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RESEARCH ARTICLE

ICESat/GLAS-derived changes in the water level of Hulun Lake, Inner Mongolia, from 2003 to 2009

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Abstract Hulun Lake is the largest freshwater lake in northern Inner Mongolia and even minor changes in its level may have major effects on the ecology of the lake and the surrounding area. In this study, we used high-precision elevation data for the interval from 2003–2009 measured by the Geoscience Laser Altimetry System (GLAS) on board the Ice, Cloud, and land Elevation Satellite (ICESat) to assess annual and seasonal water level variations of Hulun Lake. The altimetry data of 32 satellite tracks were processed using the RANdom SAmple Consensus algorithm (RANSAC) to eliminate elevation outliers, and subsequently the Normalized Difference Water Index (NDWI) was used to delineate the area of the lake. From 2003–2009, the shoreline of Hulun Lake retreated westwards, which was especially notable in the southern part of the lake. There was only a small decrease in water level, from 530.72 m to 529.22 m during 2003–2009, an average rate of 0.08 m/yr. The area of the lake decreased at a rate of 49.52 km^2/yr, which was mainly the result of the shallow bathymetry in the southern part of the basin. The decrease in area was initially rapid, then much slower, and finally rapid again. Generally, the lake extent and water level decreased due to higher temperatures, intense evaporation, low precipitation, and decreasing runoff. And their fluctuations were caused by a decrease in intra-annual temperature, evaporation, and a slight increase in precipitation. Overall, a combination of factors related to climate change were responsible for the variations of the water level of Hulun Lake during the study interval. The results improve our understanding of the impact of climate change on Hulun Lake and may facilitate the formulation of response strategies.

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1 Introduction

Climate change may have significant effect on terrestrial hydrology, including alteration of the surface water budget (Song et al., 2014). Inland lakes, especially those in arid and semi-arid areas, are especially sensitive to change in their water budget (Leira and Cantonati, 2008; Zhang et al., 2015). Lake water level monitoring is one approach towards increasing our understanding of terrestrial hydrological cycles, potentially enabling effective appropriate water resource management policies to be formulated (Liu et al., 2009). In addition, studies of past and ongoing lake level changes provide information about climate variability (Bracht-Flyr et al., 2013). Lake level responses to climate changes are likely to vary on a case-by-case basis, or even within specific areas of an individual large lake.

Hulun Lake, the fifth largest lake in China, is located in the marginal area of the East Asian monsoon in the northeastern Inner Mongolia Autonomous Region (Li and Tana, 2014). The lake is an important water source for the adjacent wetlands and is essential for maintaining the stability and biodiversity of the regional ecosystem. For example, 241 bird species have been recorded at the site, including cranes, gulls, swans, wild geese, ducks, and lovebirds (Zhao et al., 2008; Gu et al., 2012), some of which are unique to the region. The number of bird species amounts to one fifth of the total bird species in China. Accordingly, the ecological importance and biodiversity of Hulun Lake have attracted significant scientific attention. Overall, research has focused on three major areas: 1) Quaternary paleolimnology and paleoclimate (Xue et al., 2003; Xiao et al., 2004, 2006, 2008, 2009; Wen et al., 2010; Zhai et al., 2011; Jiang et al., 2014; Cui et al., 2015); 2) water quality (Zhao et al., 2007; Bai et al., 2008; Wang et al., 2015); and 3) changes in water volume related to climatic variability (Zhao et al., 2008; Gu et al., 2012; Wang et al., 2012b; Li and Tana, 2014; Zhang et al., 2015).

Lake level changes are a useful proxy for climatic variability on annual to centennial time-scales. However, they are not easy to measure with sufficient accuracy. In addition, water gauge data are not publicly accessible in China (Wang et al., 2013). Moreover, the vast area and remote location of Hulun Lake mean that hydrological gauge observations and quantitative estimates of water levels are sparse and insufficient for proper scientific evaluation. Consequently, several studies have used remote sensing data to measure the lake area and water levels. For example, Sun (2010) and Li et al. (2013) used the visible bands of Landsat images to calculate the water depth along the lake margin and combined the results with gauged water depths to generate a three-dimensional bathymetric model, which has improved our understanding of the seasonal hydrodynamics of the lake water. Wang et al. (2012a) calculated volumetric changes of the lake water by using the area calculated from Landsat imagery and the ASTER Global DEM. Wu et al. (2013) used Landsat MSS/TM/ETM+ and HJ–1A images to map the dynamics of the wetlands of Hulun Lake. These studies concluded that the area of Hulun Lake has been decreasing for the past 36 years. Chu et al. (2005) used the JASON-1 altimeter to analyze water level changes of Hulun Lake. Satellite-based laser altimetry data from ICESat/GLAS offers unprecedented accuracy for lake water level measurements at the global scale (Li et al., 2011a) and have been widely applied in lake water level research (Zhang et al., 2011; Priyeshu et al., 2013; Wang et al., 2013). For flat surfaces such as those of lakes, the ranging accuracy of ICESat/GLAS data can be up to 3 cm (Li et al., 2011b), which is sufficient to detect seasonal or annual water level fluctuations.

Detailed mapping of the changes in the area and level of Hulun Lake is vital for understanding the response of the lake to climate and anthropogenic changes. However, the number and scope of past studies of Hulun Lake are insufficient given its importance in sustaining regional ecosystem stability and biodiversity. The main aims of the present study are (i) to select the appropriate water body delineation method to derive the Hulun Lake boundary, (ii) to choose inliers for analyzing water level change by generation and assessment of a database using the ICESat/GLAS altimetry data, and (iii) to link water level fluctuations to climate changes.

2 Study area

Hulun Lake (116°58′–117°48′E and 48°31′–49°20′N), also known as Dalai Lake, is situated in the Hulun Buir Grassland in the Inner Mongolia Autonomous Region of China. It is the fifth largest lake in China. The lake area is 2339 km^2 (Fig. 1), with a maximum depth of 8 m and a mean depth of 5–6 m (An et al., 2012; Zhai et al., 2013). The climate of the area is semi-arid continental due to the blocking effect of the Great Xingan Mountains on the passage of moist air from the ocean to the Mongolian Plateau. The lake is fed by year-round precipitation and melt water from the adjacent mountains and supplied by inflowing rivers, which include the Crulen, Orshun-Gol and Hailaer Rivers (Huang, 2011). The Crulen River

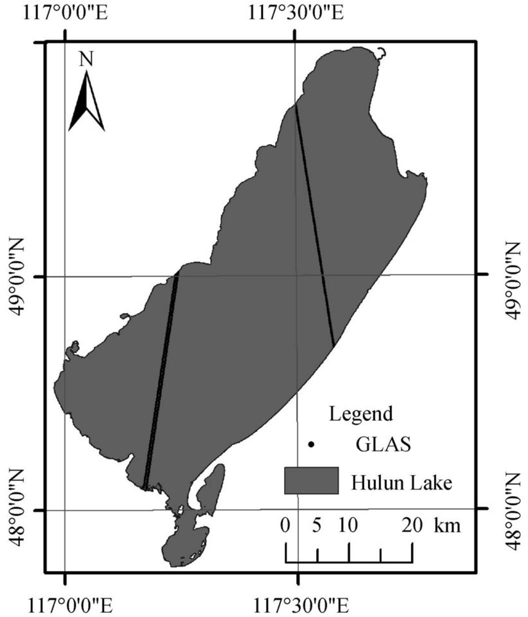

Fig. 1 Hulun Lake in Inner Mongolia, with ICESat satellite tracks superimposed on the map.

originates in Mongolia, the Orshun-Gol River flows from nearby Buir-nur Lake on the Sino-Mongolian border, and the Hailaer River drains the eastern part of the Hulun Basin.

3 Data and methods

3.1 Data requirements

3.1.1 ICESat/GLAS

ICESat (Ice, Cloud, and land Elevation Satellite) is the benchmark Earth Observing System mission for measuring ice sheet mass balance, cloud and aerosol heights, as well as land topography and vegetation characteristics. It was the first space-borne laser altimetry satellite orbiting the earth. From 2003 to 2009, the ICESat mission provided repetitive elevation data that are crucial for determining ice sheet mass balance as well as cloud property information, especially for stratospheric clouds common over polar areas. It also provides global topography and vegetation structure data, in addition to polar-specific coverage over the Greenland and Antarctic ice sheets.

The Geoscience Laser Altimeter System (GLAS) includes a laser system to measure distance, a Global Positioning System (GPS) receiver, and a star-tracker attitude determination system. It operates at a frequency of 40 Hz with two channels, infrared light (1064 nm wavelength) and visible green light (532 nm). The 1064 nm channel is used to measure the elevation of land, ice sheets, sea ice and ocean (Abshire et al., 2005). The accuracy and precision of GLAS for altimetry are about 14 cm and 2 cm, respectively (Zwally et al., 2002). The GLAS footprints are about 70 m in diameter and 170 m apart along the satellite tracks.

ICESat data is distributed by the National Snow and Ice Data Center (NSIDC). GLAS produces 16 data products including Levels 1A, 1B, and two laser altimetry and atmospheric Lidar datasets. Tools for extracting and visualizing the GLAS data are made available from the NSIDC website. In the present study we used the GLAS product GLA14 data. Excluding the outliers, there were 32 tracks of water level points located in the Hulun Lake area for the interval from 2003 to 2009.

3.1.2 Delineating the lake boundary from Landsat images

The Landsat 5 Thematic Mapper (TM) and Landsat 7 Enhanced Thematic Mapper Plus images were obtained from the USGS Landsat archive. Cloud-free images coincident with the ICESat tracks were identified and processed (Table 1).

3.1.3 Meteorological data

The three closest weather stations to Hulun Lake were identified from the China Meteorological Database (http://cdc.nmic.cn/home.do). They provide continuous meteorological records, including annual and monthly mean precipitation, temperature, and evaporation (Table 2).

3.2 Methods

The methodologies and data flows are summarized and illustrated in Fig. 2. The main methods used include the RANdom Sample Consensus (RANSAC, Fischler and Bolles, 1981) algorithm for outlier removal, Normalized Difference Water Index (NDWI) for water boundary delineation (McFeeters, 1996), and a linear regression for the climate data (Eric et al., 2015).

Table 1 Landsat images used in this study

Number	Day of Acquisition	Satellites	Sensor	Orbit number
1	2003-05-23	Landsat-7	ETM +	125–26
2	2004-06-11	Landsat-7	ETM +	124–26
3	2005-09-02	Landsat4-5	TM	124–26
4	2006-10-23	Landsat4-5	TM	124–26
5	2007-10-01	Landsat4-5	TM	125–26
6	2008-08-25	Landsat4-5	TM	124–26
7	2009-08-12	Landsat4-5	TM	124–26

Table 2 Meteorological stations used in this study

Station	Longitude/(°)	Latitude/(°)	Altitude/m
New Barag Right Banner	116.82	48.67	554.2
New Barag Left Banner	118.27	48.22	642
Manzhouli City	117.43	49.57	661.7

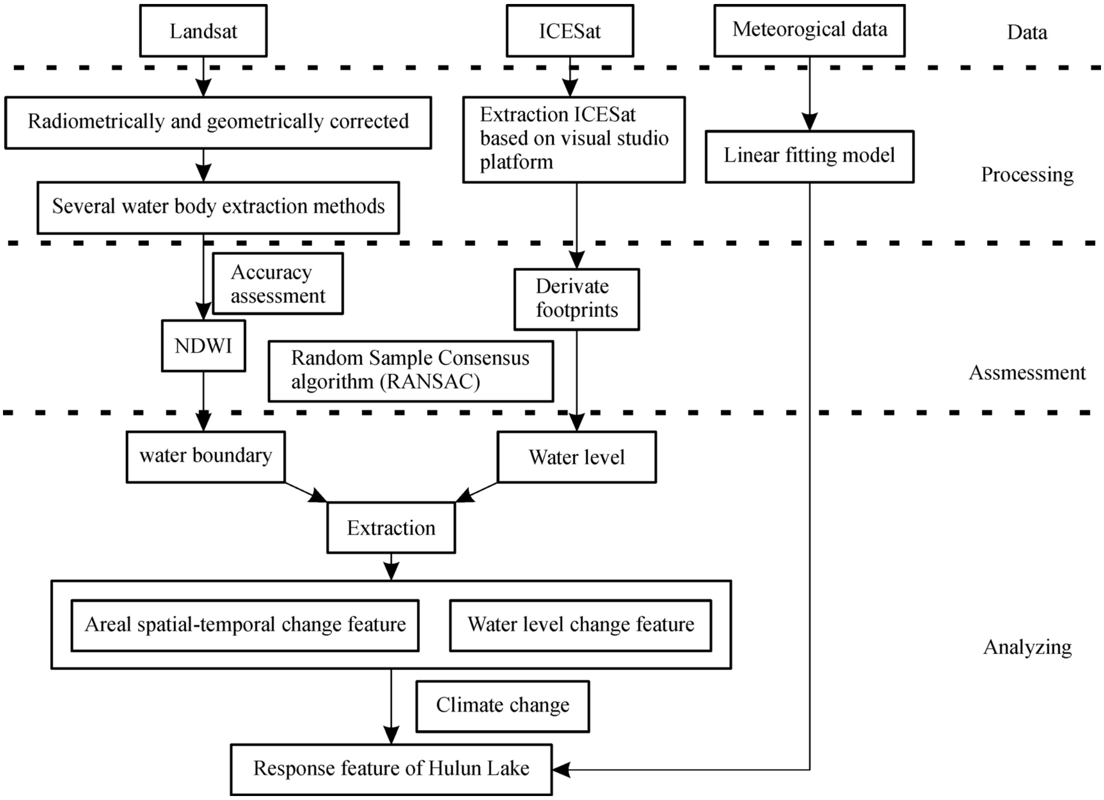

Fig. 2 Data processing flow chart.

3.2.1 Landsat image processing

The Landsat images were radiometrically calibrated to at-satellite reflectance. Then, image-to-image georeferencing was performed on all images to ensure locational accuracy. The SLC-off Landsat ETM+ images were repaired using the method given in Vivek et al. (2015).

We tested several water extraction techniques, including the single band threshold algorithm (SBTA) (Frazier and Page, 2000), the multi-spectral integrated analysis method (MSIAM) (Zhou et al., 1999), Normalized Difference Water Index (NDWI), Modified Normalized Difference Water Index (MNDWI) (Du et al., 2016), and Normalized Difference Vegetation Index (NDVI) (Gong et al., 2015). For all methods, the maximum variance between clusters was used to acquire the optimal thresholds. The accuracy assessment indicated that the NDWI method provided the best overall accuracy and Kappa coefficient (Taylor et al., 2011) (Table 3). Thus, NDWI was determined to be the most suitable method for discriminating water and other features in the Hulun Lake area.

NDWI was used to obtain the lake boundaries. In addition, an accuracy assessment of the various methods was undertaken to determine the most suitable extraction method for the study site. ICESat data tracks were obtained using a program coded on the Visual Studio platform and RANSAC to distinguish the inliers and outliers (excluded data), and were extracted together with the water boundary to obtain the water level for the entire lake. Finally, an in-depth analysis was conducted to reveal the spatiotemporal features of the lake area and water level and their response to climate change. A detailed flow chart of the processing methodology is shown in Fig. 2.

3.2.2 Extracting lake water level from GLAS data

Although the GLAS data has high precision and accuracy, uncertainties resulting from the large footprint and atmo-

Table 3 Accuracy assessment of the water body extraction method

	SBTA	MSIAM	NDWI	MNDWI	NDVI
Overall accuracy	0.914	0.970	0.975	0.959	0.965
Kappa	0.828	0.940	0.950	0.918	0.930

spheric interference could still potentially bias the quantitative analysis. Therefore, we used RANSAC (Fischler and Bolles, 1981) algorithm to remove the influence of outliers. The RANSAC algorithm is a learning algorithm that uses random sampling of the data to classify the data elements as outliers (noise data) and inliers (consensus set). The algorithm was implemented in Visual Studio and the ArcGIS platform. A 10-cm threshold was used as the parameter for RANSAC to determine an outlier. With all outliers removed, the mean lake water level was calculated for each ICESat track. Then, a trend line was fitted to the water levels from 2003 to 2009.

4 Results

4.1 Changes in the area of Hulun Lake

Figure 3 illustrates the changes in the total area of Hulun Lake during the study interval. The lake area decreased dramatically from 2003 to 2009, with the largest changes occurring on the south coast of the lake, which is characterized by relatively flat terrain (Zhao, 1992). In 2009 the bay in the southern part of the lake almost dried up and caused a regression of the aquatic plants and an interruption of the swamp deposition process. This result is consistent with that of Sun (2010), who also found that the recent shrinking of Hulun Lake was mainly manifested in the southern part of lake with shallow bathymetry.

The changes in the area of Hulun Lake from 2003 to 2009 are illustrated in Fig. 4. The trend is linear with an R^2 of 0.97. A piecewise regression with three phases was also used: 2003 to 2006 (phase I), 2006 to 2007 (phase II), and 2007 to 2009 (phase III). During phase I the area of Hulun Lake decreased from 2071.54 km^2 in 2003 to 1882.21 km^2 in 2006. The area was relatively stable during phase II. During phase III, the area decreased sharply to a minimum in 2009. The changes in the observed area are consistent with the results of Sun (2010). The average rate of decrease in area from 2003–2009 was 49.52 km^2/yr, about one-third of the rate from 1975 to 2009 as reported by Wang et al. (2012a).

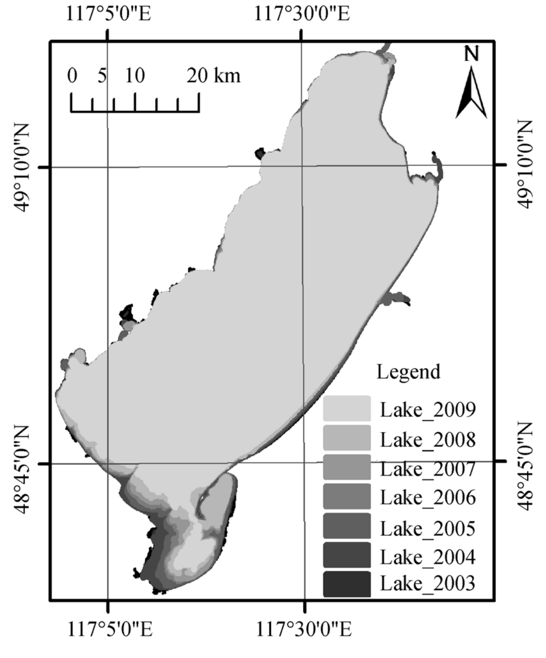

Fig. 3 Changes in the coastline of Hulun Lake from 2003 to 2009.

4.2 Changes in the water level of Hulun Lake

A time series of water level change from 2003 to 2009, based on ICESat/GLAS data, is shown in Fig. 5. The water level decreased from 530.72 m in 2003 to 529.22 m in 2009. In addition, there is an obvious intra-annual pattern of seasonal water level fluctuations, with decreases in summer and increases in winter. This is consistent with the findings of Wang et al. (2013).

Overall, the rate of decrease in water level was relatively low during the study interval, with an average rate of 0.08 m/yr ($R^2 = 0.6$). However, a rate of decrease of 0.424 m/yr between 1999 and 2006 was reported by Zhao et al. (2008), who suggested that several severe droughts had caused the sharp decrease in water level. This inconsistency with the results of our analysis may suggest that during the interval of concern (2003−2009), the loss of water was not as great as it was from 1999 to 2003. This may be the result of the protection measures introduced by the Chinese government, such as the Hulun Water Resources Management and Environmental Protection Project in 2006, despite the drying up of the Kherlen River originating from Outer Mongolia in 2007. Seasonally, the water level was low in winter and high in summer. Flake ice typically occurs during the last ten days of October, and the entire lake

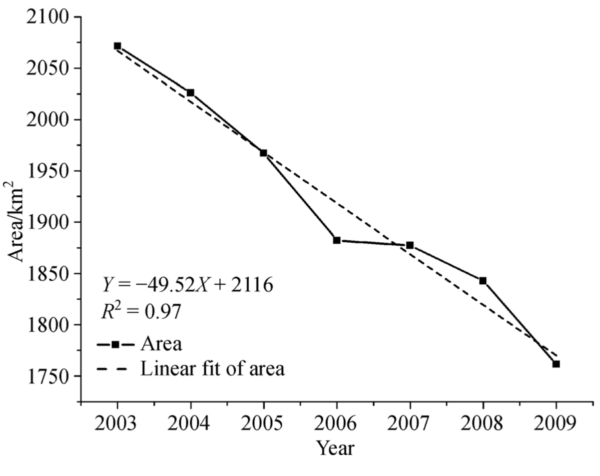

Fig. 4 Changes in the area of Hulun Lake from 2003−2009.

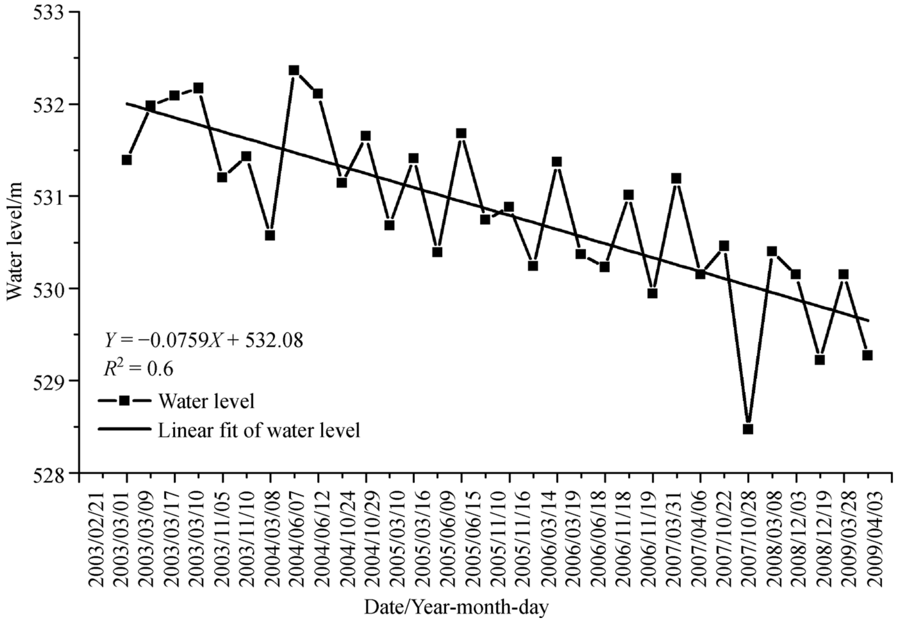

Fig. 5 Water level changes of Hulun Lake from 2003 to 2009.

surface would normally freeze at the beginning of November (Chu et al., 2005).

5 Discussion

5.1 The use of RANSAC in the applications of ICESat/GLAS data

Due to an unexpected fitting error in the waveform of the GLAS data, some outliers may exist in the data and therefore the RANSAC algorithm (Phan et al., 2012) was applied to remove the outliers. The lake water level is regarded as a gentle slope along an ICESat track. Using the RANSAC algorithm, a line was repeatedly fitted through a random subset of points and the remaining points were classified as inliers and outliers depending on their distance to the regression line. A point is considered an inlier if its distance to the fitted line is within a predefined threshold. If sufficient outliers are identified, the iterations will cease. In this study, the threshold value used to define a point as an outlier was about 10 cm, corresponding to the GLAS vertical accuracy reported in Schutz et al. (2002), in which a 1° surface slope was assumed. The final line and the corresponding outliers and inliers of the ICESat track at Hulun Lake are illustrated in Fig. 6. There were several extreme outliers that would have biased the water level retrieval if they were not excluded. Therefore, we highly recommend the use of RANSAC with the application of GLAS elevation data. Our tests showed that the algorithm is not sensitive to the selection of the threshold, providing it is within a reasonable range, e.g., the reported vertical accuracy of GLAS (14 cm).

5.2 Response of Hulun Lake to climate change

5.2.1 Temperature

All three meteorological stations exhibit similar changes in annual mean temperature from 1959 to 2014, and the annual mean temperature around Hulun Lake was about −0.97°C to 1.36°C during this interval. Based on the data provided by the meteorological stations, the annual temperature exhibits a slightly increasing trend from 1959 to 1980 (Fig. 7(a)) and a drastic decrease from 2007 to 2009. Coincidently, during 2007 to 2009, the area of Hulun Lake increased slightly, despite the reduced water supply from the inflowing rivers.

Figure 7(b) shows that the average monthly temperature fluctuated considerably during the cold season. In the cold season, the lake was frozen and the surrounding areas were snow-covered due to the low temperatures, which may have contributed to the water level increase in 2007. Therefore, temperature is a contributing factor for the water level change; specifically, higher temperatures tend to reduce the lake area. In addition, the high frequency of occurrence of extreme high temperatures during the 1999 to 2005 interval (Bai et al., 2008), together with the overall high annual temperature, may have contributed to the loss of water from Hulun Lake from 2003 to 2006. Consistent with previous studies, temperature is significantly negatively correlated with the area of Hulun Lake. An increase of 1°C might reduce the lake area by 80 km^2 a year. It can be further deduced that the increasing number of extreme high temperature events during 1961 to 2010 (Bai et al., 2014) may have contributed to the long-term decrease in water level.

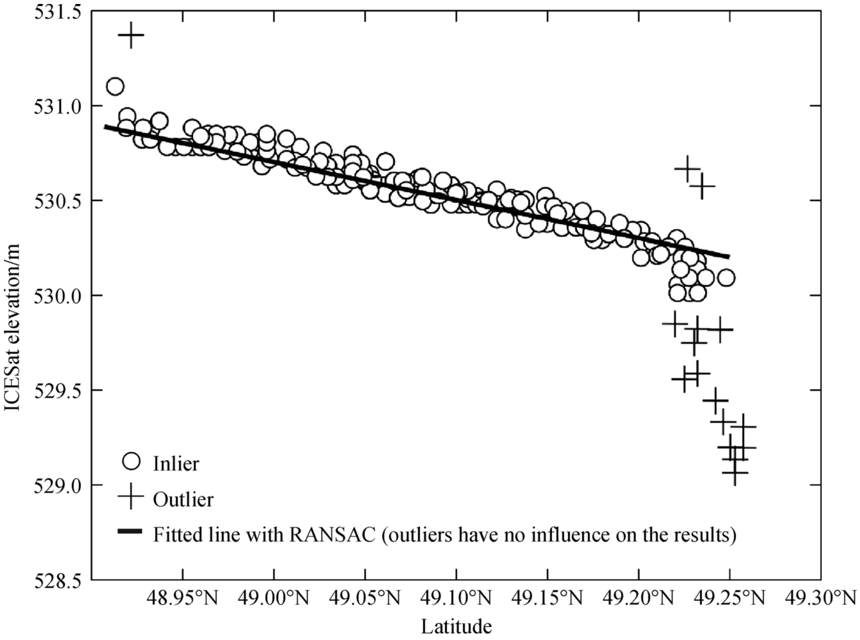

Fig. 6 RANSAC test for ICESat/GLAS data.

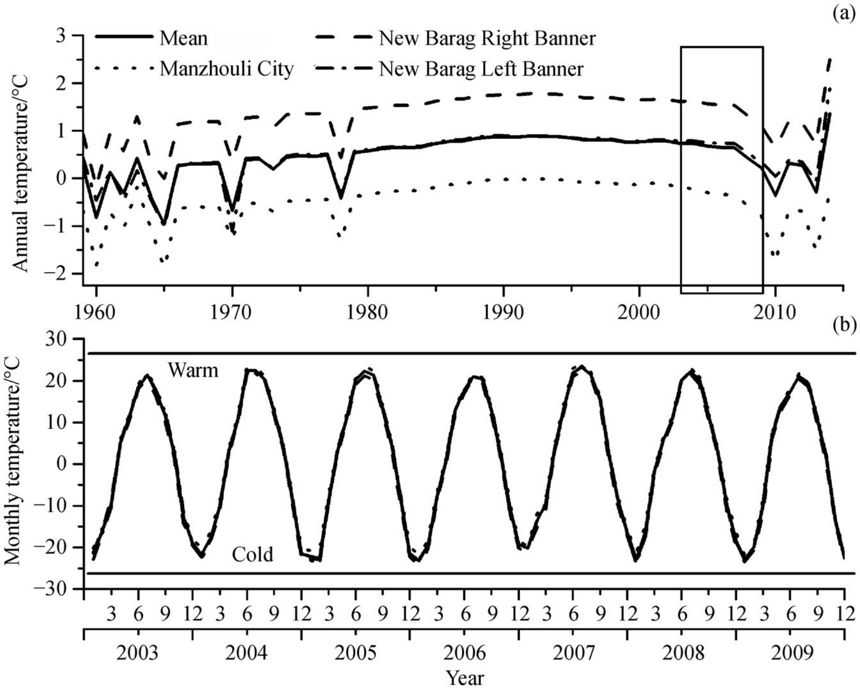

Fig. 7 Temperature change in the vicinity of Hulun Lake.

5.2.2 Precipitation

The range of mean annual precipitation around Hulun Lake during the study interval was approximately 137.87 mm/yr to 590.1 mm/yr (Fig. 8). Precipitation varied significantly within different intervals: minor fluctuations from 1959 to 1980, large fluctuations from 1981 to 2000, minor fluctuations from 2001 to 2010, and large fluctuations from 2011 to 2014. Precipitation during the 2003 to 2009 period showed a decreasing trend, while the water level of Hulun Lake decreased. This co-occurrence is consistent with previous findings that decreasing precipitation has

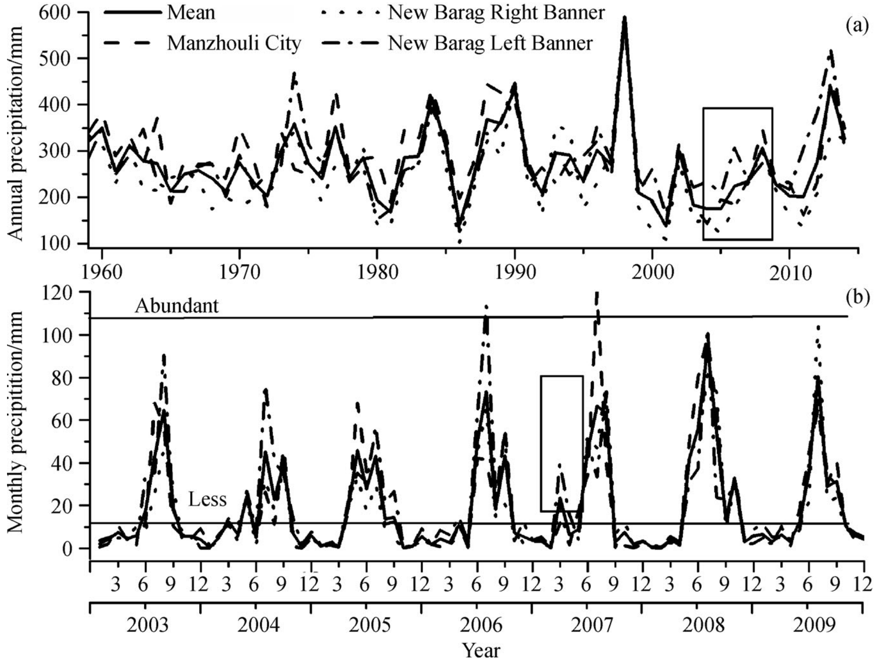

Fig. 8 Precipitation in the vicinity of Hulun Lake from 2003 to 2009.

contributed to the water level decrease (Zhao et al., 2007; Wang et al., 2013). The precipitation during the wet season (April to October) from 2006 to 2009 was much greater than the average. Winter is relatively dry and the precipitation is relatively constant; however, 2007 was an exception in which the precipitation was much greater than during the other years, which may have contributed to the slight increase in the lake area. Moreover, from 1961 to 2010, extreme precipitation events in Inner Mongolia (Bai et al., 2014) (extreme precipitation, maximum five-day precipitation and maximum one-day precipitation) exhibited decreasing trends. This may be a key factor responsible for the long-term decrease in the water level of Hulun Lake.

5.2.3 Evaporation

There are several meteorological stations around Hulun Lake recording evaporation from January to April and from October to December during the interval from 2003 to 2009 (Fig. 9(a)). In Fig. 9(a), it can be seen that highest evaporation occurred in spring and lowest in autumn and winter. There was an increase in the annual minimum values of evaporation from 2003 to 2009. Zhao et al. (2007) found that evaporation in Hulun Buir wetland was greater in autumn and winter than in spring. Due to the lack of continuous evaporation data, we calculated the sum of evaporation for 7 months within a year and reference it hereafter as the cumulative evaporation. Cumulative evaporation was the lowest in 2007 and 2009 (Fig. 9(b)), which corresponded to a slight increase in the lake area.

5.2.4 Runoff

Runoff contributes both directly and indirectly to lake water recharge and therefore it is one of the primary factors influencing lake level and lake level change (Wang et al., 2012b). Wang et al. (2012b) found that decreases in the water level of Hulun Lake were mainly the result of shifts to a drier climate, 90% of the effects of which was related to changes in runoff. Runoff around Hulun Lake decreased greatly from 1961 to 2008 (Gu et al., 2012), and the main inflows (Kherlen River and Wuerxun River) dried up several times after 2000 (Huang, 2011). Wang et al. (2012a) concluded that the main cause of the decrease in water level of Hulun Lake after 1999 was the decrease in runoff from Kerulen River and Wuerxun River. In 2003, the runoff to Hulun Lake had decreased to less than 5×10^8 m^3/yr (Wang et al., 2013). Thus, the decrease in runoff recharge was a major contributing factor to the water level change of Hulun Lake during the study interval.

6 Conclusions

In this study, high-precision elevation data measured by the Geoscience Laser Altimetry System (GLAS) onboard the Ice, Cloud, and land Elevation Satellite (ICESat) were used to assess annual and seasonal variations in the water level of Hulun Lake from 2003 to 2009. A trend of decreasing water level during this interval was observed, which may have been caused by high temperatures during the same interval. However, a slight decrease in intra-annual

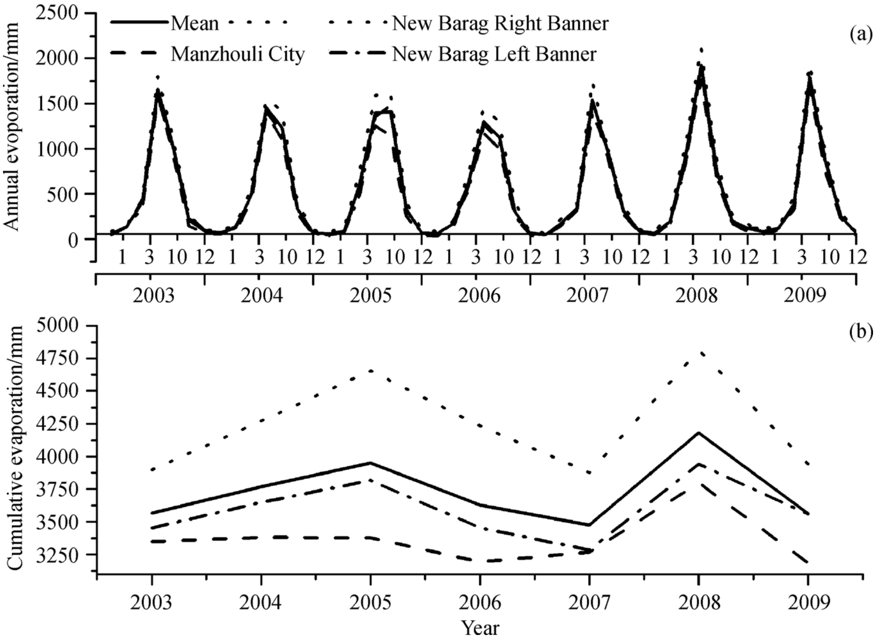

Fig. 9 Cumulative and annual evaporation for the Hulun Lake area from 2003 to 2009.

temperatures could have caused the water level to increase slightly between 2007 and 2009. Long-term low precipitation may have caused the decrease in water level, while high precipitation during low rainfall periods could have contributed to the increase in the area of the lake in 2007. Low cumulative evaporation may be an additional reason for the slight increases in water level evident in 2007 and 2009. Therefore, increased temperature and evaporation, and decreased precipitation, were the major factors responsible for the decrease in the water level of Hulun Lake. Decreased runoff may be an additional reason for the decreased water level.

ICESat/GLAS data have already been extensively used for studies of lake-level change, especially in the case of lakes with steeply sloping margins where changes in area may not be obvious. In the present study, based on ICESat/GLAS data and Landsat data, trends in water level and area change of Hulun Lake were calculated. Some degree of bias in monitoring water level may be inevitable since the footprints do not cover the same track, meaning that a biasing effect of the mean value cannot be avoided. Even though the changes in mean water level can be used to represent water level change to some extent, it cannot reflect the actual change. Valuable information was lost due to the deviation between the mean value and the actual data. In addition, some intra-annual fluctuations in water level cannot be detected because of the limited observations from ICESat/GLAS. Therefore, it is difficult to fully understand and analyze the changes in the water level of the lake. Smaller lakes and fewer footprints were unavailable as the ICESat/GLAS tracks did not pass over all lakes and cover all areas. However, the method can be used for the detailed monitoring of large and moderate-sized lakes. In the present study, the meteorological data may be another source of uncertainty because the meteorological stations were not located at Hulun Lake. Using monitored data to analyze lake level changes may lead to a decrease in precision. Moreover, temperature and evaporation affect each other and are not completely independent. In addition, this study is only able to provide qualitative and semi-quantitative explanations for the water level changes, and further research is needed to assess the contribution of different factors to the water level changes of specific lakes to provide an optimum basis for future environmental management decisions.

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References

Abshire J B, Sun X, Riris H, Sirota J M, McGarry J F, Palm S, Yi D, Liiva P (2005). Geoscience Laser Altimeter (GLAS) on the ICESat Mission: on-orbit measurement performance. Geophys Res Lett, 32 (21): L21S02

An X P, Du Z H, Zhang J H, Li Y P, Qi J W (2012). Structure of the zooplankton community in Hulun Lake, China. Procedia Environmental Sciences, 13: 1099–1109

Bai M L, Hao R Q, Li X C, Yang J (2014). Variable characteristics of extreme climate events during 1961−2010 in Inner Mongolia. Arid Meteorology, 32(2): 189–193 (in Chinese)

Bai M L, Hao R Q, Shen J G (2008). Effects of climatic change on eco-environment in HuLunHu Lake Area in last 46 years. J Desert Res, 28(1): 101–107 (in Chinese)

Bracht-Flyr B, Istanbulluoglu E, Fritz S C (2013). A hydro-climatological lake classification model and its evaluation using global data. J Hydrol (Amst), 486: 376–383

Chu Y H, Li J C, Jiang W P, Zhang Y (2005). Monitoring of water level variations of Hulun lake with JASON-1 altimetric data. Journal of geodesy and geodynamics, 25(4): 11–16 (in Chinese)

Cui X Y, Yang J, Hao J X, Bu T G, Liu Z G (2015). The formation of history and change of Hulu Lake. Inner Mongolia Science Technology and Economy, (1): 43–47 (in Chinese)

Du Y, Zhang Y H, Ling F, Wang Q M, Li W B, Li X D (2016). Water bodies' mapping from sentinel-2 imagery with modified normalized difference water index at 10-m spatial resolution produced by sharpening the SWIR band. Remote Sens, 354(8): 1–19

Eric M, Li J, Joksimovic D (2015). Performance evaluation of low impact development practices using linear regression. British Journal of Environment and Climate Change, 5(2): 78–90

Fischler M A, Bolles R C (1981). Random sample consensus: a paradigm for model fitting with applications to image analysis and automated cartography. Commun ACM, 24(6): 381–395

Frazier P S, Page K J (2000). Water body detection and delineation with Landsat TM data. Photogramm Eng Remote Sensing, 66(12): 1461–1467

Gautam V K, Gaurav P K, Murugan P, Annadurai M (2015). Assessment of surface water dynamics in bangalore using WRI, NDWI, MNDWI, supervised classification and K-T transformation. Aquatic Procedia, (4): 739–746

Gong Z, Kawamura K, Ishikawa N, Goto M, Wulan T, Alateng D, Yin T, Ito Y (2015). MODIS normalized difference vegetation index (NDVI) and vegetation phenology dynamics in the Inner Mongolia grassland. Solid Earth, 6(4): 1185–1194

Gu R Y, Li S H, Zhao H Y, Li C, Song W S, Meng J, Wang Y P (2012). Responses of runoff in Hulun lake basin of Inner Mongolia to climate change. Chinese Journal of Ecology, 31(6): 1517–1524 (in Chinese)

Huang J (2011). Stochastic analysis of hydrological time series based on wavelet theory in Hulun Basin. Dissertation for Master Degree. Inner Mongolia Agricultural University (in Chinese)

Jiang Z F, Li C Y, Zhang S (2014). Zooplankton in Hulun Lake and the eutrophication evaluation. Journal of Arid Land Resources and Environment, 28(1): 158–162 (in Chinese)

Leira M, Cantonati M (2008). Effects of water-level fluctuations on lakes: annotated bibliography. Hydrobiologia, 613(1): 171–184

Li C Y, Sun B, Jia K L, Zhang S, Li W P, Shi X H, Cordovil C M D S, Pereira L S (2013). Multi-band remote sensing based retrieval model and 3D analysis of water depth in Hulun Lake, China. Math Comput Model, 58(3–4): 771–781

Li J L, Chen X, Bao A M (2011a). Spatial-temporal characteristics of lake level changes in Central Asia during 2003–2009. Acta Geogr Sin, 66(9): 1219–1229 (in Chinese)

Li J L, Sheng Y W, Luo J C (2011b). Automatic extraction of Himalayan glacial lakes with remote sensing. Journal of Remote Sensing, 15(1): 29–43

Li X R, Tana (2014). Analysis of the relationship between the level of Hulun Lake and meteorological factors. Meteorology Jsournal of Inner Mongolia, (6): 26–28 (in Chinese)

Liu J S, Wang S Y, Yu S M, Yang D, Zhang L (2009). Climate warming and growth of high-elevation inland lakes on the Tibetan Plateau. Global Planet Change, 67(3–4): 209–217

McFeeters S K (1996). The use of the Normalized Difference Water Index (NDWI) in the delineation of Open water features. Int J Remote Sens, 17(7): 1425–1432

Phan V H, Lindenbergh R, Menenti M (2012). ICESat derived elevation changes of Tibetan lakes between 2003 and 2009. Int J Appl Earth Obs Geoinf, 17: 12–22

Priyeshu S, Rakesh B, Prashant K, Dobhal D P (2013). Water level changes of high altitude lakes in Himalaya–Karakoram from ICESat altimetry. J Earth Syst Sci, 6: 1533–1543

Schutz B E, Laser F L, Surface P (2002). Technical Report of Geoscience Laser Altimeter System (GLAS). Center for Space Research, The University of Texas at Austin

Song C, Huang B, Ke L, Richards K S (2014). Seasonal and abrupt changes in the water level of closed lakes on the Tibetan Plateau and implications for climate impacts. J Hydrol (Amst), 514: 131–144

Sun B (2010). The Dynamic Change of Water Based on Spatial Information Technology for Hunlun Lake in Inner Mongolia. Dissertation for PhD Degree. Inner Mongolia Agricultural University (in Chinese)

Taylor S, Kumar L, Reid N (2011). Accuracy comparison of Quickbird, Landsat TM and SPOT 5 imagery for Lantana camara mapping. Journal of Spatial Science, 56(2): 241–252

Wang B, Lv C W, He J (2012a). Spatio-temporal monitoring of Hulun Lake using remote sensing. Environ Sci Technol, 35(9): 94–98

Wang W, Liu L N, Ma L Z, He J (2015). Spatial distributions and environmental implications of diatom assemblages in surface sediments of Hulun Lake, China. Environ Earth Sci, 74(2): 1803–1813

Wang X W, Gong P, Zhao Y Y, Xu Y, Cheng X, Niu Z G, Luo Z C, Huang H B, Sun F D, Li X W (2013). Water-level changes in China's large lakes determined from ICESat/GLAS data. Remote Sens Environ, 132: 131–144

Wang Y P, Zhao H Y, Li C, Song W S (2012b). The review of the relationship with climate change and Hulun Lake wetland. Chinese Agricultural Science Bulletin, 28(8): 300–305 (in Chinese)

Wen R L, Xiao J, Chang Z G, Zhai D Y, Xu Q H, Li Y C, Itoh S, Lomtatidze Z (2010). Holocene precipitation and temperature variations in the East Asian monsoonal margin from pollen data from Hulun Lake in northeastern Inner Mongolia. Quat Res, 73: 293–303

Wu Y A, Pang Z G, Lu J X, Qu W (2013). Dynamic changes of Hulun Lake Wetland area through remote sensing monitoring and driving forces analysis. Journal of China Institute of Water Resources and Hydropower Research, 11(1): 20–26 (in Chinese)

Xiao J L, Chang Z G, Wen R L, Zhai D Y, Itoh S, Lomtatidze Z (2009). Holocene weak monsoon intervals indicated by low lake levels at Hulun Lake in the monsoonal margin region of northeastern Inner Mongolia. China. Holocene, 19(6): 899–908

Xiao J L, Si B, Zhai D Y, Itoh S, Lomtatidze Z (2008). Hydrology of Dali Lake in centraleastern Inner Mongolia and Holocene East Asian monsoon variability. J Paleolimnol, 40(1): 519–528

Xiao J L, Wu J T, Si B, Liang W D, Nakamura T, Liu B L, Inouchi Y (2006). Holocene climate changes in the monsoon/arid transition reflected by carbon concentration in Daihai Lake of Inner Mongolia. Holocene, 16(4): 551–560

Xiao J L, Xu Q H, Nakamura T, Yang X L, Liang W D, Inouchi Y (2004). Holocene vegetation variation in the Daihai Lake region of north-central China: a direct indication of the Asian monsoon climatic history. Quat Sci Rev, 23(14−15): 1669–1679

Xue B, Qu W C, Wang S M, Ma Y, Dickman D (2003). Lake level changes documented by sediment properties and diatom of Hulun Lake, China since the late Glacial. Hydrobiologia, 498(1/3): 133–141

Zhai D Y, Xiao J L, Fan J W, Zhou L, Wen R L, Pang Q Q (2013). Spatial heterogeneity of the population age structure of the ostracode *Limnocythere inopinata* in Hulun Lake, Inner Mongolia and its implications. Hydrobiologia, 716: 29–46

Zhai D Y, Xiao J L, Zhou L, Wen R L, Chang Z G, Wang X, Jin X D, Pang Q Q, Itoh S (2011). Holocene East Asian monsoon variation inferred species assemblage and shell chemistry of the ostracodes from Hulun Lake, Inner Mongolia. Quat Res, 75(03): 512–522

Zhang G Q, Xie H J, Kang S C, Yi D H, Ackley S F (2011). Monitoring lake level changes on the Tibetan Plateau using ICESat altimetry data (2003−2009). Remote Sens Environ, 115(7): 1733–1742

Zhang N, Wu L J, Liu S T, Dou H S, Li J (2015). The characteristics of climate change and its influence on water area of Hulun Lake. Journal of Arid Land Resources and Environment, 29(7): 192–197 (in Chinese)

Zhao F L (1992). Hulun Buir Union Hydrology. Inner Mongolia Culture Press (in Chinese)

Zhao H Y, Li C C, Zhao H H, Tian H C, Song Q W, Kou Z Q (2007). The climate change and its effect on the water environment in the Hulun Lake wetland. Journal of Glaciology and Geocryology, 29(5): 795–801 (in Chinese)

Zhao H Y, Wu L J, Hao W J (2008). Influences of climate change to ecological and environmental evolvement in the Hulun Lake wetland and its surrounding areas. Acta Ecol Sin, 28(3): 1064–1071 (in Chinese)

Zhou C H, Luo J C, Yang X M (1999). Geo-understanding and Analysis of Remote Sensing Images. Beijing: Science and Technology Press (in Chinese)

Zwally J, Schutz B, Abdalati W, Abshire J, Bentley C, Brenner A, Bufton J, Dezio J, Hancock D, Harding D, Herring T, Minster B, Quinn K, Palm S, Spinhirne J, Thomas R (2002). ICESat's laser measurements of polar ice, atmosphere, ocean and land. J Geodyn, 34 (3–4): 405–445