Iran subtropical high eastward expansion type, West Pacific subtropical high westward extension type, and Xinjiang ridge development type. The South Asia high shows a single-center pattern, and Xinjiang is controlled by a high-pressure ridge from 100 hPa to lower levels, representing a deep high-pressure system. The stronger the Xinjiang high-pressure ridge and the more northward its ridge top, the more severe the snowmelt (ice) flood and the more northward its impact area. Before snowmelt (ice) floods occur, the 850 hPa temperature can rise above 15°C in spring and above 25°C in summer.

4) Before snowmelt floods occur, the upper-air 0°C layer height is significantly higher and precipitation is substantially above normal. In typical years, the 0°C layer height is more than 600 m higher than normal, and precipitation in the one to two months before snowmelt (ice) floods is about double the normal amount, with significantly thicker and more extensive snow cover in mountainous areas.

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Note: Figure translations are in progress. See original paper for figures.