Spatiotemporal Variations of Aksai Chin Lake and its influencing factors during 1972-2018

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Abstract. In the context of increasing lake expansion on the Tibetan Plateau, which is sensitive to climate change, it is of great significance to strengthen the research on the characteristics of lake change and its response to climate change. This paper was designed to investigate the spatiotemporal variations of Aksai Chin Lake (ACL), a typical large lake on the Tibetan Plateau, by using Landsat MSS/TM/ETM+/OLI images during 1972-2018, and to quantitatively discuss the effects of climate on lake changes based on meteorological data from Shiquanhe station. During 1961-2018, annual mean air temperature and precipitation in this region increased at rates of 0.44 ℃/decade and 1.35 mm/decade, respectively, with a mutation point of 1999 for temperature, while evaporation decreased at the rate of -54.3 mm/decade, with two mutation points in 1972 and 2014, respectively. The area of ACL had increased at an average rate of 2.51 km² per year, with a fluctuation of “slight expansion – shrinkage – rapid expansion – slight expansion – rapid expansion” during 1972-2018. Controlled by the topography, the ACL expanded to the southeast by 3851.6 m in total. In terms of the lake area response to climate change, air temperature and evaporation were the main factors affecting ACL area directly, while precipitation mainly regulated ACL by the indirect effect through air temperature and evaporation. Generally, rising air temperature, increasing precipitation and decreasing evaporation all contribute to promote the expansion of ACL.

1. Introduction
Across the Tibetan Plateau, there are 1,171 lakes (area ≥ 1km²), with a total area of about 46,500km² [1]. As the connection point of interaction between atmosphere, biosphere, pedosphere and terrestrial hydrosphere, lakes on the Tibetan Plateau are sensitive to environmental variability and have been one of the important indicators of climate change [2]. Therefore, variations and influence factors of lakes on the Tibetan Plateau have attracted great attention of scientists. For lake variations, spatiotemporal
characteristics of the area, volume, level of lakes have been studied by using field observation data (e.g. bathymetry and shoreline data) [3, 4] and remote sensing images, such as Landsat, ICESat and SRTM [5-7]. And results showed that the characteristics of lake variations vary greatly in different regions of the Tibetan Plateau [8]. In terms of influence factors, glacial meltwater, permafrost degradation, precipitation and evaporation are the main influencing factors of lake changes by qualitative or semi-quantitative analysis, while the main controlling factors of lake changes are different in different regions [9-11].

Aksai Chin Lake (ACL), located in the northwest of Tibetan Plateau, is a typical large enclosed inner flow lake, whose water mainly comes from glacial meltwater and precipitation in the surrounding mountainous areas. ACL is largely affected by natural factors due to a lack of human activities. At present, characteristics and influencing factors of ACL have been involved in some studies. Results show that both area and volume of ACL decreased before the mid-1990s and then increased [6, 12]. In the period of lake shrinkage, less meltwater and precipitation were the main influencing factors with a 13% evaporation contribution, while rising temperature controlled ACL change with a 2% evaporation contribution in the period of lake expansion [13]. However, the interaction of climatic factors, such as air temperature, precipitation and evaporation, is not considered. Therefore, this paper takes ACL as the research object to clarify the characteristics of lake changes using Landsat images during 1972-2018, and try to deeply explore direct and indirect effects of climate factors on lake changes using the path analysis method.

2. Study area, Data and Methods

2.1. Study area

Aksai Chin Lake (35°7’-35°18’N, 79°44’-80°2’E, 4848 m a.s.l., figure 1), located in the intermountain arc tectonic basin of the West Kunlun Mountains in the southwestern Xinjiang, is one of the important lakes in Hotan region. The west side of ACL is a vast lacustrine plain, and the east is a valley plain, reaching to GoZha Co, and the north and south banks are distributed with ancient lakeshore sand embankments [14]. The basin of ACL covers an area of 7992.5 km², with a glacier area of 712.8 km² [15], accounting for 8.92% of the basin area. The ACL has a plateau arid climate with an average annual air temperature of -8°C and an average annual precipitation of 20-50 mm [14].
2.2. Data

2.2.1. Remote sensing data

Table 1. Parameters of ACL extracted from Landsat MSS/TM/ETM+/OLI images.

| Date         | Area (km²) | Rate of area change (%/a) a | Center of lake area gravity b | Sensor Path/row | spatial resolution (m) |
|--------------|------------|-----------------------------|-------------------------------|----------------|------------------------|
| Oct-27-1972  | 169.6      | -0.367                      | 79.8355 35.2143               | MSS 157/035    | 60                     |
| Feb-12-1973  | 169.3      | -0.367                      | 79.8357 35.2146               | MSS 157/036    | 60                     |
| Oct-15-1976  | 169.0      | -0.042                      | 79.8356 35.2143               | MSS 157/036    | 60                     |
| Sep-22-1977  | 172.3      | 1.953                       | 79.8363 35.2152               | MSS 157/036    | 60                     |
| Dec-05-1989  | 173.1      | 0.035                       | 79.8361 35.2146               | TM 146/036     | 30                     |
| Aug-02-1990  | 172.6      | -0.299                      | 79.8362 35.2144               | TM 146/036     | 30                     |
| May-17-1991  | 171.3      | -0.734                      | 79.8360 35.2145               | TM 146/036     | 30                     |
| Nov-11-1992  | 169.7      | -0.912                      | 79.8356 35.2143               | TM 146/036     | 30                     |
| Oct-29-1993  | 167.7      | -1.218                      | 79.8354 35.2141               | TM 146/036     | 30                     |
| Oct-16-1994  | 168.0      | 0.224                       | 79.8355 35.2141               | TM 146/036     | 30                     |
| Nov-04-1995  | 166.4      | -0.947                      | 79.8352 35.2139               | TM 146/036     | 30                     |
| Nov-06-1996  | 166.4      | -0.028                      | 79.8353 35.2138               | TM 146/036     | 30                     |
| Aug-21-1997  | 167.2      | 0.474                       | 79.8356 35.2136               | TM 146/036     | 30                     |
| Sep-25-1998  | 166.8      | -0.234                      | 79.8356 35.2136               | TM 146/036     | 30                     |
| Aug-19-1999  | 167.3      | 0.283                       | 79.8355 35.2138               | ETM+ 146/036   | 30/15                  |
| Oct-08-2000  | 170.6      | 1.968                       | 79.8364 35.2139               | ETM+ 146/036   | 30/15                  |
| Sep-25-2001  | 175.2      | 2.750                       | 79.8373 35.2142               | ETM+ 146/036   | 30/15                  |
| Aug-27-2002  | 177.4      | 1.233                       | 79.8370 35.2146               | ETM+ 146/036   | 30/15                  |
| Oct-17-2003  | 184.0      | 3.719                       | 79.8384 35.2149               | ETM+ 146/036   | 30/15                  |
| Nov-04-2004  | 183.8      | -0.104                      | 79.8383 35.2150               | ETM+ 146/036   | 30/15                  |
| Sep-04-2005  | 189.0      | 2.832                       | 79.8398 35.2150               | ETM+ 146/036   | 30/15                  |
| Oct-09-2006  | 211.8      | 12.049                      | 79.8472 35.2104               | ETM+ 146/036   | 30/15                  |
| Oct-28-2007  | 214.7      | 1.365                       | 79.8479 35.2100               | ETM+ 146/036   | 30/15                  |
| Nov-23-2008  | 234.5      | 9.218                       | 79.8563 35.2068               | TM 146/036     | 30                     |
| Sep-23-2009  | 228.3      | -2.629                      | 79.8539 35.2078               | TM 146/036     | 30                     |
| Oct-12-2010  | 235.9      | 3.322                       | 79.8571 35.2066               | TM 146/036     | 30                     |
| Sep-13-2011  | 236.2      | 0.113                       | 79.8573 35.2066               | TM 146/036     | 30                     |
| Oct-25-2012  | 235.8      | -0.163                      | 79.8562 35.2070               | ETM+ 146/036   | 30/15                  |
| Sep-18-2013  | 259.7      | 10.168                      | 79.8659 35.2029               | OLI 146/036    | 30/15                  |
| Oct-23-2014  | 261.2      | 0.578                       | 79.8661 35.2029               | OLI 146/036    | 30/15                  |
| Oct-10-2015  | 265.5      | 1.610                       | 79.8676 35.2022               | OLI 146/036    | 30/15                  |
| Oct-28-2016  | 274.8      | 3.537                       | 79.8706 35.2009               | OLI 146/036    | 30/15                  |
| Sep-29-2017  | 283.9      | 3.298                       | 79.8734 35.1996               | OLI 146/036    | 30/15                  |
| Oct-02-2018  | 285.0      | 0.380                       | 79.8737 35.1995               | OLI 146/036    | 30/15                  |

a Rate of area change = \( \frac{S_b - S_a}{S_a} \times T \times 100\% \), Where \( S_a \) and \( S_b \) represent lake area in the previous and the later period, respectively. \( T \) is the length of the period.

b Locations of the center of lake area gravity are calculated according to the method from the literature [16].

The remote sensing images of Landsat MSS/TM/ETM+/OLI of ACL were downloaded from the website of USGS (https://earthexplorer.usgs.gov/) during 1972-2018, which were used to extract ACL boundary. Given the influence of seasonal variation of the lake, images are mainly from October. If the image of October is missing or obscured by cloud cover, the other image from the adjacent month or close to the year will be chosen. The specific information of images is shown in Table 1.
2.2.2. Meteorological Data
Shiquanhe station (32°30′N, 80°05′E, 4278.6 m a.s.l, figure 1) is the nearest meteorological station to ACL. The meteorological data of the station, including air temperature, precipitation and evaporation during 1961-2018, were obtained from the website of China Meteorological Data Service Centre (http://data.cma.cn/).

2.3. Methods
In this study, the normalized difference water index (NDWI) [17] and visual interpretation method were mainly used to extract ACL boundary, and then parameters of ACL were calculated. This process was mainly completed on platforms of ENVI and ArcGIS. The Mann-Kendall trend and mutation test methods [18, 19] were used to explore climate change in the study area.

In order to further quantitatively explore the influencing factors of lake change, the path analysis method [20], which can deal with complex relationships among multiple variables and provide a reliable basis for the statistical decision, was used in this paper. The path analysis method was used to differentiate the direct and indirect effects of each independent variable on the dependent variable by the decomposition of correlation coefficients between independent and dependent variables. Its calculation formula is as follows:

Suppose there are multiple independent variables \( x_i \) \((i = 1, 2, 3, ..., n)\) and dependent variable \( y \):

\[
r_{ij} = P_{ij} + \sum_{j=1, j\neq i}^{n} r_{ij} \times P_{jy}
\]

Where, \( r_{ij} \) is the correlation coefficient between \( x_i \) and \( y \), the direct effect of an independent variable \( x_i \) on the dependent variable \( y \) is called the direct path coefficient \( (P_{ij}) \), and the indirect effect of an independent variable \( x_i \) on the dependent variable \( y \) through \( x_j \) is called the indirect path coefficient \( (r_{ij} \times P_{jy}) \).

3. Results and Discussion

3.1. Variation Characteristics of Climate
In this paper, the variation and mutation characteristics of annual mean air temperature, precipitation and evaporation at Shiquanhe station were analyzed by the Mann-Kendall trend and mutation test method, respectively (figure 2).

The Shiquanhe station had an average annual mean air temperature of 0.9 ℃, with a significant warming trend at the rate of 0.44 ℃/decade due to Mann-Kendall test value \( Z_c = 5.74 \) > 3.292 (figure 2 a1). According to figure 2 a2, UF values of annual mean air temperature during 1961-1963 and 1965-1991 were less than zero, indicating a downward trend of air temperature during these periods. On the contrary, annual mean air temperature showed an upward trend during 1992-2018, with a significant increasing trend after 2000 indicated by the subsequent UF curves passed the significance level of 0.05 test. In addition, the abrupt change of air temperature occurred in 1999, with a mean air temperature of 0.3 ℃ and 2.0 ℃ for periods of before and after mutation, respectively.

Figure 2 b1 showed that the average annual precipitation was 71.4 mm, with an insignificant increasing rate of 1.35 mm/decade, and there was no abrupt change (figure 2 b2). According to the 5-year moving average curve, the change of annual precipitation can be divided into seven stages, which showed an upward trend during 1963-1971, 1981-1986, 1991-2000 and 2005-2016, respectively, while the other periods showed a downward trend.

Changes of evaporation in Shiquanhe station revealed a significant downward trend of -54.3 mm/decade due to likely to be affected by wind stilling on the Tibetan Plateau [21], with an average annual evaporation of 2404.4 mm (figure 2 c1). And there were two mutation points occurred in 1972 and 2014 (figure 2 c2), respectively. Based on the 5-year moving average curve, the annual evaporation suffered a “downward – upward – downward – upward – downward” trend, with the downward trend during the periods of 1962-1968, 1997-2004 and 2010-2018, respectively.
Figure 2. Mann-Kendall trend (Left) and mutation test (right) of annual mean air temperature (a1, a2), precipitation (b1, b2), evaporation (c1, c2) during 1961-2018 of Shiquanhe station. Noted that dotted lines represent critical $Z_c$ at a significance level of 0.05.

3.2. Spatiotemporal variation characteristics of ACL

Table 1 displays the area, rate of area changes and center of lake area gravity location of ACL from 1972 to 2018. The direction and distance of spatial expansion of the lake can be determined by the location of the center of gravity. Figure 3 and figure 4 show the characteristics of spatial and temporal changes of ACL, respectively.

Results showed that ACL area changes could be roughly divided into five stages: (1) From 1972 to 1989, the lake area showed a slight expansion trend, increasing by 3.51 km$^2$ in total, with an average increasing rate of 0.206 km$^2$/a. In space, it mainly expanded to the northeast with an expansion distance of about 66.4 m. (2) From 1990 to 1998, the ACL shrunk mainly to the southwest by a distance of about 103.4 m, with an average area changes rate of -0.072 km$^2$/a. (3) From 1999 to 2008, the ACL area was rapidly expanding at an average rate of 7.74 km$^2$/a. Especially in 2006, the ACL area expanded by 12.049% compared with that of 2005. In space, the lake expanded rapidly to the southeast by 2046.6 m, with an average annual expansion of 227.4 m. (4) The lake area expanded slightly at the average rate of area change of 1.09%/a during 2009-2012. (5) From 2012 to 2018, the lake area increased rapidly again, increasing by 49.21 km$^2$ with an average rate of 8.20 km$^2$/a and
expanding by 1789.5 m at an average rate of 299.8 m/a in the southeast direction. Compared with 2012, the area in 2013 increased by 10.168%, which was the fastest year of lake expansion in this stage.

Overall, ACL expanded with a total area of 115.43 km$^2$ during 1972-2018, and the average growth rate was 2.51 km$^2$/a. The highest rate of area change was 12.049% in 2006, and the lowest rate appeared in 1996 with only 0.028%. Spatially, the lake mainly expanded to the southeast by 3851.6 m. This is mainly because the southeastern shore of ACL is relatively low and gentle, while the northern, western and southern shores are relatively steep [14].

Figure 3. Spatial changes of ACL during 1972-2018.
3.3. Influence of climate factors on ACL area change
Path coefficients, listed in table 2, were calculated to quantitatively explore the influence of climate change on ACL area change. Results showed that the direct effects of air temperature and evaporation on the lake area were 0.443 and -0.448, respectively, which indicated that the lake area increased with the increase of air temperature and the decrease of evaporation. In the indirect effect, air temperature indirectly affected lake area through evaporation, with an indirect effect coefficient of 0.187, while the indirect effect of evaporation on the lake area through air temperature was -0.185. Air temperature and evaporation through precipitation had little effect on the lake. It was worth noting that the indirect path coefficients of precipitation on lake area through air temperature and evaporation were 0.065 and 0.173, respectively, both of which were greater than the direct path coefficients of precipitation, indicating the effect of precipitation on the lake was mainly indirect.

In general, the total effects of air temperature, precipitation and evaporation on ACL area were 0.632, 0.253 and -0.638, respectively, indicating that air temperature and evaporation had similar but opposite effects on lake area, which is different from the result of [13], while precipitation had the least effect due to less annual precipitation. ACL is a closed inland lake with glacial and snow meltwater and precipitation as water supply sources and evaporation as the main water loss. Both air temperature and precipitation promoted the expansion of the lake, and their combined effects were greater than evaporation, which was the main reason for the expansion of the lake area.

Table 2. Path analysis among air temperature, precipitation, evaporation and ACL area during 1972-2018.

| Climate Factor | Direct path coefficient | Indirect path coefficient | Correlation coefficient |
|----------------|-------------------------|--------------------------|------------------------|
| Air Temperature | 0.443 | 0.002 | 0.187 | 0.632 |
| Precipitation | 0.015 | 0.065 | 0.173 | 0.253 |
| Evaporation | -0.448 | -0.185 | -0.006 | -0.638 |
4. Conclusions
Based on Landsat MSS/TM/ETM+/OLI images from 1972 to 2018 and meteorological data of Shiquanhe station from 1961 to 2018, the characteristics of lake area and climate change in the ACL region were studied and the influence of climate change on ACL area was also discussed. The conclusions are as follows:

(1) From 1961 to 2018, the annual mean air temperature of the Shiquanhe station increased with a significant trend of 0.44 °C/decade, and mutation occurred in 1999. Precipitation showed an insignificant upward trend at a rate of 1.35 mm/decade. The annual evaporation decreased significantly at the rate of -54.3 mm/decade, and the overall fluctuation trend was presented as “downward – upward – downward – upward – downward” with 1969, 1997, 2005 and 2010 as the turning point.

(2) From 1972 to 2018, the lake area of ACL showed a trend of "slight expansion – shrinkage – rapid expansion – slight expansion – rapid expansion", and the total area increased by 115.43 km². The annual rate of lake area change in 2006, 2013 and 2008 was 12.049%, 10.168% and 9.218%, respectively, while the rate in 1996 was the lowest, only 0.028%. In space, the ACL expanded 3851.6 m to the southeast at an average rate of 83.7m/a due to topography.

(3) Air temperature and evaporation had a similar effect on lake area, but the effect was opposite. Both of them regulated lake change mainly through direct influence, while precipitation presented the indirect effect on lake area change through air temperature and evaporation. In general, the expansion of ACL was promoted during 1972-2018 by the increasing snow and glacial meltwater caused by warming, the increasing precipitation and the decreasing evaporation, which resulted in the decrease of lake water loss.

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