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Estimation and trend detection of water storage at Nam Co Lake, central Tibetan Plateau

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SUMMARY

Nam Co Lake is the highest lake in the central Tibetan Plateau, and existing research on water storage and water level variations are lacking. This paper provides a method for estimating the lake water storage based on historical meteorological records from 1976 to 2009, remote sensing images scattered in this period, in situ bathymetric survey, and GIS techniques, and presents a comprehensive 34-year analysis of intra-annual and inter-annual variations of Nam Co Lake water storage. The multi-year mean water storage of Nam Co Lake is 842.36×10^8 m^3, with the maximum water depth of about 98 m. During 1976–2009, the lake water storage increased from 786.06×10^8 m^3 to 870.30×10^8 m^3, with a tendency value of 2.67×10^8 m^3/a; the lake area enlarged from 1927.48 km^2 to 2015.12 km^2, with a tendency value of 2.71 km^2/a. The lake area fluctuations annually, increasing from April of each year until late September and early October, then decreasing until March of the next year. Climate change has a significant impact on the water storage variation of the lake. A general pattern of warming temperature is evident with the regional annual mean air temperature increasing significantly by 0.404 °C/10 a. Preliminary analysis indicates that the enlarging status of Nam Co Lake water storage is closely related to increasing of precipitation and stream runoff especially coming from the input of glacial meltwater. By combining this data with other research, it can be presented that under the trend of global warming, on Tibetan Plateau, the inland lakes which depend on the rainfall and river supply in the basin are shrinking, while the lakes which depend on glacial meltwater supply are enlarging. Climate change is an important factor promoting the lake variation.

1. Introduction

Climate changes are expected to seriously affect the water resources of the Tibetan Plateau (Immerzeel et al., 2010). Inland lakes that are widely distributed on the Tibetan Plateau have minimum impact of human activities and are an important component of the water supply in China. The enlargement and shrinkage of inland lakes reflect the changes in water and heat balance, which is a sensitive indicator of the climate change (Shi, 1990). Lake water storage variation provides information about temperature, rainfall, humidity and solar radiation, while regional water storage variations reflect the climate change in a larger scale (Redway, 1924; Hartmann, 1990; Jones et al., 2001; Novaky, 2008). Lake water level variation directly records the process of water storage balance in the basin, which is a quite sensitive response to the climate change (Li et al., 1998). Therefore, fluctuation of inland lakes in the Tibetan Plateau (variation of area, water level, water storage, etc.) is an important indicator of climate change. Understanding these variations and the role of climate is important for water resource management as well as for predicting future changes in lake hydrology as a result of climate change.

Existing research on lake variations mainly focus on the monitoring of area changes in lake. Due to the wide monitoring scope, fast speed and low cost, remote sensing technology has unique advantages in the dynamic monitoring of lakes in inaccessible areas of the Tibetan Plateau (Quincey et al., 2007; Chu et al., 2008; Yang et al., 2008). Previous work utilized middle and high resolution optical image data to analyze the fluctuation in the area of main lakes on Tibetan Plateau and the results indicated that lakes which depend on the supply of glacial meltwater in the middle and northern Tibetan Plateau are stable and tending to enlarge, including Nam Co Lake, Serlincuo Lake, Palgon Lake and Hala Lake (Yang et al., 2003; Zhao et al., 2006; Wu and Zhu, 2008). Lakes located in the northeastern and western Tibetan Plateau, which depend on the supply of inland rivers and rainfall are shrinking, including Qinghai Lake, Yamdrok Lake, Zhari Namco Lake, Dangreyong Lake, Ayakkum Lake and Ulan Ul Lake (Morrill, 2004; Lu et al.,

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2005; Shao et al., 2007;Ye et al., 2007). Still, research related to water storage only exists in three areas with hydrological observation stations, namely, Qinghai Lake, Yamdrok Lake and Zabuye Salt Lake (Ding and Liu, 1995; Li et al., 2005; Qi and Zheng, 2006; Bian et al., 2009), and the water storage research of lakes in other areas of the vast Tibetan Plateau is limited.

This study focuses on the Nam Co lake, the largest lake on Tibet plateau as well as the highest large lake in the world. Altogether 42 images of three kinds of remote sensing image data were used in combination with hydrological data actually measured in the field, and meteorological station data, to quantitatively acquire the information of surface fluctuation, water storage variation, and to study the lake response to climate change from 1976 to 2009 for the first time. The results provide theoretical support and data for further understanding the processes and extent of water resource response to global climate change, and provide a scientific basis for rational development and utilization of water resource in Tibetan plateau.

2. Study area and data

Nam Co Lake is the largest lake in the Tibet Plateau as well as the highest large lake in the world. It is located at 90°16′–91°03′E, 30°30′–30°55′N (Fig. 1). It belongs to Damxung County of Lhasa City and Baingoin County of Nagqu Prefecture of Tibetan Autonomous Region. Its elevation is 4718 m and the water area is 1920 km^2 measured in 1979 (Guan et al., 1984), and the maximum depth is over 90 m (according to the data measured from 2005 to 2007).

Nam Co Lake Basin is located at 89°21′–91°23′E, 29°56′–31°7′N, with an area of 10,610 km^2. It is a closed basin in the north of Gangdise-Nyainqentanglha Mountain in the plateau lake basin region of southern Qiangtang in Northern Tibet. The average altitude of Nyainqentanglha Mountain in the southeast of the basin is about 5500 m. There are many modern glaciers on the mountain, mostly short and small ones, and the glacial meltwater directly flows into the lake in a comb-like form passing a short distance of piedmont area. Northern and northwestern parts of the basin belong to a gently undulating, low mountainous area whose average altitude is about 5000 m. The whole basin receives strong solar radiation and gets a long duration of sunshine, which can reach 2900–3200 h a year. The basin belongs to the plateau subfrigid monsoon semiarid climate zone, which is cold and has no distinct seasons. The annual temperature range is larger than daily variability.

Because of its special geographical position, Nam Co Lake is barely influenced by human activities, and its water fluctuation only reflects long-term climate change information.

There was no meteorological observation station or hydrological station in the basin before 2005. After 2005, the Institute of Tibetan Plateau Research established the Nam Co Lake Multi-Layer Comprehensive Observation and Research Station (Nam Co Lake Station) of China Academy of Sciences and gradually began the monitoring of some regular parameters. Researchers conducted

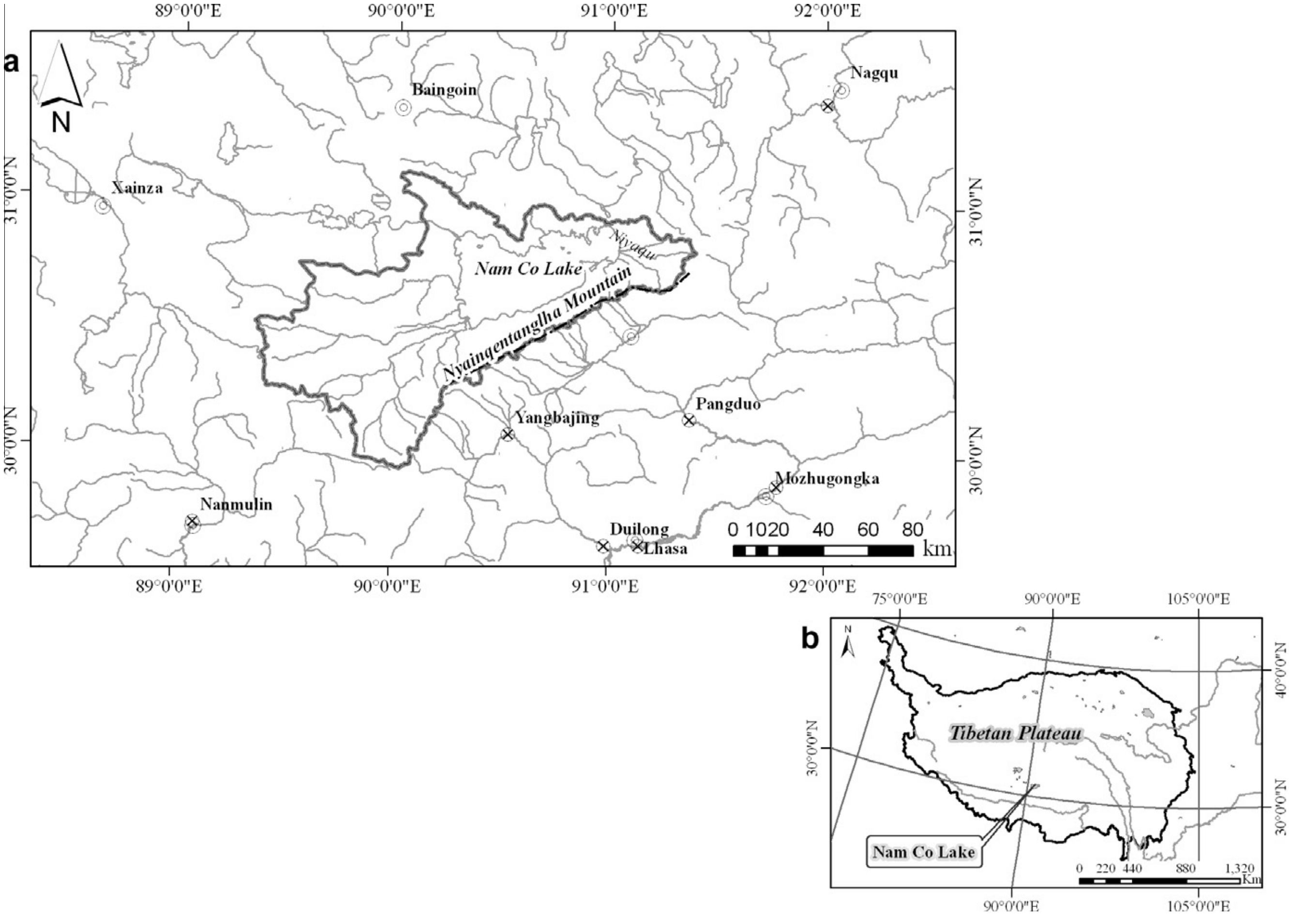

Fig. 1. Map-a showing the location of observation stations around Nam Co lake, the region enclosed by the dashed gray line represents the Nam Co lake basin, the light gray lines around the lake represent rivers, the double circle symbol represent the meteorological stations, and the fork circle symbol represent the hydrological stations; Map-b showing the position of Nam Co on the Tibetan Plateau.

Table 1
Remote sensing data and digital elevation model (DEM) data used in this paper. DEM is downloaded from: http://asterweb.jpl.nasa.gov/gdem-wist.asp.

SN	Data type	Acquisition time (year/month/day)	Resolution (m)
1	Landsat2 MSS	1976/11/11; 1976/12/17; 1977/01/22; 1977/02/09	57
2	Landsat4 TM	1989/01/19; 1992/12/13; 1993/01/14; 1993/03/03	30
3	Landsat5 TM	1991/09/14; 2007/05/15; 2009/10/17; 2009/12/04	30
4	Landsat7 ETM	1999/12/17; 2000/03/06; 2000/04/07; 2000/10/16; 2000/11/01; 2000/12/19; 2001/02/25; 2001/06/13; 2001/11/04; 2001/12/06; 2002/02/24; 2002/03/28; 2002/05/15; 2002/12/09; 2003/01/10; 2003/04/16	30
5	CBERS-CCD	2003/11/07; 2004/09/14; 2004/10/10; 2005/11/30; 2006/01/21	19.5
6	HJ-CCD	2008/12/13; 2009/01/07; 2009/02/06; 2009/03/14; 2009/04/16; 2009/05/19; 2009/06/25; 2009/08/30; 2009/11/08	30

three comprehensive investigations from 2005 to 2007 and obtained the water depth data of Nam Co Lake (Wang et al., 2009).

In this paper 42 visible and near infrared remote sensing images from landsat MSS/TM/ETM, CBERS and HJ-1A/1B satellites covering the study area from 1976 to 2009 were used to estimate water surface areas in different time periods. The details of their acquisition time and spatial resolution can be found in Table 1. The ground pixel resolution of CBERS image is 19.5 m, and its 5 bands according to spectral response ranges from visible light to near infrared spectrum are 0.45–0.52 μm, 0.52–0.59 μm, 0.63–0.69 μm, 0.77–0.89 μm and 0.51–0.73 μm respectively. The ground pixel resolution of the HJ-1A/1B image is 30 m, and its 4 bands are 0.43–0.52 μm, 0.52–0.60 μm, 0.63–0.69 μm and 0.76–0.90 μm respectively.

The regular monitoring data of the 11 meteorological stations around Nam Co Lake from 1976 to 2009 were used, including daily average temperature, lowest temperature, highest temperature, rainfall, sunshine duration, wind speed and water vapor pressure. The locations of all the meteorological stations are listed in Table 2, and some of them are shown in Fig. 1.

3. Methodology

3.1. Water storage calculation

The water storage W for a lake can be written as $W = f(S,H)$ (1)

where S is the lake surface area, H is the water depth of the lake underwater landform.

A series of multi-temporal remote sensing images were used to acquire the lake surface area (S) in different periods. First, all the images were conducted geometric correction, registering and inlaying, and the inaccuracy is controlled within a pixel. Then according to the characteristics of the sensors CBERS and HJ-1A/1B, band 4, 3 and 2 (red, green, blue) were adopted to determine the lake surface area; as to the landsat satellite data, a total of six bands of ETM + band 1–5 and band 7 were utilized to confirm the lake surface area according to the band threshold value and spectral relationships of each ground object, supplemented by visual interpretation method to rectify the result (Niu et al., 2008).

Table 2
Meteorological stations used in this paper.

SN.	Station	Longitude	Latitude	Altitude (m)	Record period
1	Baingoin	31°23′	90°01′	4700	1956.10–2009.12
2	Damxung	30°29′	91°06′	4200	1962.08–2009.12
3	Nagqu	31°29′	92°04′	4507	1954.07–2009.12
4	Xainza	30°57′	88°38′	4672	1960.04–2009.12
5	Amdo	32°21′	91°06′	4800	1965.11–2009.12
6	Shigatse	29°15′	88°53′	3836	1955.12–2009.12
7	Lhasa	29°40′	91°08′	3648.7	1955.01–2009.12
8	Tsedang	29°15′	91°46′	3551.7	1956.09–2009.12
9	Gyantse	28°55′	89°36′	4040	1956.11–2009.12
10	Sokshan	31°53′	93°47′	4022.8	1956.11–2009.12
11	Lhari	30°40′	93°17′	4488.8	1954.11–2009.12

The lake underwater landform data (H) were obtained through measurements taken in the field. Based on the lake bathymetric survey data measured from 2005 to 2007 with the accuracy of 0.01 m and 305721 measuring points, we drew the isobathic map (Fig. 2), and then established the underwater landform digital elevation model (DEM) with grid units of 30 m × 30 m by the extended module (3D Analyst) in ArcMap.

And formula (1) can be further written as $W = \sum_{i=1}^{n} S_i \times \Delta h$ (2)

where n is the equally parted cells number of the elevation difference, $\Delta h = (h_s - h_r)/n$ is the distance with each cell, and S_i is the water surface area with the elevation of $h_r + (i-1)\Delta h$, which can be automatically derived from the DEM data mentioned above.

Then, the series of water storage data (W) were obtained by the "Area and Volume" module of 3D analysis in ArcGIS, utilizing the calculation of excavation and filling based on the underwater landform DEM and the lake surface area data.

3.2. Lake surface evaporation and precipitation estimation

Since there was no meteorological station in the Nam Co basin before 2005, it is very difficult to accurately estimate the average rainfall and evaporation of the whole basin. Because there is so few records on the direct evaporation of the lake surface, in this paper the Penman–Monteith model recommended by the Food and Agriculture Organization (FAO) of the United Nation was adopted to estimate the lake evaporation (Allen et al., 1998), and the formula is:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} U_2 (e_s - e_d)}{\Delta + \gamma(1 + 0.34U_2)} \quad (3)$$

where $\varDelta$ represents the curve slope of saturated water vapor pressure (kPa °C^{-1}) at temperature T; R_n represents the solar net radiation at the top layer (MJ m^{-2} d^{-1}); G represents soil-pass heat (MJ m^{-2} d^{-1}); γ is the dry–wet constant (kPa °C^{-1}); T is the average monthly temperature (°C); U_2 is the wind speed at the height of 2 m (m/s); e_s and e_d are the saturated water vapor pressure and actual water vapor pressure (kPa) respectively at temperature T.

The thin-plate spline method (TPS) (Hutchinson, 1998) was adopted to interpolate the evaporation and precipitation data of the whole basin considering the terrain factor, and the lake surface evaporation and precipitation time series data were further extracted, based on the 11 stations near the study area.

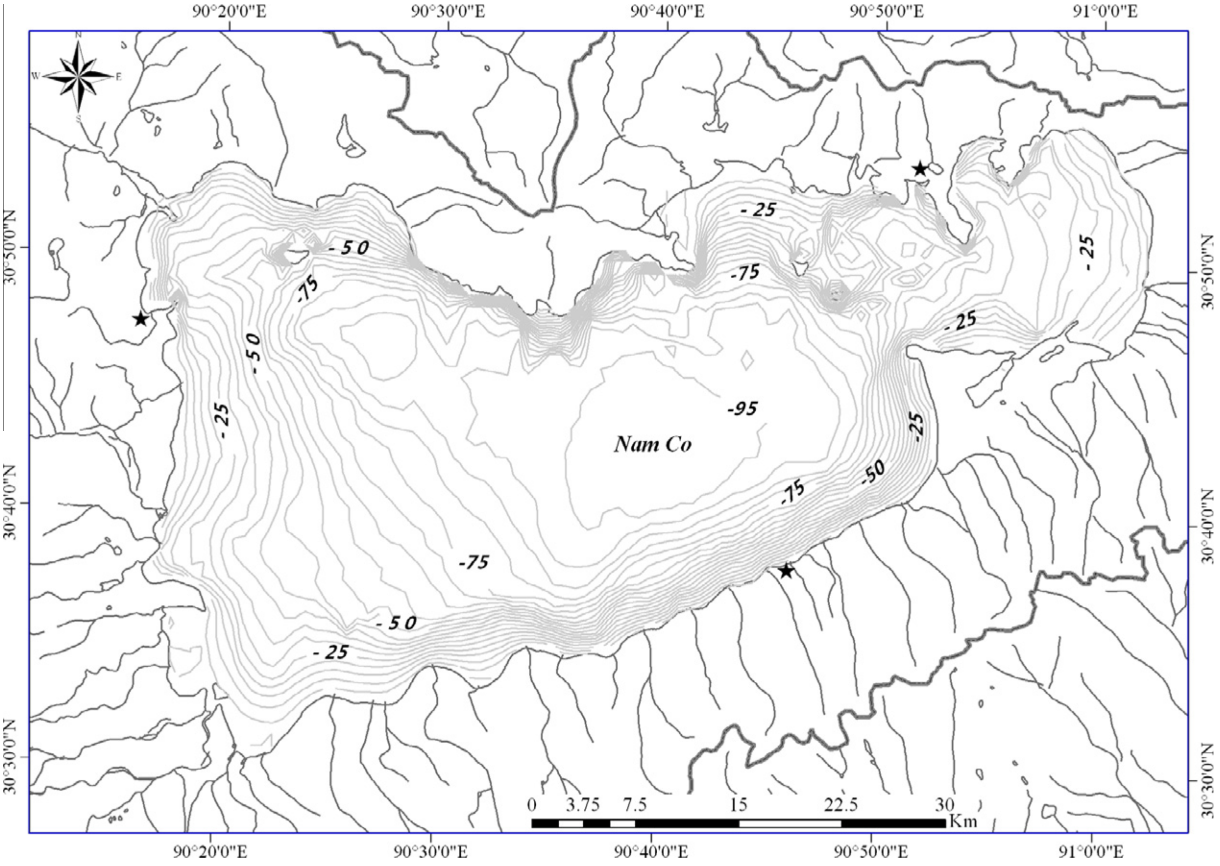

Fig. 2. Isobathic map of Nam Co Lake. The light gray lines represent the bathymetric lines, the pentacle symbol represent the investigation camp, and the dashed line with dark gray represents the Nam Co lake basin.

3.3. Analysis of long-term trends in meteorological variables and water storage

To assess the significance of climatic factors and lake water storage trends, we employed the non-parametric Mann–Kendall test (Mann, 1945; Kendall, 1975) to conduct trends analysis. This test has been identified as one of the most robust techniques available to uncover and estimate linear trends in environmental data (Hess et al., 2001). As to the series $X_t = (x_1, x_2, \ldots, x_n)$, this method defines the standard normal variate U_{MK} as:

$$U_{MK} = \frac{S}{\sqrt{Var(s)}} \tag{4}$$

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}(x_j - x_i) \tag{5}$$

$$\mathrm{sgn}(x) = \begin{cases} 1, x > 0 \\ 0, x = 0 \\ -1, x < 0 \end{cases} \tag{6}$$

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{n} t_i i(i-1)(2i+5)}{18} \tag{7}$$

where S denotes the relationship between the number of observation pairs (x_i, x_j, $j > i$), and n is the total number of samples. A time series has a clear trend, defined as a level of significance of 5%, if $|U_{MK}| > U_{a/2} = 1.96$. A positive U_{MK} indicates an increasing trend in the time series, while a negative U_{MK} indicates a decreasing trend.

4. Results

4.1. Water storage of Nam Co Lake

According to the lake underwater landform data acquired in the field, the maximum lake depth is about 98 m, and the average lake depth is about 45.63 m. Fig. 3 shows the water level-storage curve based on the calculation from Section 3.1.

The multi-year mean water storage of Nam Co Lake is $842.36 \times 10^8\,\mathrm{m}^3$, with the maximum $870.30 \times 10^8\,\mathrm{m}^3$, the minimum $786.06 \times 10^8\,\mathrm{m}^3$, and the coefficient of variation of 0.033.

4.2. Water storage intra-annual variation

Selecting 2009 as a sample study period, based on the water surface areas obtained from the 10 images and bathymetric survey data, the intra-annual variation trend of water storage and surface area of Nam Co Lake can be acquired (Fig. 4). The intra-annual variation show that the water storage increases from March ($861.68 \times 10^8\,\mathrm{m}^3$) to late September and early October ($876.69 \times 10^8\,\mathrm{m}^3$), then begins to decrease until December ($870.30 \times 10^8\,\mathrm{m}^3$). The lake surface fluctuation appears to be similar (Table 3).

The intra-annual character of lake water storage fluctuation is in line with that of the precipitation, which appears to increase from late April and reaches the maximum at the end of the warm season (from April to October) (Fig. 5).

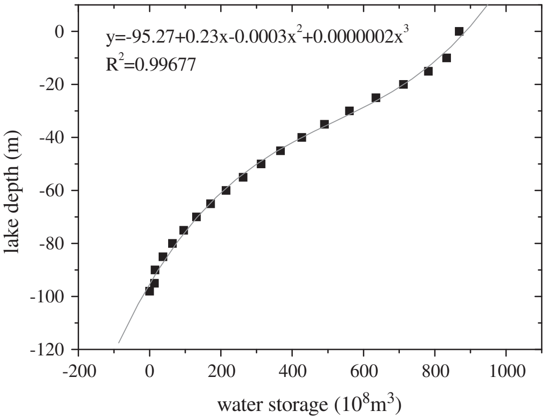

Fig. 3. Water level-storage capacity curve of Nam Co Lake.

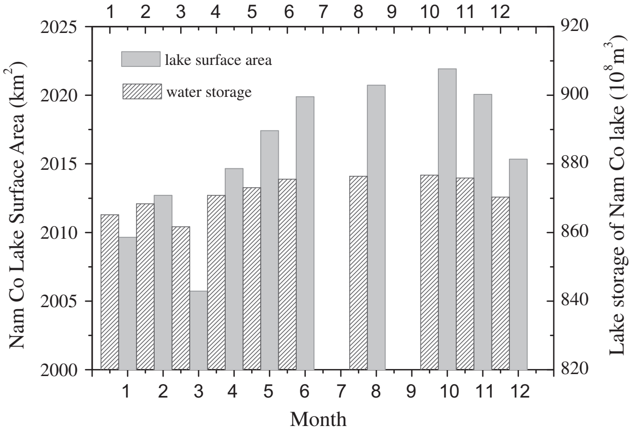

Fig. 4. Nam Co lake water storage and surface area variation trend in 2009. (The data of 2009 are lack of July and September because the images of the corresponding period were not acquired.)

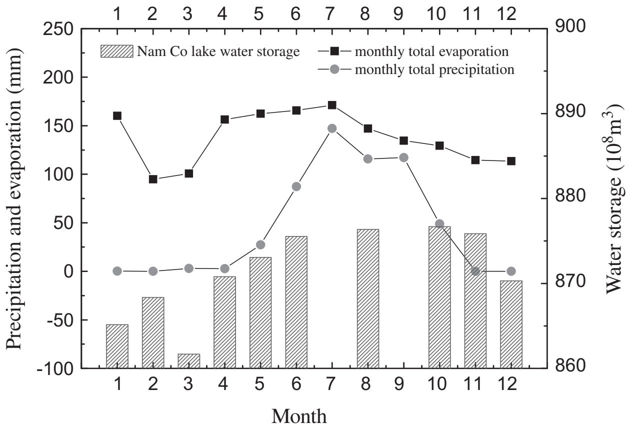

Fig. 5. Monthly water storage of the Nam Co Lake in 2009 and the monthly total precipitation and evaporation of 2008 measured by the Nam Co station. The precipitation and evaporation data come from the daily observation data acquired by Nam Co Lake Multi-Layer Comprehensive Observation and Research Station of China Academy of Sciences. The lake water storage data of 2009 is lack of July and September because the images of the corresponding period were not acquired.

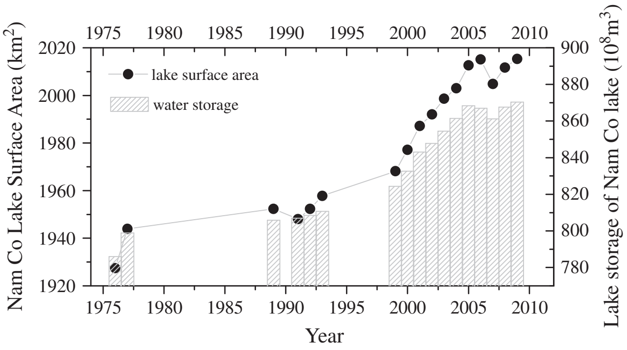

Fig. 6. Interannual variation trend of water storage and surface area of Nam Co lake of 1976–2009.

4.3. Water storage inter-annual variation

Fig. 6 shows the inter-annual variation in water storage and lake surface area of Nam Co Lake in the past 34 years based on the water surface areas obtained from the 42 images and bathymetric survey data. From 1976 to 2009, the lake water storage is obviously increased from 786.06×10^8 m^3 to 870.30×10^8 m^3. The period can be divided into three phases with the respective tendency values listed in Table 4, which shows that the greatest increases and largest number of significant upward trends for lake water storage occurred during 1999–2006, with a tendency value of 6.41×10^8 m^3/a, and then maybe have gone into the placidly increasing phase. The lake surface area also showed the same character.

A comparative analysis of lake storage series and climate factor series shows a similar trend. Liu et al. (2009) concluded that the changes point to an abrupt increase in the annual precipitation, mean temperature and runoff occurring at the end of the 1990s, and a decrease in the annual pan evaporation also happened at the end of 1990s. The timing of the lake surface area increase with great rate changes corresponds closely with rapid increases in the annual precipitation and runoff and with the decrease in the annual evaporation since the end of the 1990s. This shows that climate is the main factor affecting the lake water variation.

We also selected the data from the same month in different years to make further comparisons. Compared with the lake water storage in November 1976, the storage in November of 2000, 2001, 2003, 2005 and 2009 increased by 5.05%, 5.91%, 7.31%, 9.05% and 10% respectively; compared with the lake water storage in January of 1977, the storage in January of 1989, 1993, 2003, 2006 and 2006 increased by 0.87%, 1.48%, 6.03%, 8.53% and 8.61% respectively.

The seasonal variation of lake water storage during 1976–2009, showed that all years increased from each April and to late September and early October, then decrease until March of the next year. This result is basically in line with the in field measured water level variation trend of Nam Co Lake (Chen et al., 2009). From the spatial perspective, the east and west flat bank areas of the lake obviously enlarge, while the south and north abrupt slope areas of the lake enlarge slightly (Fig. 7). Compared with the lake surface area in November of 1976, areas in November of 2000,

Table 3
The monthly water storage and lake surface area of Nam Co Lake in 2009.

Month	1	2	3	4	5	6	8	10	11	12	Mean value
Water storage(10^8 m^3)	865.16	868.35	861.68	870.80	873.07	875.54	876.37	876.69	875.86	870.30	871.38
Surface area (km^2)	2009.65	2012.70	2005.73	2014.66	2017.41	2019.89	2020.73	2021.92	2020.06	2015.35	2015.81

Table 4
Variation character of lake water storage and surface area in different periods.

Period	Water storage (10^8 m^3)			Lake surface area (km^2)		
	At the beginning of each period	At the end of each period	Tendency value(10^8 m^3/a)	At the beginning of each period	At the end of each period	Tendency value (km^2/a)
1976–1999	786.06	824.35	1.59	1927.48	1968.23	5.35
1999–2006	824.35	866.97	6.41	1968.23	2015.12	6.67
2006–2009	866.97	870.30	1.63	2015.12	2015.35	0.76

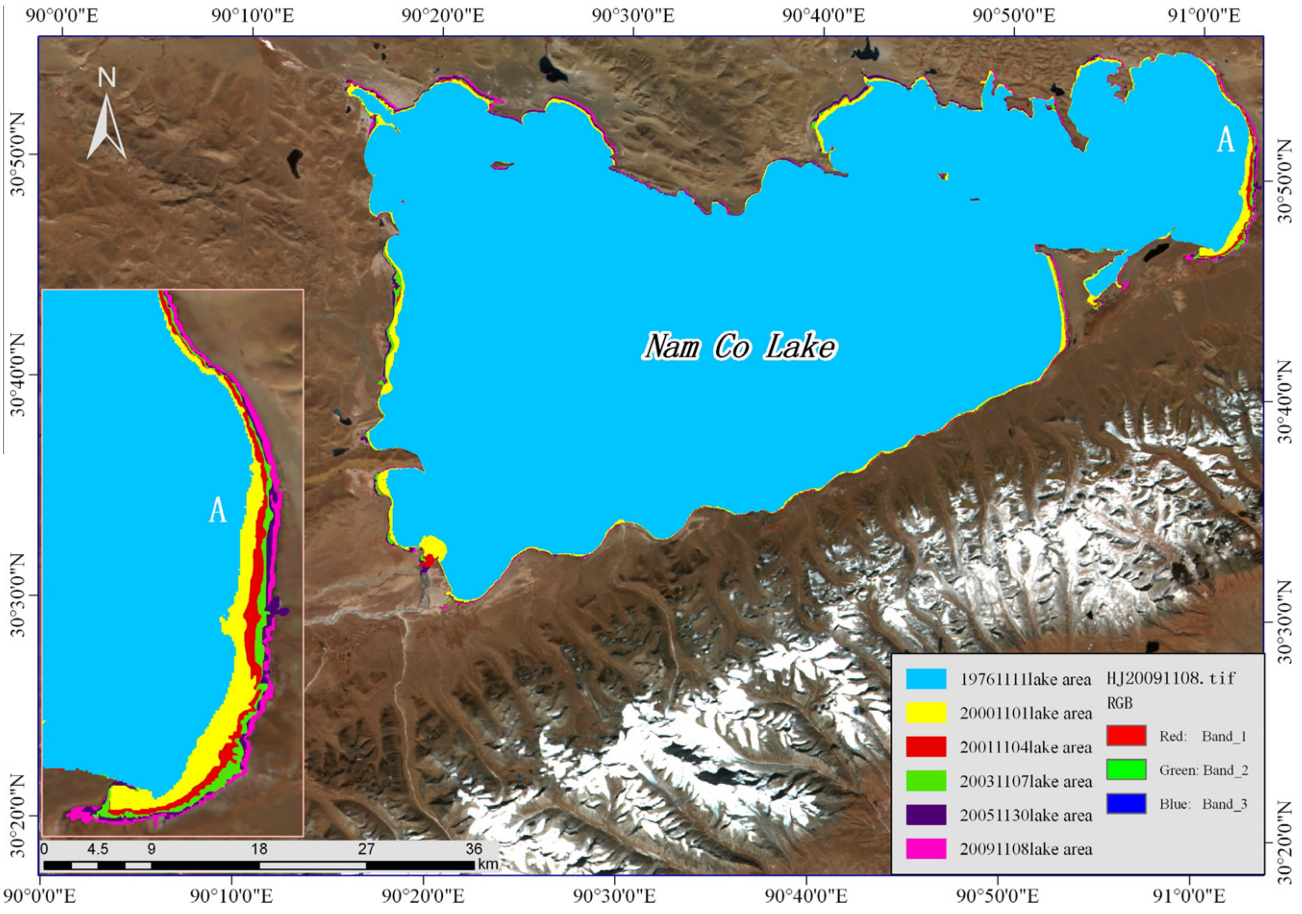

Fig. 7. Surface fluctuation trend of Nam Co Lake. The base map is a fake color composite image of HJ-CCD acquired on November 8th, 2009. Six colors represent the lake of different period respectively, with the middle lake area overlapped. A is the enlarged view of the east bank area of the lake.

2001, 2003, 2005 and 2009 are enlarged by 41.06 km^2, 48.00 km^2, 59.32 km^2, 73.26 km^2 and 80.70 km^2 respectively.

Additionally, the reasons for the seasonal variation of Nam Co Lake are summarily analyzed. In the Nam Co Lake Basin, the temperature rises to about 0 °C in April and enters the warm period which is from April to October. The centralized rainfall from June to September reach over 90% of a year's total according to the meteorological station data analysis. Therefore, the rainfall supply for the lake reaches the maximum in the end of summer, along with the timing of glacial meltwater, and the lake surface area reaches the maximum value. After October, the temperature falls below 0 °C, the rainfall becomes rare and the glacial meltwater also decreases, and the lake surface area decreases.

4.4. Climate change

Climate change directly or indirectly influences the fluctuation of lake water storage, and it is an important driving factor for lake variability (Holzhauser et al., 2005). By correlation analysis of the mean monthly temperature acquired by the Nam Co station and the neighboring meteorological stations, from December 2005 to December 2007, Chen et al. (2009) found a positive relationship between them. Therefore, this paper selects the annual mean air temperature measured by Baingoin Station to conduct trend analysis of Nam Co Lake basin, and the data of rainfall and evaporation are acquired according to the methods mentioned above.

We used the non-parametric Mann–Kendall test to evaluate annual trends in air temperature, precipitation and evaporation on the Nam Co Lake during 1971–2009 based on the data acquired (Table 5). A general pattern of warming temperature and decreasing evaporation on the lake is evident, whereas the precipitation showed an increasing trend, but with $p \geqslant 0.05$ (Fig. 8). Regional annual mean air temperature increased significantly ($p = 0.008$) by 0.404 °C/10 a, and the annual mean evaporation decreased significantly ($p = 0.0000976$) by 40.89 mm/10 a during the period (Fig. 8).

We chose air temperature, precipitation and evaporation data of the same year as water storage data, and normalized the four series

Table 5
Annual Mann–Kendall test results for air temperature, precipitation and evaporation series. Numbers in bold are statistically significant. Positive values indicate increasing trend, negative ones indicate decreasing trend.

Series	Average annual mean value	MK coefficients	*P*-value
Annual mean air temperature of Nam Co Lake	−0.28 °C	**2.640395****	0.008281
Precipitation on the lake	410.94 mm	1.704811	0.08823
Evaporation on the lake	1183.96 mm	−**3.89883*****	0.0000976

$^{*}p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

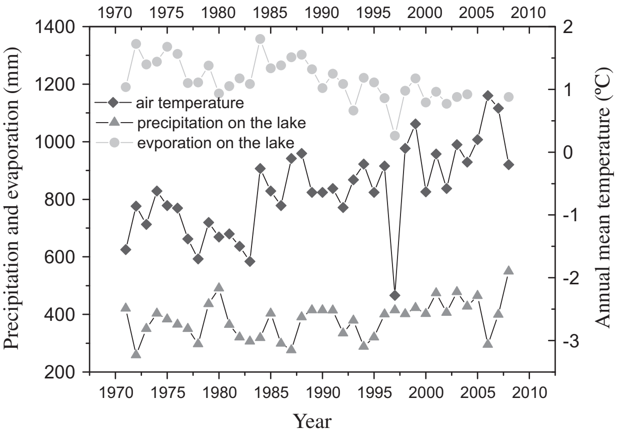

Fig. 8. Interannual variation trend analysis of air temperature in the Nam Co lake basin, precipitation and evaporation on the lake from 1971 to 2009.

for further analysis of the trends (Fig. 9). Results indicate that the variation and trend of the water storage correlated well with air temperature and is in general agreement with precipitation, except two anomalous years. Evaporation is always more than precipitation during the study period, which indicates that the enlarging status of lake water storage is closely related to the supply of runoff.

Nam Co Lake is a closed inland lake, whose water storage supply depends on three sources: precipitation, stream runoff and underground runoff. The increasing precipitation on the lake directly contributed to the increment of the lake water storage. Also the lake's south bank is the steep Nyainqentanglha Mountain, whose glacial meltwater flows into the lake in a comb-like form and comprises the important part of stream runoff (Guan et al., 1984). So it is also an inland lake with the dependence on the supply of glacial meltwater (Keil et al., 2010; Wang et al., 2010). The detailed runoff data of the Qugaqie River, which lies in the south of the Nam Co basin, shows strong daily amplitudes of 2–5 $m^3\ s^{-1}$, caused by glacial melting and freezing processes in the headwater area (Zhou et al., 2006). The increase in glacial meltwater against the background of increasing temperature makes important contributions to maintaining the increment status of the lake's water storage. Considering the underground runoff, since

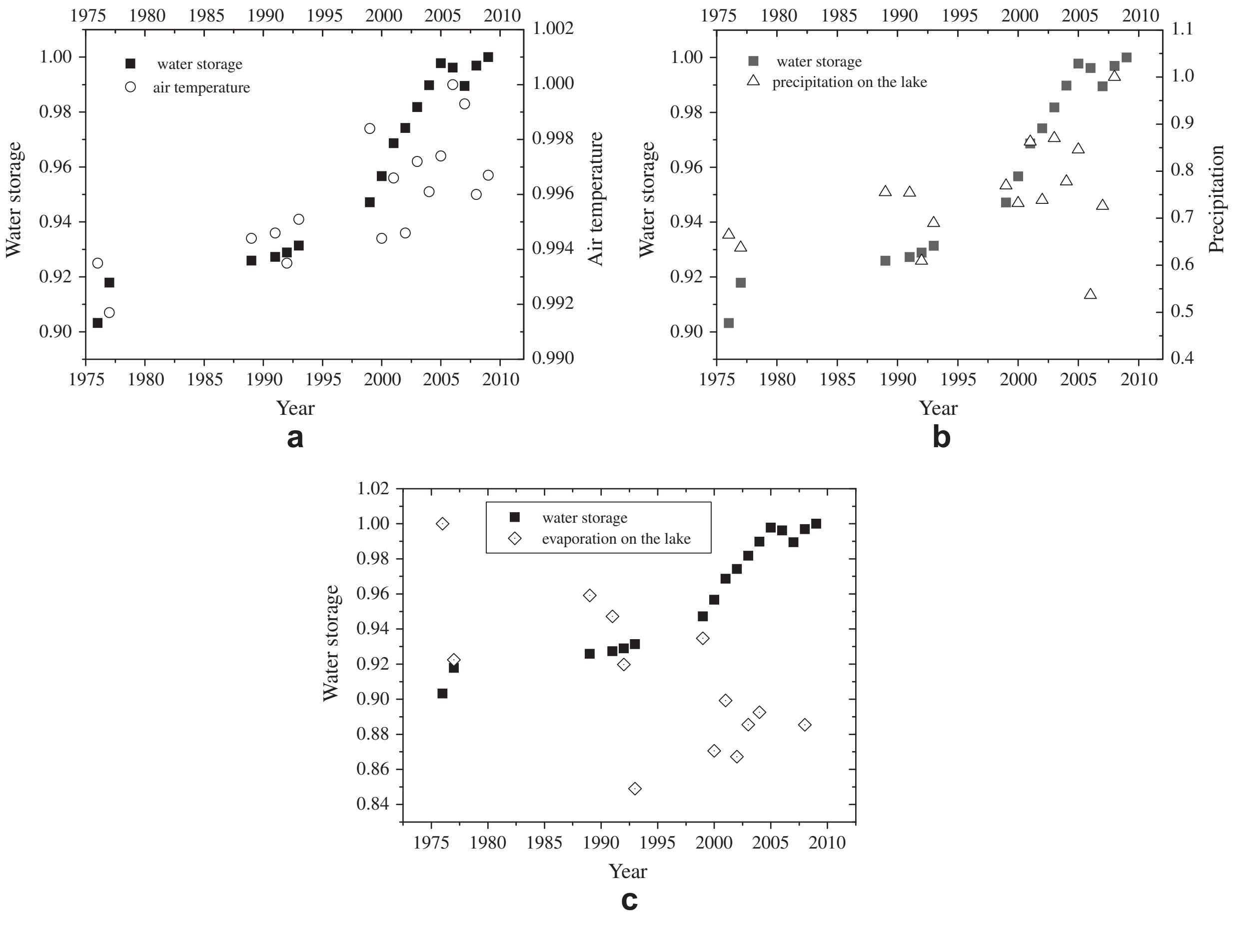

Fig. 9. Interannual variation trend analysis of normalized series of air temperature, precipitation, evaporation and water storage from 1976 to 2009.

piezometric data is scarce around the lake, quantifying groundwater flow around the lake using physical approaches was not possible. The Nam Co Lake is in the untraversed central Tibetan Plateau, and the groundwater has never been exploited for any purpose. As for the average annual variation, the groundwater can be supposed to be invariable. So the increased precipitation and stream runoff may be the main factors contributed to the enlarging of the lake. Zhu et al. (2010) concluded that the increased amount of water storage from precipitations accounted for 46.67% of total increased water supplies, while the increased stream runoff coming from glacier melt water reached 52.86% of total increased water supplies based on very rough estimation. It is obvious that the water storage of Nam Co Lake has significant responds significantly to the climate warming. Further studies need to be carried out based on more investigation and data in the future.

5. Discussion

Climate warming speeds up water transport and percolation into the subsurface (ground), which directly influences the highland lake volume. Closed lakes (those without surface outlets) display considerable volume changes, which are relatively easy to model in the absence of significant ground water exchange. Measurements of closed lake water storage changes are, therefore, not only important for hydrological and economic purposes, but can also provide a climate record, particularly in highland regions, where such monitoring is often extremely sparse.

Previous research on lake water level and water balance on the Tibetan Plateau are mainly conducted on a scale of 1000 years or even 10000 years. Most of these research utilize various proxy indexes such as spore and pollen, varve, midge and ostracods to reestablish the lake fluctuation sequence since Late Pleistocene (Cong et al., 2007; Yao et al., 2007; Li et al., 2008; Zhang et al., 2008). These research belong to the category of paleoclimatology.

Research on lake water level and water balance in recent decades were focused mainly on Qinghai Lake (Zhou and Wang, 1996; Li et al., 2007), Yamdrok Lake (Liu, 1995; Bian et al., 2009) and Zabuye Salt Lake (Qi and Zheng, 2006) where hydrological stations exist. Qinghai Lake is located in the northeastern Tibetan Plateau in a high cold semiarid climate zone, Yamdrok Lake is located in southern Tibet which belongs to a bush and grassland semiarid climate, and Zabuye Salt Lake is located in the central region of Tibetan Plateau, on the north side of western Gangdise Mountain, which belongs to plateau subfrigid climate zone. Generally, these three lakes all depend on the river supply of each basin and the water levels appear to descend in most years or even the whole period. While Nam Co Lake depends on the glacial meltwater supply and the water level appears to fluctuate and increase in recent decades. Therefore, the increasing glacial meltwater brought by climate warming is maybe one of the main reasons that big lakes maintain the stable surfaces or even enlargement on Tibetan Plateau in recent decades. These studies all indicate the sensitive response of lake variation to the climate change on the Tibetan Plateau. Climate change is the main reason driving the lake variability of Tibetan Plateau.

Otherwise, our estimate of water storage in the Nam Co Lake is innovative in areas without historical hydrological data on the Tibetan Plateau. As mentioned above, the earlier work about highland inland lakes mainly lies in the lake-level data measured by hydrological gauges. In this study, coupled with bathymetry DEM generated from field measuring on the Nam Co Lake, satellite images scattered into the study period were used to delineate the temporal-series changes in the lake surface areas and water storage. Similar studies were conducted in other regions of the world. Harris (1994) chose Lake Abiyata in the highlands of Ethiopia and detected its volume variations by 1 km-resolution AVHRR data and bathymetry measurements. The results showed that accurate data on closed lakes with areas ≈100 km^2 can be obtained from 1-km resolution data using the LIC technique, and a time series of areas produced from AVHRR demonstrate significant measurable variability, which is comparable to that observed in earlier ground-based measurements. A remote sensing program at the Mullard Space Science Laboratory (MSSL) that aimed to monitor short- and medium-term lake volume changes derived lake levels and lake areas using satellite radar altimeters and satellite imaging radiometers respectively, and interpreted them in terms of aridity variations as a measure of regional climate change (Birkett and Mason, 1995). Bastawesy et al. (2008) estimated water loss from Tushka lakes in Egypt using ASTER images and SPOT-4 images and bathymetry DEM data, and achieved better calculations. Swenson and Wahr (2009) examined trends in the water storage and lake levels of multiple lakes in the Great Rift Valley region of East Africa for the years 2003–2008, using satellite gravimetric and altimetric data. Remote sensing data and techniques are more and more widely used to monitor variations in inland lakes, especially in areas without historical hydrological data, and proved their reliability.

Beginning in 2001, IGBP conducted research on global climate change for the second decade and deemed the Tibetan Plateau as a key region due to its high sensitivity to climate change. Tibetan Plateau is called the "Asian Water Tower", and its water source variations and hydrological processes are a key component of global change research. The variation of the cryosphere and water sources of the Tibetan Plateau and adaptation strategies, along with the surface process changes of Tibetan Plateau and its influence on surrounding areas, are key scientific problems that need to be solved urgently. Compared with earlier research, this paper acquired a long-term lake fluctuation sequence about the area and its water storage, and discussed about the intra-annual and inter-annual variation characteristics of Nam Co Lake from 1976 to 2009. The methods presented herein provide an important source of data on past water variation on the Tibetan Plateau, and provide a necessary foundation for further research about water balance, hydrologic processes and the hydrological response to climate change.

6. Conclusion

There was previously very little research on the estimation of water storage for highland lakes due to the lack of sufficient hydrological records. This study has provided an estimation method and a comprehensive 34-year analysis of intra-annual and inter-annual variations in Nam Co Lake's water storage, using remote sensing data, in situ bathymetric survey, historical meteorological records, and GIS techniques. Results include the following:

- Nam Co Lake is a closed highland inland lake, with a multi-year mean water storage of 842.36×10^8 m^3. The water level-storage curve and the isobathic map showed that Nam Co is a deep, high-altitude lake with a large, flat basin lying in the central part of the lake, with more than 90 m water depth.
- Our estimation of water storage in the Nam Co Lake is innovative, and is much different from earlier work. Most of the earlier work on historical water storage levels was based on field hydrological records. In this study, satellite images acquired from 1976 to 2009, along with bathymetry DEM generated from in situ data, were used to estimate the changes in the lake surface areas and water storage. By combining these extracted water surfaces with the lake's 3D profile, accurate water storage can be estimated. Our results concerning the intra-annual and

inter-annual variations in lake storage demonstrate that historical water surface extracted from remotely sensed data is feasible and reliable. The method used in this study can be applied to other areas where historical hydrological records are not available.

- Growth of the Nam Co Lake was observed over the late 20th and early 21st centuries in response to climate change. This study indicates that the lake water storage obviously increased from $786.06 \times 10^8\ \text{m}^3$ to $870.30 \times 10^8\ \text{m}^3$, with the area enlargement from $1927.48\ \text{km}^2$ to $2015.35\ \text{km}^2$ from 1976 to 2009, and the lake growth with great changing rate during 1999–2006, which are quite consistent with climate change trend. The monitoring results also show that the water storage increased from March, and reached the largest amount in late September and early October, then began to decrease up to December each year, which corresponds to the lake level change recorded at the Nam Co station.
- Trends in meteorological variables were studied. The annual mean air temperature and annual precipitation trended upwardsat the 1% and 10% significant levels respectively, while the evaporation on the lake trended downward at the 0.1% significant level in the Nam Co basin. Climate change was the main factor contributing to variations in lake water storage. The analysis of water storage supply also provides further evidence of lake growth as a proxy indicator of climate change in these permafrost highland lakes.

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