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Exploring the Relationship between Hydroclimate and Lake Area in Source Area of the Yellow River: Implications for the Paleoclimate Studies

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Abstract: The large tectonic lake is one of the most important water bodies in the source area of the Yellow River (SAYR), northeastern Qinghai-Tibet Plateau (QTP). It plays a key role in decelerating climatic change and regulating regional climate patterns. In this study, we used Landsat images (MSS, TM, ETM^+ and OLI) of Lake Gyaring and Lake Ngoring (the Two Sisters Lakes), which are the two largest tectonic lakes in the SAYR, to determine annual lake area fluctuations from 1986 to 2020. The results show that lake area increases were generally consistent with a warming trend in the SAYR. The temperature signals were separated from the lake area changes by using a detrending analysis and found that the processed data are closely correlated with variations of precipitation and streamflow in the SAYR, and the previously reported paleoclimate records, which include the $\delta^{18}O$ record from stalagmite, A/C (Artemisia/Chenopodiaceae) ratio from lake sediment and scPDSI (self-calibrating Palmer Drought Severity Index) from the tree ring on the northeastern margin of the QTP. The phase of relatively large lake areas typically coincides with a negative excursion in $\delta^{18}O$, a high A/C ratio, and elevated scPDSI values, while the opposite is true for smaller lake areas. It is suggested that the total area of the Two Sisters Lakes is closely associated with hydroclimatic conditions in the SAYR. Furthermore, an association of high TSI anomalies with the water area expansion of the Two Sisters Lakes is also observed, implying that solar activity is the key driving factor for the hydrologic variability in the SAYR on decadal timescales. The findings of our study highlight the validity of previous paleoclimate archives in the northeastern QTP and demonstrate the potential of using remote sensing techniques to investigate paleoclimate.

Keywords: Qinghai-Tibet Plateau (QTP); source area of the Yellow River (SAYR); lake volume; hydroclimate change; total solar irradiance (TSI)

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1. Introduction

As the core region of the "Third Pole" on Earth, the Qinghai-Tibet Plateau (QTP) has the largest number and area of lakes in China, as well as the largest ice and snow resources outside of the polar regions. These resources are essential for maintaining the water security and ecological balance of the region [1]. Against the backdrop of global climate change, meteorology, hydrology, ecology, and pedology scholars have taken a keen interest in studying the impact of climate change, glacier retreat, and lake changes on the QTP environment [2–4]. As a result of the combined effects of regional environment and global climate, lakes in the QTP are experiencing varying degrees of changes in lake level, water volume, and water quantity. These changes have a direct impact on plateau ecosystems and communities [5]. It is essential to understand the underlying causes in order to effectively manage the lakes and mitigate the effects of the changing climate. It is therefore vital for researchers studying climate change, the water environment, and ecological security on the QTP to understand the dynamic characteristics of these lake changes [6–9]. This requires the collection of reliable data over a long period of time.

Remote sensing data is an effective tool to provide such data, as it can provide a comprehensive view of the lake's characteristics over a large area. Additionally, it can be used to monitor long-term changes in the lake's environment [10,11]. The evolution, spatial patterns, and driving mechanisms of natural lakes over the Tibetan Plateau were reviewed by Zhang et al. (2020). The changes in lake area and level show a slight decrease from 1976 to the mid-1990s, followed by a continuous rapid increase, which is mainly driven by enhanced precipitation and regional monsoon activities [3]. The latest reports show that the lake area changes on the QTP, which were obtained using the remote-sensing images, are sensitive to the climate variations and human activities. For instance, the temperature change was a major contributor to the observed changes of Lake LongmuCo and Lake Jiezechaqia in the Source Region of Yangtze River between 1972 and 2021, while human intervention also played a vital role during 2013–2021 [12]. By using the remote sensing Landsat images, the area of lakes in the arid region of central east Asia has increased by 41% over the past five decades. Increased precipitation and temperature rise are the main driving factors of lake changes in central east Asia [13]. In addition to the changes in lake level, water volume, and water quantity, changes in lake water quality are also a major concern. The melting of glaciers and permafrost can lead to an increase in nutrient and sediment runoff, which can have negative impacts on the lake ecosystem [14]. Furthermore, changes in water temperature and acidity can also affect the lake's ecology [15]. Therefore, it is important to not only monitor changes in lake area and volume, but also changes in water quality. The use of remote sensing data can provide valuable information about these changes, allowing for better management and conservation of the lakes in the QTP region.

The SAYR plays an important role in climate regulation and water conservation on the northeastern QTP. As a result, preserving the integrity of the SAYR is essential for maintaining the region's environmental balance. However, global warming has led to an increase in temperature in the SAYR and has resulted in a series of environmental issues related to climate anomaly variations and ecological degradation [16]. Having a thorough understanding of the hydroclimate changes on the SAYR will contribute meaningfully to the regional social development and economic stability [17]. Previous studies have suggested that the climate in the SAYR has experienced a significant warm-wet increasing trend since the early 2000s, which is very different from the antecedent warm-arid trend since the late 1980s. The result of this increase is permafrost deterioration, rising groundwater levels, expansion of lakes and wetlands, and transition of grassland ecosystems from steppes to alpine meadows in the SAYR [18,19]. Nevertheless, it remains not fully clear how climate factors, including solar irradiation, temperature, and precipitation, influence hydrological regimes in the SAYR and how these factors interact, leading to discrepancies in quantitative forecasts of hydrological variabilities in the northeastern QTP [3].

The Lake Gyaring and Lake Ngoring, situated within the borders of Madoi County, mark the beginning of the Yellow River. They are the largest lakes in the SAYR, and are referred to as the "Two Sisters Lakes in the SAYR" [20]. Both lakes are situated at an altitude of over 4200 m, which is more than 1000 m higher than China's largest inland lake, Qinghai Lake, and are typical alpine lakes. In recent years, the areas of the Two Sisters Lakes have become important regions for pastoralism and fishing in northeastern QTP [21]. The area is home to a wide range of wildlife, including birds, fish, and small mammals, making it an important refuge for biodiversity. Local communities have established sustainable management practices to protect the environment, allowing both the ecosystems and the local economy to thrive.

In this investigation, we have elected to focus on two of the most sizable bodies of water within the SAYR: Lake Gyaring and Lake Ngoring, which are known as the Two Sisters Lakes. Utilizing Landsat remote sensing images, we have been able to extract the lake area fluctuation over the time period ranging from 1986 to 2020. By comparing these measurements with various hydroclimatic factors, such as air temperature, precipitation, and runoff amounts, as well as taking into account the paleoclimate records of lake sediment, tree rings, and stalagmite from the northeastern QTP, we try to establish correlations that may exist between these proxies. Our research objective is to provide insight into the mechanisms responsible for the observed oscillations in lake area in SAYR and highlights the importance of understanding how hydroclimatic conditions have changed over time for predicting the impact of future climate change on the region's ecosystems and water resources.

2. Study Region, Data, and Method

2.1. Study Area

The river-connected Lake Gyaring and Lake Ngoring are the two largest lakes located in the headwater area of the Yellow River, which is the second-longest river in China. The Yellow River originates in glaciers and snow melt-off of the Bayan Har Mountains (5267 m a.s.l.), which lie in the south of SRYR, and the Burhan Budai Mountains (5400 m a.s.l.) are situated in the north (Figure 1). The two lakes act as a natural reservoir for the river, collecting and storing the water before it flows downstream. Lake Ngoring (34°46′ to 35°05′ N, 97°54′ to 99°32′ E) and Lake Gyaring (34°48′ to 35°01′ N, 97°02′ to 97°30′ E) are located in Madoi County, SAYR [22]. Lake Gyaring stretches east to west and is narrow from north to south, resembling a stunning shell embedded in the SAYR (Figure 2a,b). It covers an area of 530 km^2, it has an average depth of approximately 9 m and can hold up to 4.6 × 1010 m^3 of water [23]. The shape of the Lake Ngoring is just like a bell; it covers an area of 637 km^2 and has a maximum depth of 30.7 m, with a water storage capacity of 10.76 × 1010 m^3 [22] (Figure 2a,c). Lake Gyaring and Lake Ngoring are two of the most beautiful and significant features of the SAYR. These lakes not only provide a habitat for various aquatic species but also contribute significantly to the Yellow River's water supply, which is crucial for the livelihoods of millions of people in China.

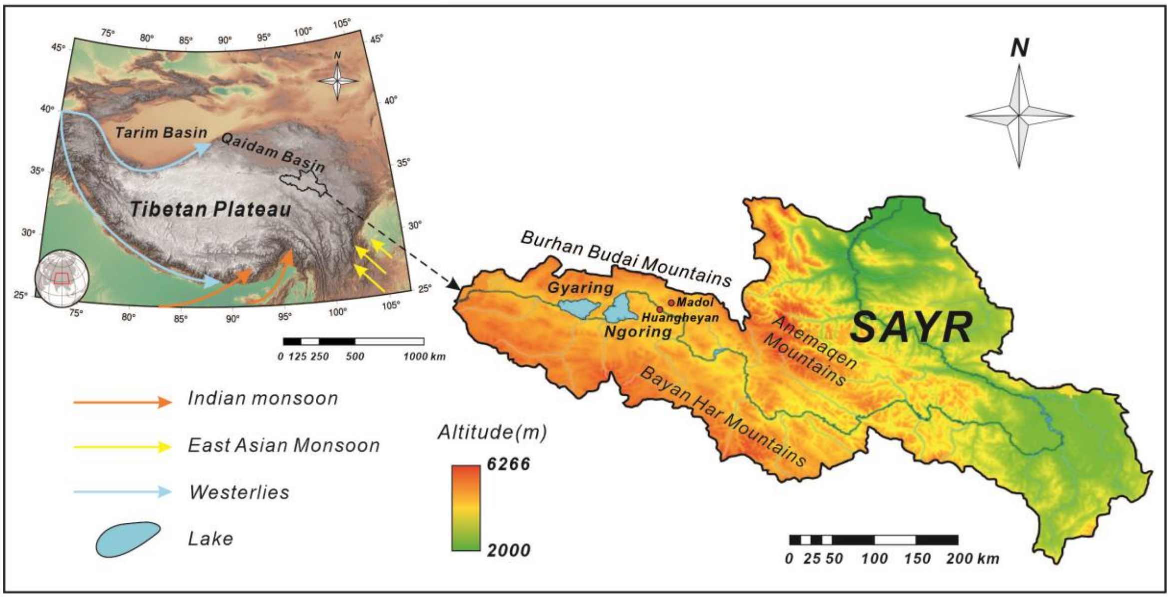

Figure 1. The spatial range of the source area of the Yellow River (SAYR) on the QTP.

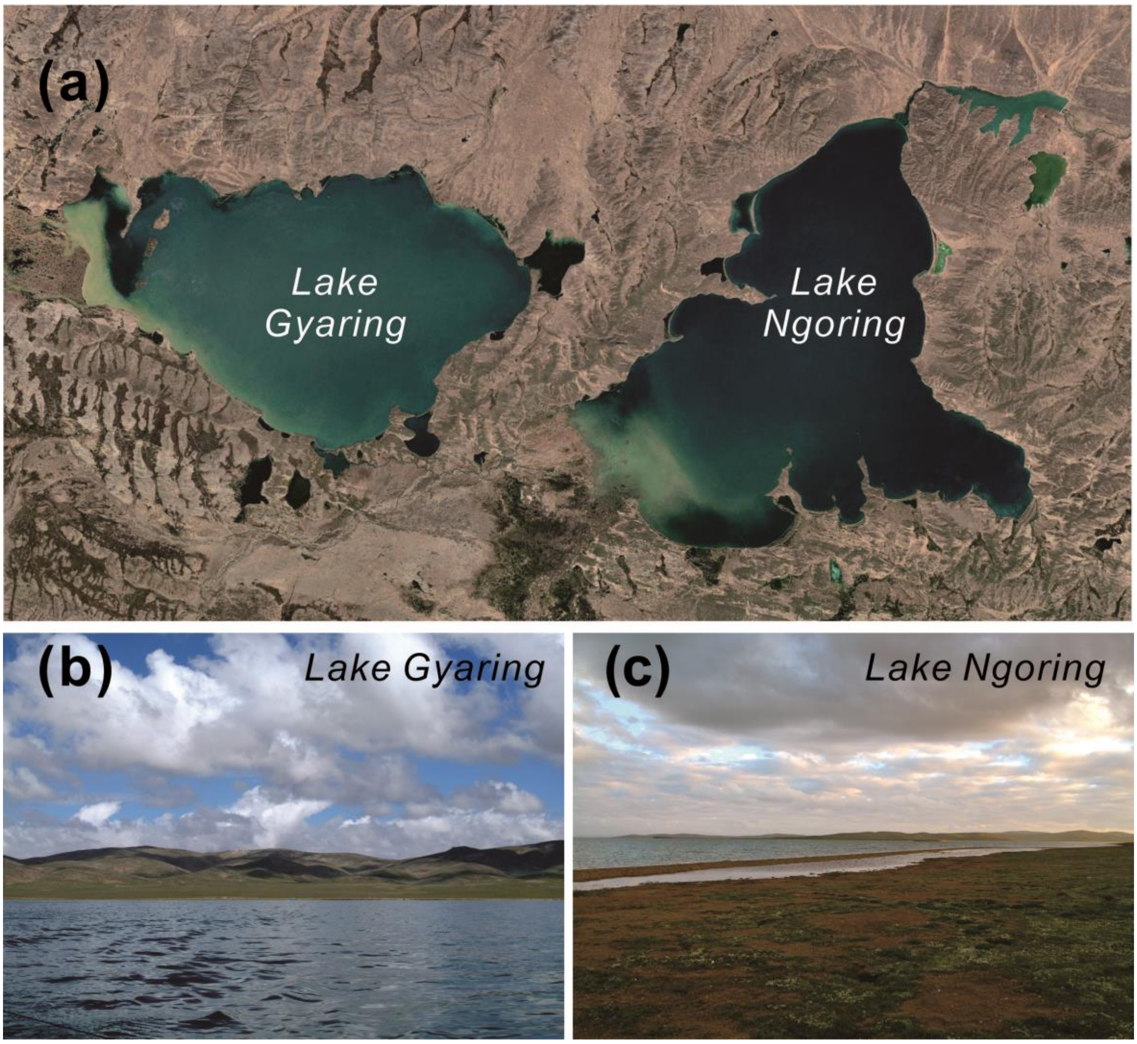

Figure 2. Remote sensing images of Lake Gyaring and Lake Ngoring obtained from the Google Earth (**a**); the landscape of Lake Gyaring (**b**); and Lake Ngoring (**c**), SAYR. They are known as "the Two Sisters Lakes" in the SAYR.

A cold and semi-arid continental climate prevails in the lake basin. The mean daily air temperature varies from 7.7 °C in July to −16.2 °C in January, annually averaging −3.0 °C, and the annual precipitation averages 345.6 mm (1985–2020, original data from China's National Climate Center). During the period of late November to early April, the surface of the lake is completely covered in ice. Its waters are fed by numerous small rivers and streams from the surrounding mountains.

In the SAYR, due to harsh environmental conditions, such as the cold and the arid climate, the increased radiation exposure, and the lower atmospheric oxygen availability from the high elevation, terrestrial plants suffer from a significant impact on their growth and distribution [22]. The main vegetation types in the SAYR are alpine meadow and steppe in the plains area, and sparse vegetation in the high elevation area [20]. The vegetation around the Two Sisters Lakes is composed of high elevation cold-steppe species that are dominated by C3 grasses, such as Stipa purpurea and Poa annua, which provide good herbage for the animal husbandry in the lake region.

2.2. Data Source and Methods

2.2.1. GIS and Remote Sensing Methodology

NASA and the U.S. Geological Survey jointly manage the Landsat satellite missions, which have been widely used to map water bodies since 1972. We obtained high spatial resolution images from these missions, including 60 m for MSS (Multispectral Scanner) and 30 m for TM (Thematic Mapper), ETM+ (Enhanced Thematic Mapper Plus), and OLI (Operational Land Imager) [24]. The Landsat missions provided the most comprehensive lake area observations over the QTP. However, with the exceptions of a lack of products during the early stage and the lake area being impossible to determine in some years due to image blur, the available products are normally usable since 1986. This study used Landsat MSS, TM, ETM^+, and OLI images from 1986–2020 as the remote sensing data sources for investigating lake area variations. We selected remote sensing images that had little or no cloud cover, mostly during the months of September to November, when the lake area is relatively stable after the rainy season that lasts from June to August in Madoi. This is because, during this period, the lake area is most visible and any changes between images can be more easily observed. Additionally, the absence of clouds ensures that the images are not obstructed and that each lake can be viewed in its entirety. The Landsat data were acquired from the USGS Earth Explorer website (https://earthexplorer.usgs.gov/ (accessed on 18 August 2022)), and all images were pre-processed by ENVI before being used for lake area mapping in ArcMap 10.7.

2.2.2. The Acquisition of the Meteorological, Streamflow and TSI Data

The China meteorological data service center (http://data.cma.cn (accessed on 16 April 2022)) provided observation data on precipitation and temperature at the Madoi meteorological station, which is the closest station to the two lakes, from 1986 to 2020. The data was used to analyze the historical changes in precipitation and temperature over the past 35 years. The annual streamflow data (1955–2019) were measured at Huangheyan gauging station (E98°10′; N34°53′, 4035 m a.s.l.), which is provided by the Yellow River Conservancy Commission, Ministry of Water Resources. This station is the first gauging station along the Yellow River and is the nearest one to the Two Sisters Lakes. The NOAA National Centers for Environmental Information (https://www.ncdc.noaa.gov/ (accessed on 24 June 2021)) provided the annual TSI data for recent decades.

2.2.3. Mathematical Methods

In order to explore the relationship between the lake area and other hydroclimatic factors, a detrended analysis was performed. Detrended analysis is a process that removes trends and variations in data points that may be caused by external factors, such as the linear trend of globe warming. This allows us to focus on the core patterns in the data.

By applying a mathematical method like detrended analysis to this study, we can more accurately identify the correlations between variables and draw more precise conclusions. The year-detrended lake level changes represent interannual variation in the lake area that is isolated from directional temperature change; this is done because detrending statistically removes the linear trend in temperature across years, which is believed to be caused by an anthropogenic global warming scenario. The trendline of detrended lake area would be horizontal without any long-term trend. More details for detrended analysis can be found in reference [25]. It is important to note that this method doesn't remove any non-linearity or short-term signals. So, the result of the detrended analysis remains the signals of regional hydroclimate fluctuations. The detrended analysis of lake area is meant to identify the influence of hydroclimatic factors on the lake area, separate from the increasing temperature trend.

3. Results

We conducted a detailed analysis of the annual variation in the lake areas for Lake Gyaring and Lake Ngoring in the SAYR over a period of 35 years. By using the Landsat remote sensing images of the Two Sisters Lakes, we were able to determine the annual variation in the lake areas between 1986 and 2020. Based on the trends that were shown for these two lakes (Figure 3a,b), they displayed a similar pattern. It is apparent from Figure 3a that the surface area of Lake Gyaring decreased from a maximum of 527.9 km^2 to 517.7 km^2, an overall decrease of approximately 2% during the period from 1986 to 2003, while Lake Ngoring had a fluctuating surface area during this time period of 608.6 km^2, with an overall decrease of approximately 2% (Figure 3b). Both lakes have experienced significant growth in size since 2003. The maximum area of Lake Gyaring has reached 538.7 km^2, an area which has grown by 4% relative to its minimum area and the maximum area of Lake Ngoring has reached 638.7 km^2, an area which has grown by 6% compared to its minimum area. It is estimated that the area of these two lakes reached its maximum in 2018 when the total area reached 1172.4 km^2, after which the area decreased slightly, but it remained at a relatively high level.

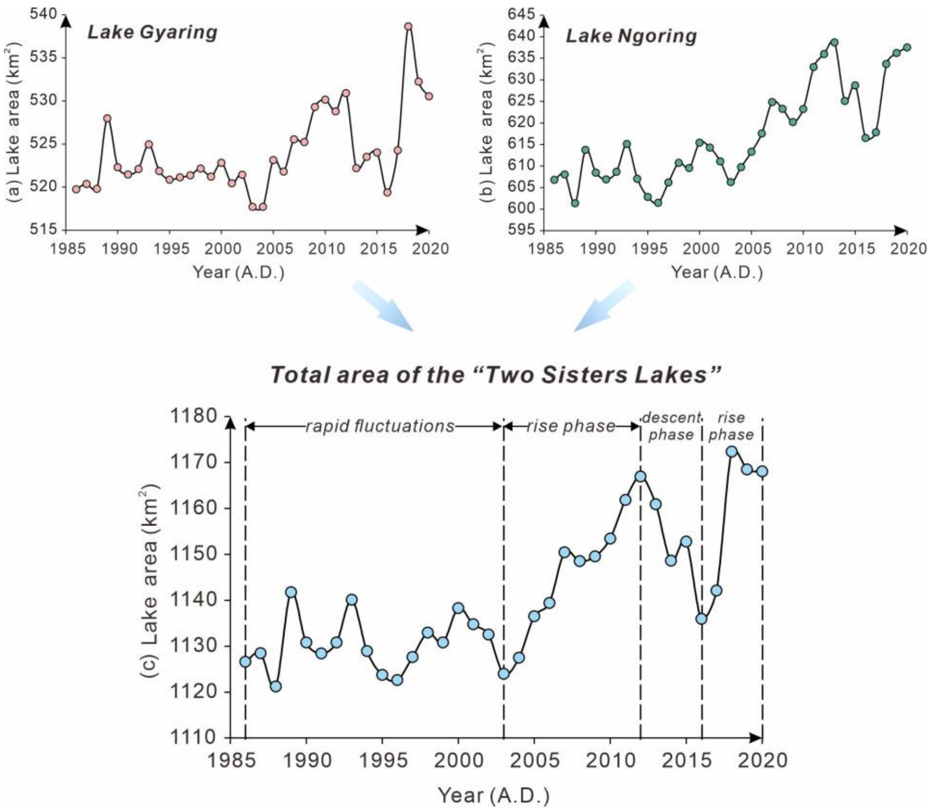

Figure 3. The water area changes of Lake Gyaring (**a**) and Lake Ngoring (**b**) from the 1986–2020, and the total area changes of Lake Gyaring and Lake Ngoring from the 1986–2020 (**c**).

Figure 3c shows that the total area of the two lakes could be divided into four stages over the past 35 years: (1) during 1986–2003, the lake area was in an apparent wavelike stage that kept it at a relatively low level; (2) during 2003–2013, the lake area experienced rapid growth; (3) between 2013 and 2016, the lake area clearly declined; and (4) between 2016 and 2020, the lake area increased again. Prior to 2003, the amplitude of the lake area fluctuation is relatively minor, and the total area fluctuates at a relatively low-value, but in the years that followed, the amplitude of the fluctuation increased quite significantly. This change in amplitude indicated a dramatic shift in the lake's ecosystem, resulting in a much more variable environment. What causes the lake area to change in this pattern? It is worthy of further discussion.

4. Discussions

4.1. Relationship between Variations in the Two Sisters Lakes' Surface Area and Warming Changes in the SAYR

Considering that human activity in the SAYR is relatively small, variations in the lake area can be used as reliable indicators for climatic and environmental variations [3]. Figure 4 shows that the smallest total water area of the Two Sisters Lakes in the 21st century was observed in 2003 (yellow line), and the largest lake area was observed in 2018 (red line). The area of the Two Sisters Lakes has undergone a noticeable change over the past decades. The trend of total lake area changes during the last 35 years is comparable with the MAT (mean annual temperature) records at the Madoi meteorological station (Figure 5a,b), which reveals a positive correlation with an R value of 0.46 ($p < 0.01$) for this period, indicating a possible connection. This suggests that the lake area expands as temperature increases, and vice versa. Until 2003, the Two Sisters Lakes area fluctuated around the mean value, and then it expanded rapidly after 2003. Meanwhile, the MAT in Madoi County did not show a significant increase trend until 1997, but it increased dramatically thereafter. In recent years, the lake area has significantly increased, which may be associated with increasing temperatures in the SAYR. The warmer temperatures have caused melting glaciers and thawing permafrost, which have in turn increased the flow of water into the lake. This increase in water volume has caused the lake area to expand [12,13].

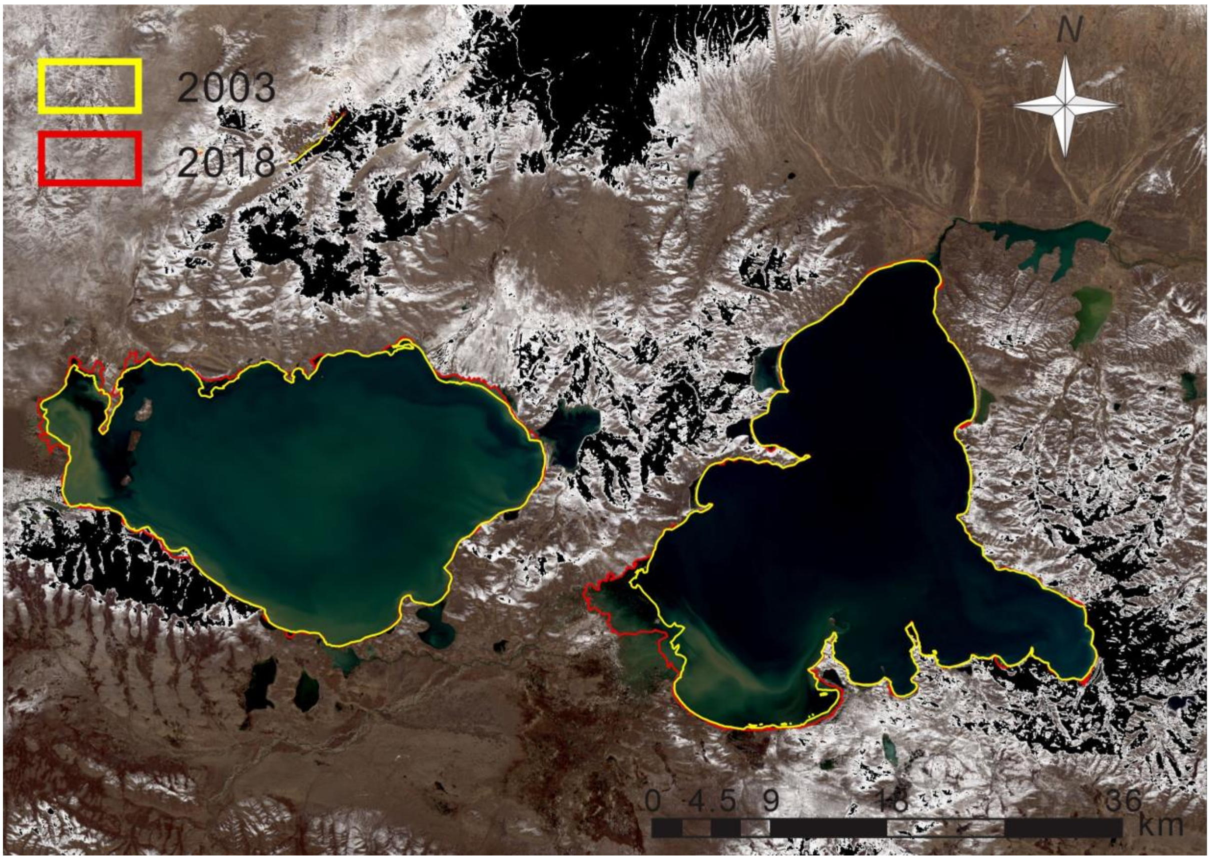

Figure 4. Comparison of Landsat images of Lake Ngoring in 2003 (the largest lake area in the 21st century) and 2018 (the smallest lake area in the 21st century).

A major consequence of human activity is global warming, which is caused by overusing fossil fuels. This has led to rising temperatures, melting ice caps, and sea level rise [26]. Meteorological observations from the QTP, especially at high elevations (more than 3000 m a.s.l.), show that temperatures tend to rise as the elevation rises, and the rising rate increases with elevation, reaching its highest value at approximately 4800 to

6200 m [27], which is in the range of glacier development. Under an anthropogenic-induced global warming scenario, the increasing trend of MAT over the SAYR starting in the middle of the 20th century is expected to result in a faster glacier recession, snow melting, and permafrost thawing on the QTP [28], and consequently increases in the amount of meltwater entering the Two Sisters Lakes, thereby leading to expansion of the lake area. This inference is supported by a snowmelt runoff simulation conducted in the SAYR. The surface water input derived from snowmelt (SWISM) in the SAYR is related to regional MAT fluctuations using the Utah Energy Balance snowmelt model (Figure 5d) [29]. Consequently, the warming trend in SAYR might be a strong forcing factor for the hydrological variability of the Two Sisters Lakes in recent decades. Nevertheless, changes in the lake area may not be solely driven by the temperature factor. The Utah Energy Balance snowmelt model constructed by Tian et al., 2021 also highlights that the amount of snowmelt constitutes only 4% of the total surface runoff [30]. This indicates that other factors, such as precipitation, streamflow, and human activity, also might contribute to the surface area variability of the Two Sisters Lakes over time.

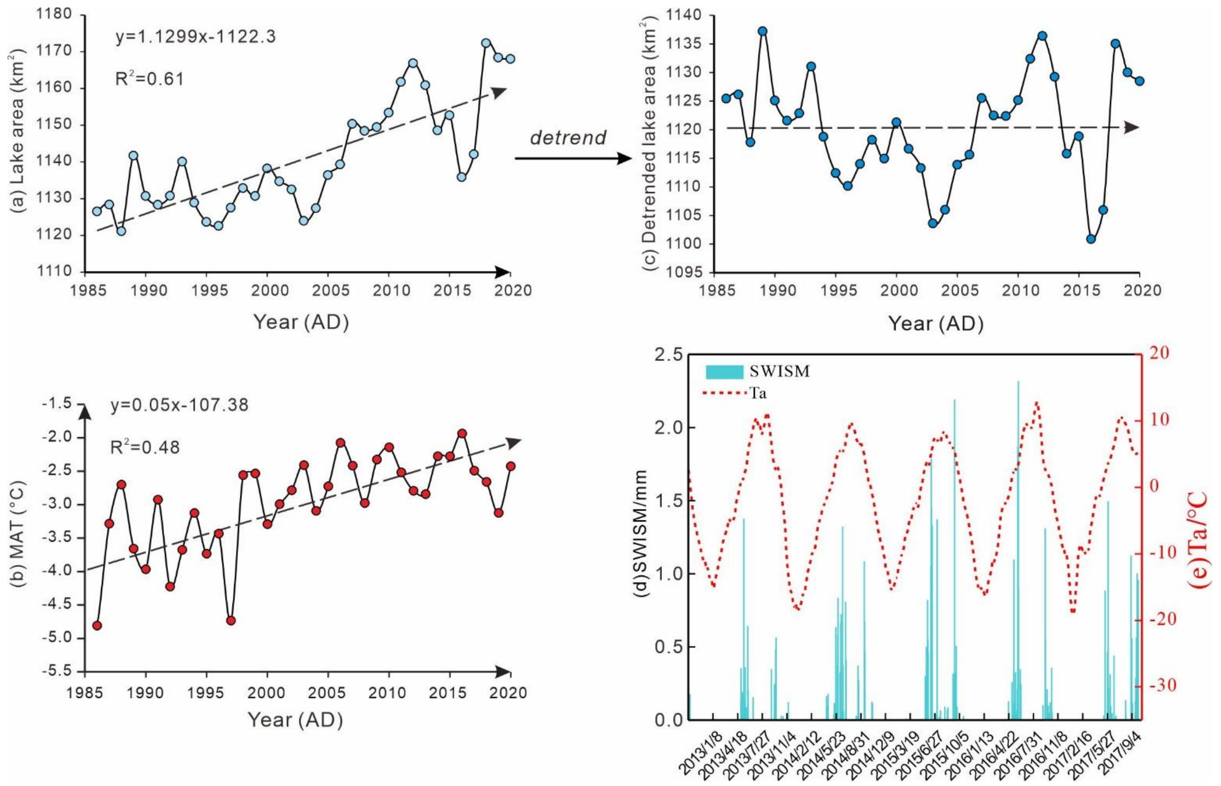

Figure 5. The total lake area changes of the Two Sisters Lakes (**a**); MAT (mean annual temperature) changes in the Madoi meteorological station (**b**); the detrended lake area changes of the Two Sisters Lakes (**c**); and the fluctuations of surface water input from the snow melt (SWISM) and atmospheric temperature (Ta) from 2012 to 2017 in the SAYR [29] (**d**).

For the purpose of clarifying the relationship between the changes in lake area and other hydroclimate factors, we performed the detrended analysis to remove the MAT trend, and other signals subsequently emerged from the lake area data.

4.2. Lake Area Changes in the Two Sisters Lakes in Response to Hydroclimatic Variations in the SAYR

In order to investigate the relationship between hydroclimatic conditions and lake area on a decadal timescale, we compared the detrended total area of the Two Sisters Lakes from 1986 to 2020 with the corresponding precipitation record from the Madoi meteorological station and the streamflow record from the Huangheyan gauging station. A good agreement exists between the detrended total lake area and the precipitation amount, with a correlation coefficient of 0.43 ($p < 0.01$). This has been attributed to increased precipitation levels in the catchment due to climate change. The lake has seen a steady increase in water area after 2003 (Figure 3c). As a result, the overall area of the lake has increased significantly during the study period. Two obvious fluctuations of total lake area that are highlighted by blue arrows correspond well with precipitation changes in the Madoi station (Figure 6c).

Moreover, the changes in lake area are also closely related to streamflow at the Huangheyan gauging station, and the R value reaches 0.52 (Figure 6a), indicating that a large lake area usually corresponds to a higher streamflow. With the precipitation increase, the surface runoff in the region experienced an increase. Hence, the streamflow in the SAYR is also sensitive to the changes of precipitation, and these two factors exhibit a highly significant correlation coefficient (R = 0.65, $p < 0.01$). These agreements between the detrended lake area, precipitation amount, and streamflow indicate that precipitation is another potential driver affecting the water area of the Two Sisters Lakes, and this conclusion is consistent with those reached in previous studies on the QTP [3,7,16,30].

Solar radiation and precipitation are thought to be correlated in part by the Asian summer monsoon, according to previous studies [31,32]. In light of this, we used the stalagmite $\delta^{18}O$ from Wanxiang Cave, situated in the northeastern margin of QTP [32], to represent the intensity of monsoon activities in the SAYR. Although the time span of stalagmite $\delta^{18}O$ record does not exceed 2003 and is obviously shorter than the lake area changes, streamflow, and precipitation variations, they show a good agreement with the stalagmite $\delta^{18}O$ variations (Figure 6d). It is worth noting that the overlapping period of stalagmite $\delta^{18}O$, as well as lake area, streamflow, and precipitation, displayed a highly similar pattern of fluctuations (pink stripes in Figure 6), implying that the total area of the Two Sisters Lakes is chiefly controlled by regional precipitation, which is supposed to be closely associated with the regional monsoon intensity. Yang et al., 2019 calculated a 1556 year-long ring-width chronology based on the 416 Qilian juniper ring-width series in the Hexi Corridor, northwestern margin of QTP. They found the early-summer scPDSI (self-calibrating Palmer Drought Severity Index) is the most important factor controlling tree growth and then developed a May–June scPDSI reconstruction in this area, which represents the growth season precipitation variation in the northwestern margin of QTP [33] (Figure 6f). Additionally, Wang et al., 2020 use a pollen record from Tian'E Lake, Qilian Mountain, northeastern margin of QTP to reconstruct the regional humidity history over the past 300 years (Figure 6e). As the pollen assemblage is dominated by Artemisia and Chenopodiaceae, the A/C (Artemisia/Chenopodiaceae) ratio can be utilized to reconstruct changes in humidity conditions [34]. These two authentic precipitation-related records generally display the same trend as the detrended total area of the Two Sisters Lakes during their overlap period (pink stripes in Figure 6). A good correlation appears to exist between the changes in lake area in the SAYR and variations in regional precipitation. On the other hand, it is also proof that the previous high-resolution paleoclimate reconstructions in the northeastern part of the QTP are credible. This is because the modern observational data collected from the Two Sisters Lakes are consistent with the previous paleoclimate reconstructions, which suggests that the earlier data was correctly interpreted and the climate reconstructions were authentic. This indicates that the conclusions drawn from the paleoclimate reconstructions are reliable and can be used to inform our understanding of current and future climate change.

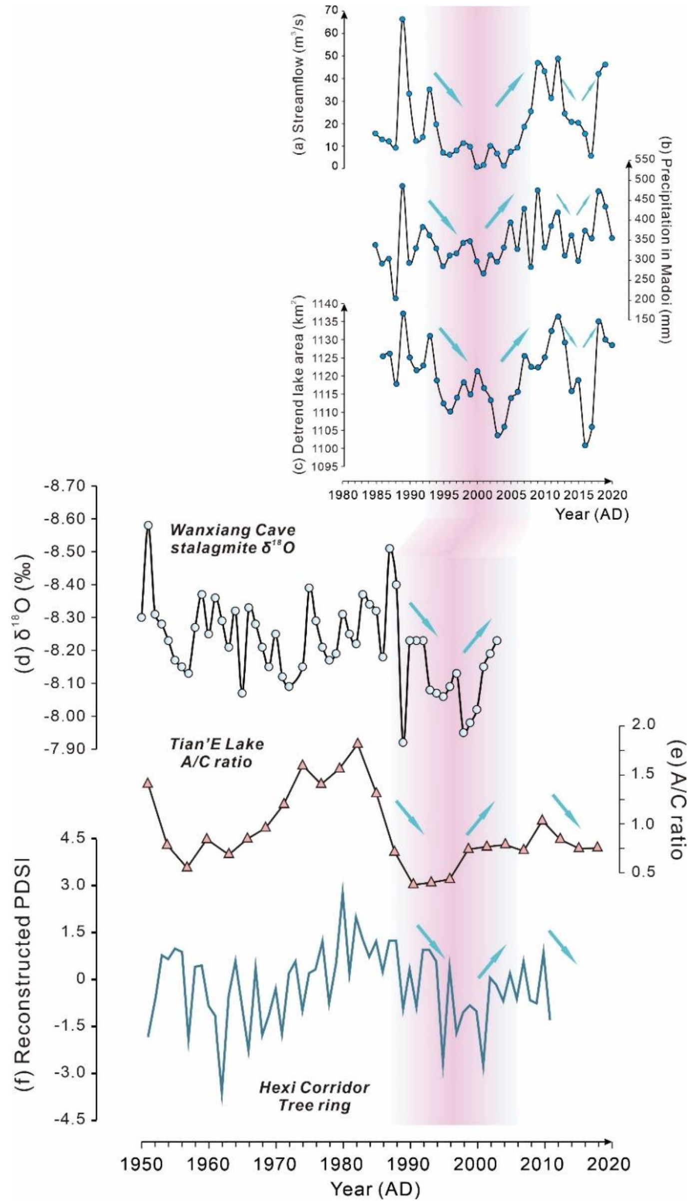

Figure 6. The detrended total lake area of the Two Sisters Lakes (**c**) compared with the streamflow of Huangheyan hydrologic station (**a**) and precipitation in the Madoi meteorological station (**b**), and the stalagmite $\delta^{18}O$ record from the Wanxiang Cave [32], the A/C ratio of the Tian'E Lake [33] and scPDSI based on tree ring record from the Hexi Corridor [34]. The records are all derived from the northeastern margin of the QTP. The pink shadow indicates the similar changes of different proxies.

4.3. Mechanism of the Water Area Changes of the Two Sisters Lakes and Their Implications for the SAYR's Hydrological Environment

Former studies have demonstrated that TSI is probably responsible for the changes in the summer monsoon precipitation on multi-timescales on the QTP [31,34–38]. In this study, we found that the positive anomalies in TSI generally correspond to periods with a larger water area of the Two Sisters Lakes and vice versa (Figure 7). The solar cycles exhibited similar variations as the detrended total area of the Two Sisters Lakes, implying the lake area variations follow a similar pattern to the solar activity cycles. Therefore, we suggest that solar activity may play an important role in driving the climatic fluctuations in SAYR on decadal-scale.

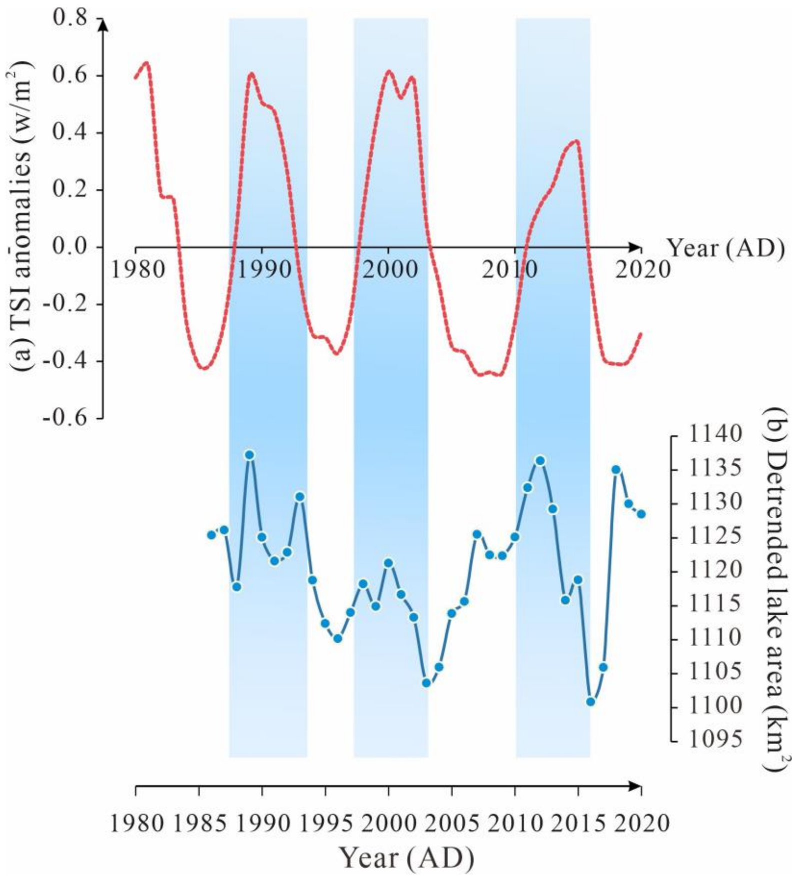

Figure 7. Detrended total lake area of the Two Sisters Lakes (**b**) compared with TSI anomalies (https://www.ncdc.noaa.gov/ (accessed on 24 June 2021)) (**a**).

Although the solar activity fluctuations are relatively weak, their effect on precipitation could be amplified through interactions with sea surface temperatures and atmospheric circulation systems [39]. It is believed that the relationship between the solar activity and lake area variation is not random and may indicate a closer dependency between solar irradiance, monsoon activities and associated precipitation in the SAYR. The potential mechanism would be the additional amplification of small thermal effects. Solar warming of land or water surfaces could enhance local convection and precipitation over the SAYR. Also, solar maxima contribute to the warming of the troposphere over most of the planet; this can raise the water vapor content of East Asian onshore winds because of increased marine evaporation and moisture retention [40]. As a result, higher humidity could lead to an increased precipitation within the Asian monsoon region while simultaneously reducing regional evaporation, thereby expanding the lake areas.

By combining the results presented in the previous section, we concluded that a high TSI would result in intensified monsoon precipitation on the QTP [41] and abundant meltwater derived from adjacent glaciers, snow, and frozen earth [42], leading to an increase in surface runoff in the watershed, and that would result in the lake expansion. Meanwhile, solar warming of land or water surfaces could enhance local convection and precipitation over the SAYR. Solar maxima slightly warm the troposphere over most of the planet; by increasing marine evaporation and the moisture retention capacity of the air, this could raise the water vapor content of winds that blow over northeastern QTP. Higher humidity, in turn, could increase rainfall within the SAYR and simultaneously reduce evaporation, thereby raising the water area of the Two Sisters Lakes and most of the lakes in the SAYR. According to the TSI trends, we predict that the area of Lake Gyaring and Lake Ngoring, as well as other small lakes in the SAYR, will continue to expand over the next decade at least. The correlation between the solar cycles and the lake area variations suggests that the fluctuations in the lake area may be driven by the solar activity cycles. These cycles are known to have a significant impact on the climate, which may explain why the lake area variations follow a similar pattern to the solar activity. It is therefore important to monitor the solar activity in order to better predict lake area change in the SAYR.

The hydroclimate conditions were found to have a significant impact on the water area of the Two Sisters Lakes, while the influence of human activity in the SAYR was assumed to be relatively minor. This is due to the fact that the SAYR is largely unexploited and sparsely populated, meaning there are few anthropogenic activities that affect water balance to these two lakes. It means that the local economic development and the water used for human production and living do not significantly alter the hydrological regimes of the Two Sisters Lakes up to now. In contrast to other parts of the Yellow River basin with a large population, the SAYR appears to have a well-protected hydrologic environment. This is perhaps due to the local government's focus on environmental conservation and greater regulation of human activity in the SAYR.

5. Conclusions

Changes in lake area provide us with a link to understanding the relationship between climate change and hydrological regime changes. Investigations of the Two Sisters Lakes, which are the two largest tectonic lakes in the SAYR, reveal their hydrological regime is influenced by hydroclimate factors. In the last 35 years, the melting of glaciers and snow due to anthropogenic-induced global warming may be associated with the water area expansion of the Two Sisters Lakes. Meanwhile, the detrended lake area changes correspond well with regional precipitation and streamflow, indicating that precipitation variation is the principal cause of lake area changes in SAYR. Furthermore, the changes of TSI anomalies correspond well with the detrended lake area variations, indicating that solar activity might be the controlling factor behind the hydrological regime in the SAYR. The lake area variations collected from the Two Sisters Lakes are consistent with the previous high-resolution paleoclimate reconstructions, including the stalagmite $\delta^{18}O$, A/C ratio in lake sediment and scPDSI record obtained from the tree ring, which suggests that the earlier paleoclimate data was correctly interpreted and the climate reconstructions were accurate. By comparing the remote sensing images and paleoclimate data, we were able to observe changes in lake area over time and determine that both sources of data accurately reflect the same climate change trends. In conclusion, both remote sensing techniques and paleoclimate analyses are reliable methodologies for identifying climate variations. These techniques are complementary and allow us to accurately reconstruct past climate changes.

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