water

MDPI

Communication

Effects of Winter Warming on Alpine Permafrost Streamflow in Xinjiang China and Teleconnections with the Siberian High

Jingshi Liu [1,2,*], Guligena Halimulati [1], Yuting Liu [1], Jianxin Mu [3] and Namaiti Tuoheti [1]

1 School of Life and Geography, Kashi University, Xuefu Road 380, Kashi 844000, China; namaiti@ksu.edu.cn (N.T.)
2 Institute of Tibetan Plateau Research, 16 Lincui Road, Beijing 100101, China
3 Northwest Institute of Eco-Environment and Resources, West Donggang Road, Lanzhou 730000, China
* Correspondence: jsliu@itpcas.ac.cn

Abstract: The climatic warming-induced shrinking of permafrost currently encompasses 65% of alpine areas in North China, where a large population relies on its water and land resources. With increasing recognition of the economic and ecological impacts of permafrost basins, forecasts of environmental vulnerability have gained prominence. However, the links between permafrost and winter water resources remain inadequately explored, with most studies focusing on in-situ measurements related to snow cover and frozen layer thickness. Evaluating more complex phenomena, such as the magnitude and persistence of air temperature or low streamflow, depends on numerous climate-driven factors interacting through various subsurface flow mechanisms, basin drainage mechanics, and hydro-climatic correlations at a macroscale. The present study focuses on winter warming, flow increases, and their teleconnections in Xinjiang, China. The research analyzes their links to the atmospheric cycle of the Siberian High (SH) using long-term data spanning 55 years from two large alpine permafrost basins. Changes in variability and correlation persistence were explored for the past decades, and significant variability and connections were constructed using statistical correlation. The years 1980 and 1990 were a turning point when both winter temperatures and winter river flow began to exhibit a notable and consistent upward trend. Subsequently, the period from the mid-1990s to 2013 was characterized by high variability and persistence in these trends. The influence of the SH plays a dominant role in regard to both winter temperatures and river flow, and these variabilities and correlations can be utilized to estimate and predict winter flow in ungauged permafrost rivers in Xinjiang China.

Keywords: winter warming; winter streamflow; change point; permafrost; Siberian High; teleconnection

Citation: Liu, J.; Halimulati, G.; Liu, Y.; Mu, J.; Tuoheti, N. Effects of Winter Warming on Alpine Permafrost Streamflow in Xinjiang China and Teleconnections with the Siberian High. *Water* **2024**, *16*, 993. https://doi.org/10.3390/w16070993

Academic Editor: David Dunkerley

Received: 9 December 2023
Revised: 14 February 2024
Accepted: 24 February 2024
Published: 29 March 2024

1. Introduction

Global warming has influenced the watersheds in permafrost regions, especially during the last two decades when permafrost degradation has accelerated and intensified in China [1,2]. Permafrost degradation has been reported due to the rising of ground temperatures, thickening of the active layer since the 1980s, thawing of ground ice, and shrinking and thinning of seasonal permafrost. The annual temperature of permafrost increased by 0.3 °C globally, by 0.4 °C in the continuous permafrost areas, and by 0.2 °C in discontinuous permafrost areas during 2007 to 2016, respectively [3].

Studies show that the degradation of permafrost can speed up water transfer, increase soil moisture, and improve agricultural productivity and the local ecology. Permafrost degradation resulting from climatic changes is expected to impact the hydrological, ecological, and biogeochemical responses of Northwest China and the high-latitude tundra [4,5], which is a proof of concept implementation in the massively parallel subsurface flow, and reactive transport was summarized [6]. Permafrost covers the majority of alpine and plateau regions in China, encompassing approximately 65% of the country's land area. This permafrost coverage significantly affects environmental changes, particularly in regions such as Northeast and Northwest China [7,8].

The southern border of permafrost in Northeast China has moved northward by 40–120 km, with a reduction in area of about 70 $\times$ 10^3 km^2 during the 1970s to the mid-2000s, and parts of permafrost islands have disappeared. The thickness of the active layer on the Tibetan Plateau has increased by 22 cm/10a, and the mean warming of this layer was 0.45 °C/10a in the last 15 years [9]. These are the headwaters of many large rivers, such as the Ergis River and the Keziy River from the Pamirs plateau in the Xinjiang region of Northwest China. This region is home to a large population (7 million) that relies on hydrological, agricultural, and biological resources. In response to the increasing recognition of the economic, hydrological, and eco-environmental significance of rivers in glacier and permafrost areas, there is growing demand for the analysis of the response of these rivers to environmental vulnerabilities resulting from global warming. According to IPCC reports, climate change is expected to affect the components of the hydrological cycle such as precipitation amount and distribution, snow accumulation and meltwater, evapotranspiration, land surface, and subsurface flows, particularly in permafrost areas. Striking changes in climate have significant implications for water resources in the cold, arid, and high-altitude parts of Northwest China [9,10].

Notably, the regional climates in Northwest China have shifted and intensified from a warm–dry pattern to a warm–wet pattern, resulting in increases in winter streamflow by 10–20% [11,12]. In the permafrost region of China, the thickness of the active layer has increased by 14 cm, expanding from 190 cm to 206 cm, and the freezing period has shortened by almost 30 days from October to November [13–15]. In the plateau region, the maximum frozen depth has reduced by 3.6 cm per decade since the mid-1980s, with the greatest thinning observed in the high alpine area [16]. However, the teleconnections between winter temperatures and river flows have been rarely studied, primarily due to a lack of macroscale investigations in the extremely high and cold areas of northern China.

The connections between permafrost and winter water resources in northern China have been inadequately explored, with most works concentrating on simple measures directly associated with snow cover, including changes in their area and thickness. Evaluations of more complex phenomena, such as the magnitude and persistence of air temperature or low flows, rely on numerous factors influenced by the climate. These factors interact through a variety of geophysical mechanisms, including basin drainage mechanics, and meteorological, hydrological, and hydraulic processes [17–19].

The high-latitude drainage rivers, however, are representative of the climatic regime in North China and have not been significantly affected by human interventions (e.g., no irrigation and hydroelectric developments). This study quantifies the response of the permafrost basin to climatic, hydrological, and permafrost changes. Moreover, it investigates the teleconnections between the winter air temperature and atmospheric circulation in the highlands of the world. In other words, these winter changes are related to the Siberia High (SH) over the Northern Hemisphere [20–22]. This study explores the continental winter climate, the hydrological trend of permafrost, and variability for two river basins in high-latitude China. The periglacial basins are in a rectangle transect spanning from the Altay mountains of northern Xinjiang via the huge Keizy Basin of southern Xinjiang in China, such as the Erkis River in the Altay mountains and the Keizy River in the Pamirs plateau. These rivers are in the far field of 1800 km, as shown in Figure 1. Studies show that high-latitude basins are particularly responsive to the impacts of climatic changes [18,23].

The IPCC reports that snowmelt frequencies and increases in runoff are probably due to increased air temperature and precipitation at high altitudes [3]. However, relatively limited research has been conducted regarding the variability and connections between the macroscale of the plateau and high alpine permafrost climate, winter streamflow, and atmospheric circulation of the Siberia High at the scale of the high-alpine permafrost regions. This scarcity of studies is primarily due to the lack of river data in these frozen regions. These catchments are representative of the inland arid and alpine climate regimes over the plateau respectively. It is worth noting that these catchments have experienced minimal human activities and have not been used for winter irrigation or hydroelectric development.

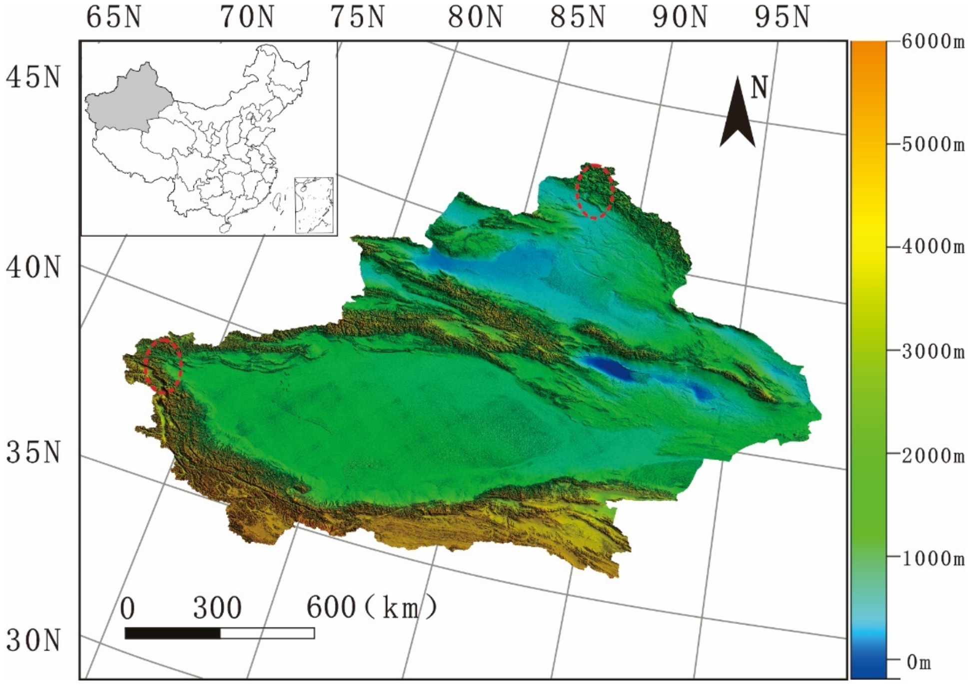

Figure 1. Permafrost extent in China and Xinjiang region and location of the studied two basins in northern and western Xinjiang.

Permafrost change influences not only the regime of river runoff, but also its seasonality, and thus the governance of water resources in downstream regions. Ice, snow, and permafrost in the Tibetan Plateau and its surrounding area were projected to decrease by 49% and 64% under representative concentration pathways (RCP) 4.5 and 8.5, respectively, directly affecting the vulnerability of water resources in the cryosphere.

The challenge lies in quantifying the unclear effects of these changes in streamflow in areas where winter flow observations are lacking. Additionally, geocryological data are often unavailable in these areas, partly because winter flow disturbances produce feedback that affects many subsystems, such as the atmosphere, hydrosphere, cryosphere, and land surface. Instead of using deterministic snowmelt–runoff models to assess the impacts of climate change or human activities on runoff in each watershed, this article uses the observed winter air temperature, streamflow, and frozen depth and estimated SH data to separate the direct impacts of climate change on winter hydrology and streamflow which is not related to human impacts based on a systematic framework at the regional and continental scales.

The goal of this study is to detect the hydrological response to the winter warming in Xinjiang, China, and to connect the winter hydro-meteorological variability and the Siberian High. This is important for managing and predicting changes in winter water resources and the ecological environment in the Xinjiang region, China. Some correlation between indicators of winter streamflow and the Siberian High, such as the maximum water supply in winter, streamflow, and active-layer thickness might be expected.

2. Materials and Methods

2.1. Study Area and Data

The Burkin River is the largest tributary of the Erkis River. The basin, situated above the Qunkul hydrometric station, spans an area of 8700 km^2 (48°06′ to 49°18′ N, 86°43′ to 87°38′ E). The elevation of the basin ranges from 660 to 4376 m above sea level, with an average elevation of 2150 m above sea level. Notably, the lower limit of permafrost in this region begins at elevations above 2420 m above sea level.

The Keziy River is a significant tributary of the Kashgar River, originating in the Tajikistan Pamirs. Moreover, the Kashgar River is a large tributary of the Tarim River in southern Xinjiang, China. The basin, located above the Karabel hydrometric station, encompasses an area of 14,570 km^2 (37°06′ to 39°18′ N, 75°43′ to 75°38′ E). The elevation within this basin ranges from 1460 to 6576 m above sea level, with an average elevation of 3450 m above sea level.

Notably, between 51% and 66% of these basin areas are underlain by continuous mountain permafrost in the upstream regions, an additional 20% to 32% falls into the discontinuous (sporadic/isolated) permafrost areas, and the remaining portion comprises seasonally frozen ground [19,20]. Monthly hydroclimatic data utilized in this study have been sourced from available hydrology Redbooks of governmental databases in Xinjiang, China.

Two hydrometric stations situated at elevations higher than 1200 m above sea level, namely Qunkul in the Burkin River and Karabel in the Keziy River were chosen in this research. This selection was made because they offer a continuous dataset spanning 55 years (1958–2013) and are located within their respective river basins. The mean annual air temperature at the gauging stations is 3.2 °C at Qunkul and 9.2 °C at Touyun. Additionally, the average annual precipitation at the stations varies, with a minimum of 250 mm at Qunkul and an annual average of 290 mm at Touyun. Generally, the mean annual temperature falls below −1 °C, which can be considered the threshold temperature for the existence of permafrost or the lower limit of alpine permafrost in China.

The hydrometeorological records from the stations reveal a simple streamflow pattern of an extreme continental climate. Throughout the cold and snowy winter, the weather is affected by the westerly and Arctic anticyclones, with surface flow resulting from rainfall and snowmelt being the primary forms of runoff. Snowfall in the mountains exhibits significant heterogeneity, increasing from a height of 250 mm in the valleys to 800 mm at glacier sites. There is a distinct seasonal pattern to runoff, with summer meltwater and the westerly rainfall contributing to approximately 80% of the annual total. The maximum and minimum monthly runoffs occur in June and February, constituting almost 24% and 6% of the annual total, respectively [18,23]. The results demonstrate substantial inter-annual variations. In high runoff years, cold and warm seasonal flows surpass those of a typical year like 1993 [24]. This is especially more pronounced during late fall and early winter. During the cold months, soil freezing and thawing occur for almost 190 days and 240 days at low elevations and high mountains, respectively. Furthermore, snow cover persists from October to May the following year, with the greatest snowpack thickness in the high mountains. The rivers experience flow recession during the winter period, recharged only by groundwater, which is significantly influenced by the freezing and thawing of seasonally frozen ground and the active layer over permafrost.

The primary data source for the Siberian High in this study is the NCEP–NCAR reanalysis field covering the period from January 1959 to December 2013. It utilizes a global data assimilation system with a 2.5° longitude by 2.5° latitude grid. Monthly data including sea level pressure (SLP), surface air temperature (SAT), sea surface temperature (SST), and the vertical components of the wind are incorporated into the study. The winter monthly Siberia High index is derived from the NCEP reanalysis dataset (http://www.wmo.int/pages/prog/www/ois/volume-a/volahome.htm (accessed on 10 November 2015)).

2.2. Methodology

The methodology employed to investigate hydrological trends and variability initiates by assessing trends in hydrological variables at individual stations utilized the Mann–Kendall nonparametric trend test (M–K test) [25]. This test, based on rank-order statistics, has been widely used to identify the trends in hydro-meteorological variables [26]. The outcomes of the trend test identify whether the observed time series for a specific variable exhibits trends surpassing those expected by chance. The trend results in this study were assessed at significance levels of 95% and 90%. To identify change points in trends over time, the sequential values Forward_u and Backward_u, derived from the progressive analysis based on the M–K test, were applied. It should be indicated that Forward_u is a standardized variable with a mean of zero and a unit standard deviation, resulting in sequential behavior fluctuating around zero. It is equivalent to the z values calculated between the first and last data points, considering the relative values of all terms in the time series (x_1, x_2, . . ., x_T).

2.3. Correlations

To investigate the relationships between hydrometeorological variables, a moving correlation analysis was employed. Data within a group were explored to identify significant trends following the application of the Mann–Kendall test based on harmonic analysis. Meanwhile, the correlation strength between meteorological and hydrological variables was assessed through statistical testing at the 95% significance level. Utilizing moving correlations leads to identifying correlations between variables independently of any shared trend signal in the two variables. Consequently, the observed trends in timing measures can be attributed to meteorological variables. To determine the stability of correlations between remote basins, a moving correlation was computed by opening a window of 17 years. This involved calculating a moving correlation between two sites or two hydro-meteorological variables annually, with the resulting connection values plotted on the *Y*-axis.

3. Results

The examination of winter air temperature and river flow data was conducted due to their association with regional climate, permafrost degradation, and groundwater processes in the snowy alpines and permafrost areas. Accordingly, the reflected impacts of climate shifts in these datasets can be explored. The correlations between winter monthly air temperatures at the Burkin and Yashi stations are notably widespread regionally, extending from the east to the west, i.e., from the Altay Mountains to the Pamirs Mountains, with statistical significance at the 10% level or higher ($p < 0.05$), as illustrated in Figure 2. The correlation coefficient (R) between the two stations is 0.43.

Nevertheless, the R^2 of 0.173 revealed a high correlation between the Burkin and Keziy rivers. Winter flow teleconnections were observed between the Altay and the Pamirs Mountains, despite the substantial distance of approximately 1880 km between the two stations. The observed teleconnections exhibited a strong correlation between these two areas.

Winter temperature variability: The Mann–Kendall test results for climatic variables are presented in Figure 3, highlighting trends over the 95% significance level, and the findings reveal a consistent increase in air temperatures over the studied period. The mean winter monthly air temperatures at Burkin and Yashi have exhibited a noticeable rise since 1980 for December and January and 1996 for February, respectively. Particularly, the winter climate has warmed by 2.8 °C at the Burkin and 1.5 °C at the Keziy rivers since the mid-1990s. Notably, the higher warming has occurred in the high-latitude Burkin Basin, with the warming intensity at the Burkin River being almost two times larger than that at the Keziy River. It is inferred that the warming rate increased from 3000 to 4800 m above sea level and then stabilized, with a slight decline at the highest elevations. The altitudinal dependence of the warming rate carries significant implications for water resources and environmental changes in Northwest China.

Hydrological variability: Given the substantial warming discussed earlier and the positive correlation between winter air temperature and river flow, the Mann–Kendall tests for hydrological variables were examined, as depicted in Figure 3. It illustrates trends at a significance level of over 95%, indicating an increase in discharge over the 55 years. Particularly, the Burkin and Keziy river flows have increased since 1990 and 1999, respectively. With the pronounced warming since the 1980s, the winter flow of both rivers has increased by 18% and 15% since the mid-1990s. Interestingly, the change in flow for both rivers occurred nearly a decade later than the changes in winter air temperatures. This lag is because the temperature represents atmospheric heat at a specific location, while winter flow represents interactions between surface and subsurface water and heat. The downward conduction of soil heat is much slower than that in air, and it becomes more intricate due to changes in both hydrogeology and the cryosphere.

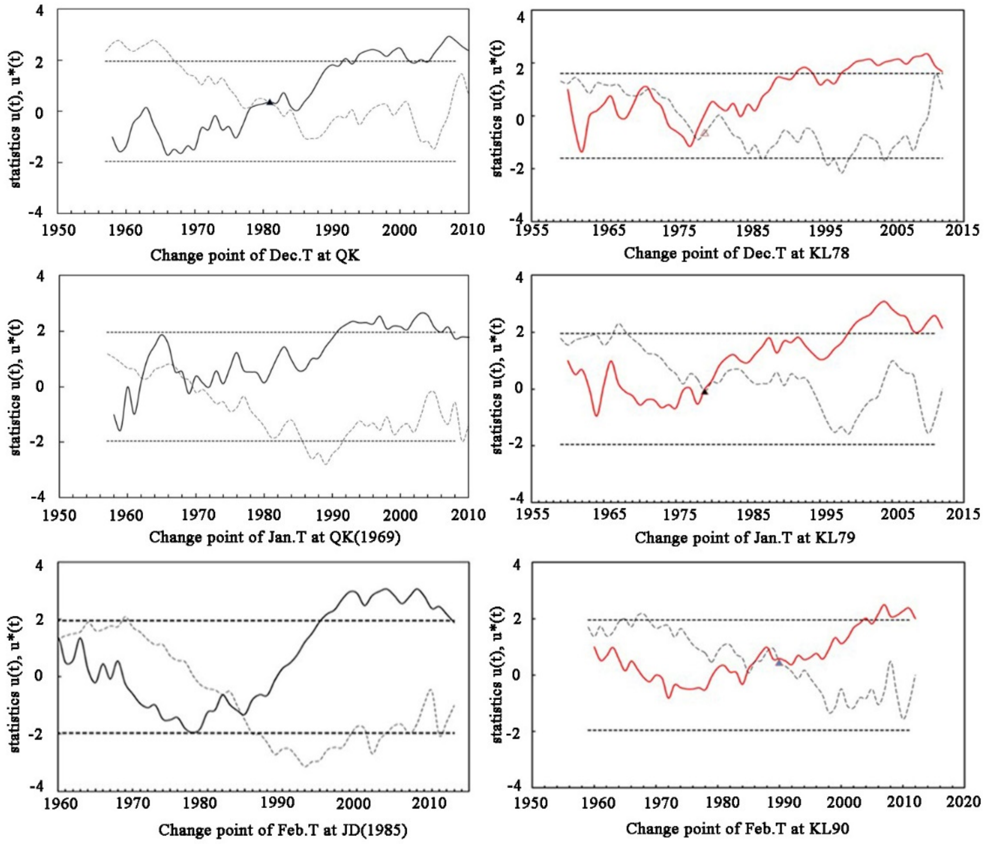

Figure 2. Changepoint (the cross point between the upline and decline line) of the winter air temperatures in two basins.

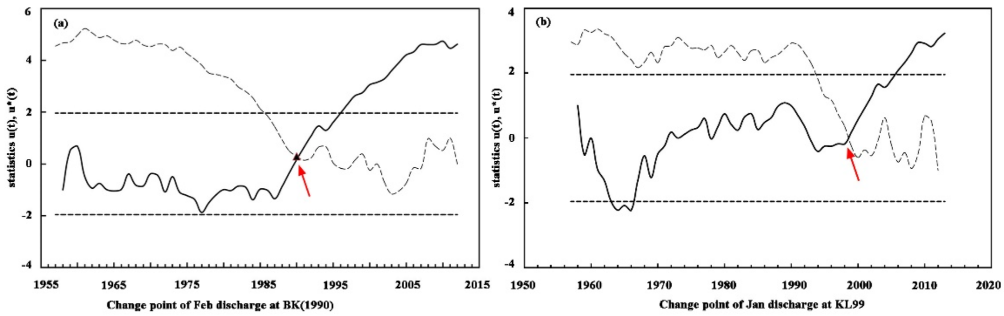

Figure 3. Changepoint (the cross point between the upline and decline line) of the winter river flow in the two basins.

Moving correlations between winter air temperature and winter streamflow are needed to be objectively and effectively detected regarding its spatiotemporal distribution. In this study, analysis of the linear correlation of hydro-meteorological data was performed at each station, to avoid the dependence of the recurrence elevation on specific spatial patterns or prior selection of areas. The moving correlation is defined as the correlation of values for one starting month (all winters) with a lag of 17 years. For example, for a starting month 1 December and 17, then month 2 December and 18, and so on, the correlation is between the air temperature and discharge in the December time series. The 80% reliability of correlative coefficient R^2 for the 17 samples is larger than 0.16, which is acceptable for winter stream data.

To assess variations associated with variations in the teleconnections of monthly air temperature and monthly river flows in winter over the studied period, a moving teleconnection (R^2) was calculated for the total 54 years and using a 17-year window ($R = 0.413$, $p < 0.05$), respectively. Figures 4–6 present the correlation between the winter air temperature and the streamflow of these two remote basins during the study window for the rivers. The R_2 correlation between December and February for the Burkin River and Keziy River alternately fluctuated from positive to negative years before the 1980s, then gradually recovered to a weakly positive correlation since the 2000s. Overall, winter flow has exhibited long-term and steady connections since the mid-1990s.

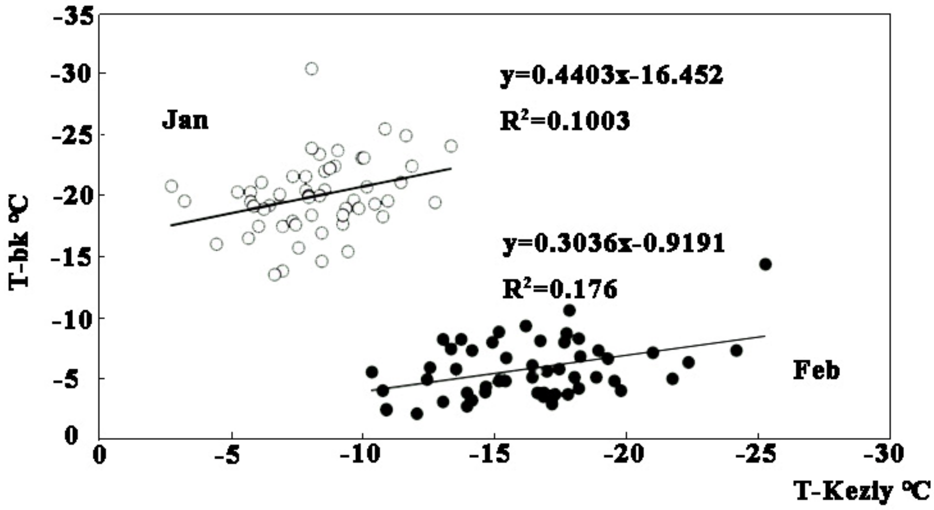

Figure 4. Teleconnections between the winter air temperature at the Burkin and Keziy stations.

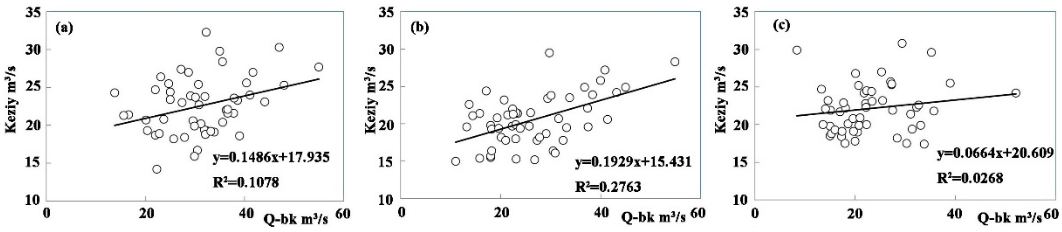

Figure 5. (**a**–**c**) Monthly teleconnections of the winter river flow between the two basins (1960–2013).

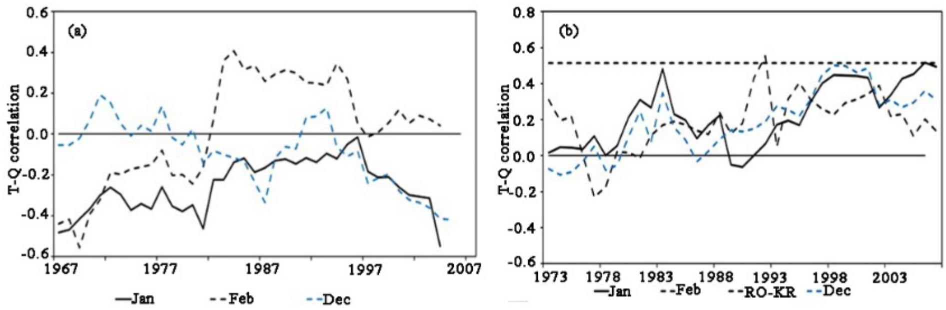

Figure 6. Moving correlation between the winter monthly air temperature and river flow (**a**) Burkin, (**b**) Keziy.

4. Discussion

The depth of the active layer is affected by various parameters, including air and ground temperature, soil moisture, and the thickness of snow cover. Typically, regional climate plays a crucial role in determining the depth of soil frost. Typically, the analyses rely on air temperatures measured at nearby locations as a primary determinant. This is because the broad spatial patterns of temperature are proportional to the macroclimate and can be predicted using local observations [22,27]. Additionally, the seasonal snowpack has significant insulating effects on the thermal regime of frozen ground and the depth of the active layer. Averaging data from monthly to seasonal scales generally enhances the correlation between air and ground temperature, with heat conduction contributing to this lag effect. The depth of the seasonally frozen ground at the Burkin station was reduced by approximately 15 cm, from 318 cm in the 1960s to 303 cm in 2014 [23,28].

In studies on investigating the parameters of cold-season river flow behaviors in subarctic river basins under the influence of the Siberia High, analyses were conducted on the winter streamflow and recession hydrographs of each basin [24]. Furthermore, the depth of annual cold-season catchment-averaged runoff was analyzed with respect to various basin attributes, aiming to detect potential controls on recession behaviors. Distinctly different behaviors were observed between the basins in discontinuous permafrost areas and continuous permafrost areas [25–27]. Studies on the spatial cross-correlation patterns of European low, average, and high flows reported that low flows occurred during prolonged dry periods governed by depleting storages, exhibiting the lowest spatial correlations over short distances [29]. Over longer distances (>1800 km), this pattern reversed, and the spatial correlation of low flows increased [30]. Partial correlation analysis demonstrated that streamflow timing in the headwaters of the Mackenzie River Basin in Canada was affected by meteorological factors, and increases in winter flows attributed to climate warming were observed in many watersheds covered by permafrost [31,32].

Overall, the research results suggest that warmer climatic conditions often lead to a deeper active layer or thinner freezing layer and greater storage capacity compared to baseline conditions, even if the warming only occurs in the winter. This increased capacity permits more infiltration and higher groundwater discharges throughout the winter. There is a strong positive correlation between monthly air temperature in late autumn and winter discharges. For instance, the presence of significant correlations between October air temperature and discharge in subsequent months, particularly in December, January, and February, suggests a proportional correlation between winter flow and the air temperature for the same month.

The correlation is notably high for discharge in January, potentially explaining why this month exhibited the largest relative increase in flow over the study period. As a result of winter warming, the increase in winter river flow began almost concurrently in the studied rivers, although warming was observed later than the increase in winter flow. Field studies in a permafrost-dominated landscape in the Northwest Territories of Canada revealed the existence of ephemeral drainage channels forming a cascade of connected bogs that ultimately discharged into channel fens. Consequently, these bogs acted as dynamic transmitters of surface and subsurface flows [33,34]. Similarly, recent investigations indicate that permafrost inland lakes at the headwaters of the Yellow River and in the central Tibetan Plateau may function as storage and evaporation features or directly influence the runoff-contributing area in the basin [35–37].

Prior investigations analyzed patterns in high-latitude basins, revealing predominantly upward trends in winter discharge, particularly within Arctic catchments [38–41]. For instance, Yang et al. proposed a correlation between the timing of spring streamflow in three major Siberian rivers and the duration of winter snow cover [42,43]. Sergio and Palanisami explored streamflow timing using stations in western North America, observing a widespread trend of an earlier onset of the spring freshet [42]. These patterns were influenced by the Pacific Decadal Oscillation and interpreted by rising spring air temperatures spanning phases of the Pacific Decadal Oscillation [44]. Although these analyses were conducted beyond the scope of the current study areas, analogous conclusions can be drawn.

The spatial variation in winter flow in permafrost regions is a complex process, including soil temperature hydrogeology, snow cover, water/ice content, and vegetation. Thus, the deterministic model requires spatial distribution data on environmental parameters that are rarely available. For this reason, Liu et al. proposed near-surface permafrost parameters, including active layer temperature (ALT) as randomly spatially distributed variables consisting of both deterministic and stochastic components and developed a stochastic model to represent mean values and variances of the ALT, assuming a normally distributed ALT [36,38,43]. They showed that the ALT spatial variability measured at several sites in Northeast China followed a normal distribution. The distributions were not highly skewed, indicating that a normal distribution assumption of ALT was sufficient. Therefore, it is uncertain whether a normal distribution adequately represents spatial thaw depth variability.

Analyses demonstrate a correlation between the spatiotemporal pattern of winter temperatures in Northwest China and the North Atlantic Oscillation (NAO) and Siberian High, aligning with the spatial distribution of the seasonal cycle. This research revealed that the winter warming in Northwest China mainly originates from changes in a climatic index, specifically the SH. The teleconnections between the winter SH index and winter air temperature at the Altay and the Pamirs Mountains reveal a negative correlation between these factors, as depicted in Figure 7. Notably, the lower the SH index, the higher the winter air temperature in Northwest China.

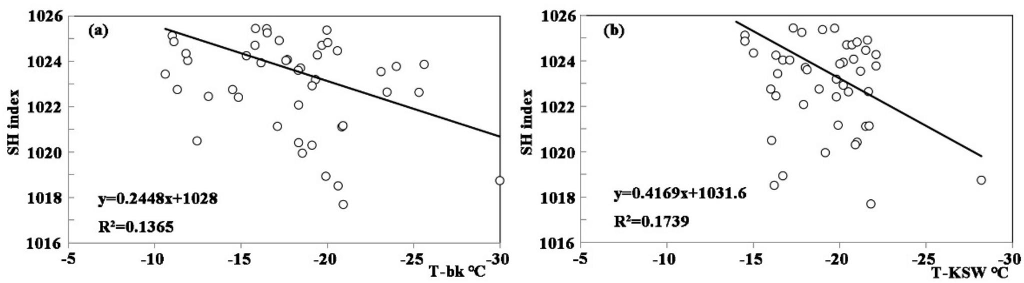

Figure 7. The teleconnections between the SH index and the winter air temperature at the Burkin (graph (**a**)) and Yashi stations (graph (**b**)) during 1957–2013.

This finding also strongly indicates a correlation between air temperature, flow, and climate change. However, further analysis is needed in this regard. For instance, investigating the relationship between the Arctic Oscillation (AO), the NAO, westerly flows, and various hydrological variables requires comprehensive analysis.

However, winter streamflow is under the river ices in Northwest China. Thus, the lack of perfect correlation could reflect one or more of the following factors: (1) the effect of storage losses or ice breakup upstream, (2) observed errors in either water depth or velocity, or (3) the both. The full freeze-up at the survey section could also decrease any correlative uncertainties between discharge and air temperature. In short, the correlation is acceptable for only generalized statements.

5. Conclusions

Changes in winter air temperature and winter river flow during the study period exhibited similarities with the majority of hydrological data, with dissimilarities observed in well-defined regions attributed to the evolution of regime shifts. The variations in winter air temperature and winter river flow were closely linked to the permafrost regime and the Siberia High. Operationally, these changes suggest that permafrost conditions in the post-1990s period, characterized by permafrost degradation, high river flows, and ample availability of winter air temperature, differed from those in the earlier period analyzed in this study.

Additionally, hydroclimatic changes in the large ungauged areas in the Xinjiang region can be estimated through interpolation. Three different patterns of the spatiotemporal correlations were identified based on associated climatic and cryospheric factors: small, medium, and large river regimes. Based on these regimes, it is possible to project spatiotemporal changes in winter air temperature and river flow in the permafrost areas of North China in the future.

Climate warming since the 1990s, especially in winter, has caused a rise in ground temperature and a significant increase in the winter river flow. The latter has enhanced water transport and percolation into subsurface (ground) water which directly influences the winter hydrograph. Runoff data measured over a 55 years period were correlated with the winter air temperature and the SH. Monthly, seasonal, and annual time frames were investigated. A seasonal time frame using three months' averages gave the closest fit for the non-linear regressions with a time lag of two to three months. Although the watershed sizes vary from 14,570 to 8750 km^2 the three-month period seemed sufficiently long to smooth out long-term hydrological processes such as infiltration, groundwater flow, and soil frost. An equation in the form of a linear curve was found for all time frames. The regressive coefficients were related to permafrost characteristics. The R^2 values were highest for the freezing thickness and lowest for the temperature in January. Overall, the results were disappointing. Geocryological parameters analyzed without hydrological inputs can characterize winter streamflow only with limits. Because the relationships found were based on past records, their future use implies that the land cover remains unchanged under global warming.

Funding: This work was supported by the Third Xinjiang Science Expedition Program (No. 2021xjkk0101; XJKK20220101), and the Scientific Foundation of Kashi University, China (2021(2750), 20213099). The authors would like to thank the NCEP of NCAR for providing data for the Siberian High.

Data Availability Statement: The datasets generated and analyzed during this study are not publicly available, but are available from the corresponding author on reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Qin, D.H.; Yao, T.D.; Ding, Y.J. The Cryospheric Science for sustainable development. *J. Glaciol. Geocryol.* **2020**, *42*, 1–10.
2. IPCC. *Fourth Assessment Report-Climate Change: Summary to Policymakers*; Houghton, J.T., Meira, F., Callander, B.A., Harris, N., Kattenberg, M.K., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2013.
3. Biskaborn, B.K.; Smith, S.L.; Noetzli, J.; Matthes, H.; Vieira, G.; Streletskiy, D.A.; Schoeneich, P.; Romanovsky, V.E.; Lewkowicz, A.G.; Abramov, A.; et al. Permafrost is warming at a global scale. *Nat. Commun.* **2019**, *10*, 1–13. [CrossRef] [PubMed]
4. Chen, Y.; Li, Z.; Fang, G.; Li, W. Large Hydrological Processes Changes in the Transboundary Rivers of Central Asia. *J. Geophys. Res.-Atmos.* **2018**, *123*, 5059–5069. [CrossRef]
5. Chen, Y.; Li, W.; Fang, G.; Li, Z. Hydrological modeling in glacierized catchments of Central Asia: Status and challenge. *Hydrol. Earth Syst. Sci.* **2017**, *21*, 669–684. [CrossRef]
6. Chen, Y.; Li, W.; Deng, H.; Fang, G.; Li, Z. Changes in Central Asia's Water Tower: Past, Present and Future. *Sci. Rep.* **2016**, *6*, 35458. [CrossRef]
7. Zhang, T. Historical Overview of Permafrost Studies in China. *Phys. Geogr.* **2013**, *26*, 279–298. [CrossRef]
8. Ding, Y.J.; Xiao, C.D. Challenges in the study of cryospheric changes and their impacts. *Adv. Earth Sci.* **2013**, *28*, 1067–1076.
9. Barnett, T.P.; Adam, J.C.; Lettenmaier, D.P. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* **2005**, *438*, 303–309. [CrossRef] [PubMed]
10. Shi, Y.F.; Shen, Y.P.; Li, D.L.; Zhang, G.W.; Ding, Y.J.; Kang, E.S. *An Assessment of the Issues of Climatic Shift from Warm-Dry to Warm-Wet in Northwest China*; Meteorologic Press: Beijing, China, 2002; pp. 7–75.
11. Zhao, L.; Hu, G.; Zou, D.; Wu, X.; Ma, L.; Sun, Z.; Yuan, L.; Zhou, H.; Liu, S. Permafrost changes and its effects on hydrological processes on Qinghai-Tibet Plateau. *Bull. Chin. Acad. Sci.* **2019**, *34*, 1233–1246. [CrossRef]
12. Yao, T.D.; Liu, S.Y.; Pu, J.C. Impacts of glacier shrinkage to water resources in the northwest China. *Sci. China D* **2004**, *34*, 535–543.
13. Wu, B.; Wang, J. Winter Arctic Oscillation, Siberian High and East Asian winter monsoon. *Geophys. Res. Lett.* **2002**, *29*, 1–4. [CrossRef]
14. Burn, D.H.; Hag Elnur, M.A. Detection of hydrologic trends and variability. *J. Hydrol.* **2002**, *255*, 107–122. [CrossRef]
15. Burn, D.H. Climatic influences on streamflow timing in the headwaters of the Mackenzie River Basin. *J. Hydrol.* **2008**, *352*, 225–238. [CrossRef]

16. Connon, R.F.; Quinton, W.L.; Craig, J.R.; Hanisch, J.; Sonnentag, O. The hydrology of interconnected bog complexes in discontinuous permafrost terrains. *Hydrol. Process.* **2015**, *29*, 3831–3847. [CrossRef]
17. Cheng, G.D.; Wu, T.H. Responses of permafrost to climate change and their environmental significance, Qinghai-Tibet Plateau. *J. Geo. Res.* **2007**, *112*, F02S03. [CrossRef]
18. Chen, S.; Liu, W.; Zhao, Q.; Zhao, L.; Wu, Q.; Lu, X.; Kang, S.; Qin, X.; Chen, S.; Ren, J.; et al. Response of freeze-thaw processes to experimental warming in the permafrost regions of the central Qinghai-Tibet Plateau. *Cryosphere* **2016**. [CrossRef]
19. Ding, R.; Li, J.; Ha, K. Decadal change of January and July persistence of monthly mean 500 hPa geopotential height anomalies. *Geophy. Res. Lett.* **2008**, *35*, L15702. [CrossRef]
20. Hasler, A.; Geertsema, M.; Foord, V.; Gruber, S.; Noetzli, J. The influence of surface characteristics, topography and continentality on mountain permafrost in British Columbia. *Cryosphere* **2015**, *9*, 1025–1038. [CrossRef]
21. Jenkins, G.M.; Watts, D.G. *Spectral Analysis and Its Applications*; Holden-Day: San Francisco, CA, USA, 1968.
22. Kendall, M.G. *Rank Correlation Measures*; Charles Griffin: London, UK, 1975.
23. Kropáček, J.; Maussion, F.; Chen, F.; Hoerz, S.; Hochschild, V. Analysis of ice phenology of lakes on the Tibetan Plateau from MODIS data. *Cryosphere* **2013**, *7*, 287–301. [CrossRef]
24. Stewart, I.T. Changes in snowpack and snowmelt runoff for key mountain regions. *Hydrol. Process. Int. J.* **2009**, *23*, 78–94. [CrossRef]
25. Liu, J.S.; Hayakawa, N.; Lu, M.J.; Dong, S.H.; Yuan, J.Y. Hydrological and geocryological response of winter streamflow to climate warming in Northeast China. *Cold Reg. Sci. Technol.* **2003**, *37*, 15–24. [CrossRef]
26. Gudmundsson, L.; Tallaksen, L.M.; Stahl, K. Spatial cross-correlation patterns of European low, mean and high flows. *Hydrol. Process.* **2011**, *25*, 1034–1045. [CrossRef]
27. Mann, H.B. Non-parametric tests against trend. *Econometrica* **1945**, *13*, 245–259. [CrossRef]
28. Zhao, X.; Li, J. Winter-to-winter recurrence of sea surface temperature anomalies in the northern Hemisphere. *J. Clim.* **2010**, *23*, 3835–3853. [CrossRef]
29. Aziz, O.I.A.; Burn, D.H. Trend and variability in the hydrological regime of the Mackenzie River Basin. *J. Hydrol.* **2006**, *319*, 282–294. [CrossRef]
30. Park, H.; Yoshikawa, Y.; Oshima, K.; Kim, Y.; Ngo-Duc, T.; Kimball, J.S.; Yang, D. Quantification of Warming Climate-Induced Changes in Terrestrial Arctic River Ice Thickness and Phenology. *J. Clim.* **2016**, *29*, 1733–1754. [CrossRef]
31. Pagano, T.; Garen, D. A recent increase in Western U.S. streamflow variability and persistence. *J. Hydrometeorol.* **2005**, *6*, 173–180. [CrossRef]
32. Gruber, S.; Fleiner, R.; Guegan, E.; Panday, P.; Schmid, M.O.; Stumm, D.; Wester, P.; Zhang, Y.; Zhao, L. Inferring permafrost and permafrost thaw in the mountains of the Hindu Kush Himalaya region. *Cryosphere* **2017**, *11*, 81–99.
33. Schmid, M.-O.; Baral, P.; Gruber, S.; Shahi, S.; Shrestha, T.; Stumm, D.; Wester, P. Assessment of permafrost distribution maps in the Hindu Kush Himalayan region using rock glaciers mapped in Google Earth. *Cryosphere* **2015**, *9*, 2089–2099. [CrossRef]
34. Smith, L.C.; Pavelsky, T.M.; Macdonald, G.M.; Shiklomanov, A.I.; Lammers, R.B. Rising minimum daily flows in northern Eurasian rivers: A growing influence of groundwater in the high-latitude hydrologic cycle. *J. Geophys. Res.* **2007**, *112*, G04S47. [CrossRef]
35. Tan, X.; Gan, T.Y. Nonstationary analysis of annual maximum streamflow of Canada. *J. Clim.* **2004**, *28*, 1788–1805. [CrossRef]
36. Wu, Q.B.; Zhang, T.J. Recent permafrost warming on the Qinghai–Tibetan Plateau. *J. Geophy. Res.* **2008**, *113*, 2008. [CrossRef]
37. Watson, V.; Kooi, H.; Bense, V. Potential controls on cold-season river flow behavior in subarctic river basins of Siberia. *J. Hydrol.* **2013**, *489*, 214–226. [CrossRef]
38. Wu, Q.B.; Hou, Y.; Yun, H. Changes in active-layer thickness and near-surface permafrost between 2002 and 2012 in alpine ecosystems, Qinghai-Xizang (Tibet) Plateau, China. *Glob. Planet. Chang.* **2015**, *124*, 149–155. [CrossRef]
39. Yang, D.; Kane, D.L.; Hinzman, L.D.; Zhang, X.; Zhang, T.; Ye, H. Siberian Lena River hydrologic regime and recent changes. *J. Geophy. Res.* **2002**, *107*, 4694. [CrossRef]
40. Yang, D.; Ye, B.; Kane, D. Streamflow changes over Siberia Yenisei river basin. *J. Hydrol.* **2004**, *296*, 59–80. [CrossRef]
41. Ye, B.; Yang, D.; Zhang, Z.; Kane, D.L. Variation of hydrological regime with permafrost coverage over Lena Basin in Siberia. *J. Geophy. Res.* **2009**, *114*, D07102. [CrossRef]
42. Sarmiento, S.; Palanisami, A. Coherence between atmospheric teleconnections and Mackenzie River Basin lake levels. *J. Great Lakes Res.* **2011**, *37*, 642–649. [CrossRef]
43. Zhou, Y.W.; Guo, D.X.; Qiu, G.Q.; Cheng, G.D.; Li, S.D. *Geocryology in China*; Science Press: Beijing, China, 2000; pp. 1–218.
44. Zhang, T.; Barry, R.G.; Knowles, K. Statistics and characteristics of permafrost and ground ice distribution in the Northern Hemisphere. *Polar Geogr.* **1999**, *23*, 147–169. [CrossRef]