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Water-level changes in China's large lakes determined from ICESat/GLAS data

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ABSTRACT

Water-level changes from 56 of the 100 largest lakes in China were derived from ICESat/GLAS data during the period of 2003 to 2009. An automated method for determining the trend of water-level change had been proposed in this study. Lake water footprints were first identified from the ICESat/GLAS GLA14 data product. Water level change was then determined from the footprints over lake water in each campaign. Trend of water-level changes was fitted with a line for each lake. Trends of water level changes from ICESat/GLAS matched well with gauge measurements in both Qinghai Lake and Nam Co. Our results showed that the trend of water-level change varied from −0.51 m/a to 0.62 m/a. Eighteen lakes showed a decreasing trend of water-level change and 38 lakes showed an increasing trend. Most lakes in Qinghai–Tibet Plateau showed an increasing trend which was probably caused by snow or glacier melts under climate warming. However, most lakes in the Yarlung Zangbu River basin showed a decreasing trend presumably resulting from intensified evaporation caused by climate warming and intensified western wind in the winter. Desertification and aggravated soil erosion in this region contributed to water level decrease. Lakes in northern Inner-Mongolia and Xinjiang and Northeast Plain of China showed decreasing trends with precipitation reduction and warming as the most probable reasons. Water consumption for agricultural use also contributed to water-level decrease in lakes of those regions. Lakes in East China Plain fluctuated presumably because most lakes were greatly affected by inflows of Yangtze River and human activities. Lakes in Yunnan–Guizhou Plateau also fluctuated. There were no obvious changes in climate warming or precipitation in this region.

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1. Introduction

Global change affects water resources around the world in generally unknown ways (Green et al., 2011). It was reported that global mean surface air temperature is expected to increase about 2.0–4.5 °C by 2100 (IPCC, 2007). Under global warming, total glacier areas have shrunk about 5.5% over the past 45 years in China (Li et al., 2008) and permafrost degraded greatly in China (Jin et al., 2000). These processes could greatly affect water resource distribution. Lakes as primary water reservoirs play important roles in water supply and adjustment (Lehner & Döll., 2004). Area of lakes can be monitored with remotely sensed data (Gong, 2012). However, water level in lakes is an important parameter in water volume estimation and its adequate and accurate measurements could be difficult especially in remote regions (Wang et al., 2012b). Because water level is sensitive to regional climatic variations on a time-scale of years to hundreds of years, it is regarded as a viable and interesting proxy of climate changes (Ponchaut & Cazenave, 1998; Vincent, 2009). Traditionally, water-level changes in lakes were derived from gauge data (Mercier et al., 2002). For a specific lake, the trend of water-level change could be derived from continuous observation data. However some lakes, particularly in remote areas and developing countries, do not have routine in situ measurements of water level (Chipman & Lillesand, 2007). In China, water gauge data are not publicly accessible.

When spaceborne radar altimeters became available, they had been used in the detection of water-level changes since the 1990s. Ponchaut and Cazenave (1998) derived lake water-level changes in three American great lakes (Superior, Michigan and Huron) and three African lakes (Tanganyika, Malawi and Turkana) based on 4 years' altimetry data from Topex/Poseidon. Other studies about lake water-level measurement with radar altimetry data include Mercier et al. (2002), Hwang et al. (2005, 2011), Zhang et al. (2006), Chipman and Lillesand (2007) and Crétaux and Birkett (2006). However, because of the relatively

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large footprint in radar altimetry data, that are on the order of a few hundred meters for 20 Hz data (e.g. 375 m for Jason-2 footprints) to a few km for 1 Hz data depending on surface attributes (water/land; smooth or rough) (Phan et al., 2012; Wang et al., 2011), its application to smaller water bodies was limited.

After the first Earth-orbiting laser altimetry satellite ICESat (Ice, Cloud and land Elevation Satellite) was launched in 2003, ICESat/GLAS (Geoscience Laser Altimetry System) demonstrated its promise in the study of lake water-level changes. Although due to instrument limitations, ICESat/GLAS lake measurements are only available during some campaign periods, and spanning over 5 years, GLAS' fine footprints (72 m) allow water level measurements over smaller water bodies. Urban et al. (2008) derived water elevation changes in Lake Pontchartrain, Louisiana, USA with ICESat/GLAS data and the result agreed well with gauge data. Abdallah et al. (2011) applied autocorrelation to improve the assessment of ICESat altimetry accuracy on water level. In China, trends of lake water-level changes are not previously available at the national scale. Phan et al. (2012), Zhang et al. (2011b), Zhang et al. (2011c) derived lake water-level changes on Qinghai–Tibet Plateau based on ICESat/GLAS data. However, the study area focused only on Qinghai–Tibet Plateau. In this paper, we estimate the trend of water-level change of large lakes in China in order to address such questions as by how much water levels of major lakes in China have changed and the speculation on reasons for these changes.

2. ICESat/GLAS

ICESat was a scientific satellite launched by NASA (National Aeronautics and Space Administration) in January 2003 with a primary objective to measure changes in ice sheet elevation and sea ice freeboard (Abdalati et al., 2010; Schutz et al., 2005; Shuman et al., 2006; Zwally et al., 2002). It was the first space-borne laser altimetry satellite orbiting the earth. It operated at an orbit of about 600 km and had a geographical coverage from 86°S to 86°N. GLAS onboard ICESat is the primary sensor and it worked at a frequency of 40 Hz with two channels, 532 nm and 1064 nm. The 1064 nm channel was used to measure elevation in land, ice sheet, sea ice and ocean (Abshire et al., 2005). The accuracy and precision of GLAS for altimetry are about 14 cm and 2 cm (Zwally et al., 2002). Laser footprints on the ground are about 72 m in diameter at about 172 m interval (sampling at 40 Hz) along the sub-satellite track. ICESat/GLAS observed two or three times a year from 2003 to 2009 and 19 campaigns (the duration of each campaign is about 30 days, Fig. 1) data has been obtained (Wang et al., 2011). 15 types of GLAS data product were produced for scientific uses, named as GLA01, GLA02, …, GLA15 (http://nsidc.org/data/icesat/data.html).

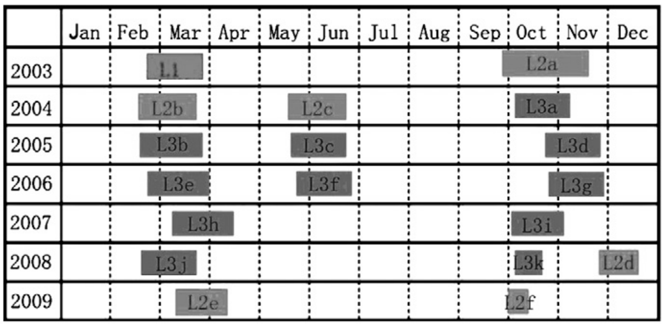

Fig. 1. Missions of ICESat/GLAS. Different colors stand for different lasers, red: Laser 1, pink: Laser 2, blue: Laser 3 and the lengths of the bars show the durations of different missions. There are a total of 18 color bars and L1a (20 February 2003 to 21 March 2003) and L1b (21 March 2003 to 29 March 2003) are shown as one bar L1 (Wang et al., 2011).

3. Method

GLA14 (the global land surface altimetry data) Release 31 was selected for this study and it contains 95 different parameters in a record of different situations. In this section, GLAS data were first preprocessed and then Lake Water Footprint (LWF) was identified. Next, the slope of along track height ('*A*' in Section 3.3) was calculated for each track. Finally the trend of lake water-level change was fitted as a line with the least squares method if available data were enough (with observations from more than 6 campaigns). In the process, Maima Co Lake on Qinghai–Tibet Plateau was taken as an example. Maima Co Lake (Figs. 2a,b, 6) is located in 33°30′–34°40′ N, 80°40′–83°30′ E. It is surrounded by many glaciers with an annual average temperature of 0–1 °C. The highest temperature is about 22 °C and the coldest temperature is about −35 °C. Here wetlands are formed and more than 100 rivers merge into wetlands with glacier melt as the primary supply (Li, 1989; Zhang et al., 2011c). GLA14 data covering Maima Co Lake are from 14 different campaigns from 2003 to 2009, which are shown in Fig. 2a,b.

3.1. Data preprocessing

In the first step, high quality data were selected (Fig. 3). Because the 1064 nm channel is influenced by cloud and saturation, laser footprints need to be preprocessed for subsequent use. Ten parameters from GLA14 data and the method proposed by Wang et al. (2012b) were used in this process, with which footprints theoretically impossible could be excluded and footprints saturated could be corrected. Fig. 2d shows both original and saturation corrected elevations from campaign L3i. The footprints over Maima Co Lake in that campaign were highly saturated. Most *i_satElevCorr* (land surface elevation not considering waveform saturation) were more than 1 m. Therefore data from L3i were excluded.

3.2. Lake water footprint identification

In the second step, LWF was identified for subsequent use (Fig. 3). LWF is defined as the footprints illuminating lake water surface and it used to be extracted by overlay of lake-boundary polygons and GLAS observation data. This required a lake-boundary data derived nearly during the same time of GLAS observation because of lake-boundary changes with rainfall or constant evaporation. Additionally, LWF influenced by cloud or saturation cannot be excluded with this method.

Wang et al. (2012b) developed an automatic and robust method to identify LWF. Six parameters from GLA14 file were used to form an LWF identification algorithm, which were number of peaks in a waveform, elevation difference from adjacent footprints, waveform width, reflectivity, skewness and kurtosis. In GLAS observations, LWF was identified in case of the waveform width less than 6.5 m, only one peak, elevation difference less than 0.22 m, reflectivity less than 0.8, kurtosis between −1.51 and 3.99 and skewness between −1.18 and 1.02 (Fig. 4). Under this algorithm of LWF identification, high quality data could be obtained (Wang et al., 2012b). Fig. 2b shows the distribution of footprints from ICESat/GLAS and Fig. 2c shows the LWF after identification. The identification result was good when taking the Landsat ETM+ imagery acquired on January 20, 2003 as the reference, with only three misclassified footprints from offshore land (Fig. 2c), which demonstrates the effectiveness of this identification algorithm.

3.3. Slope calculation

In the third step, slope of along-track height was fitted for each track (Fig. 3). For a specific lake, from 2003 to 2009, there may be about 11 campaign observations. Lake footprints may be unavailable for some campaigns because of poor data quality caused by cloud

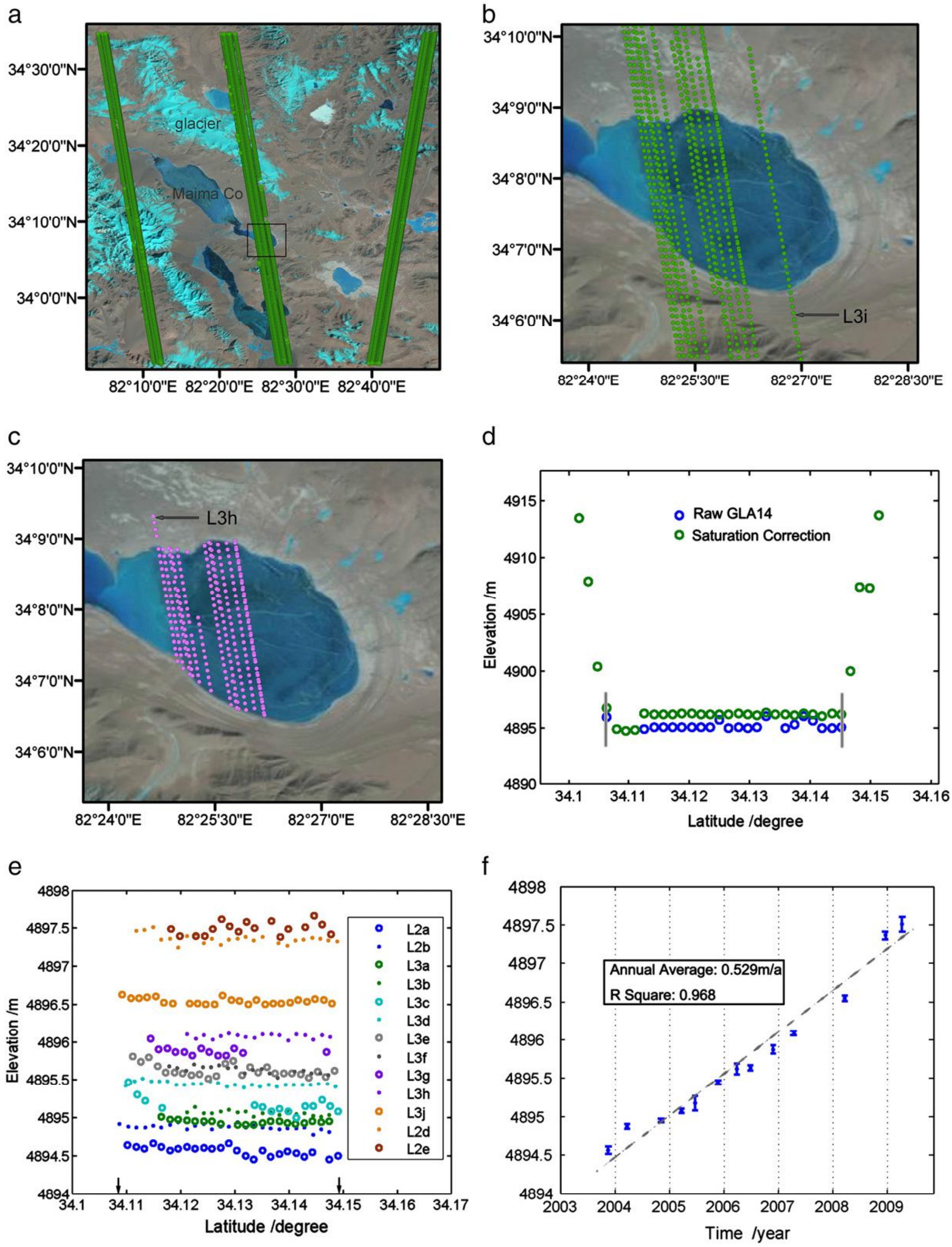

Fig. 2. Maima Co Lake was taken as an example to illustrate the method. (a): location of Maima Co Lake and GLA14 data from 2003 to 2009. The background imagery was from Landsat ETM+ acquired on January 20, 2003 and the green circles are locations of GLAS footprints. (b): Zooming in of the rectangular area in figure a. (c): distribution of lake water footprints after identification. (d) Saturation correction of GLA14 data from Campaign L3i (not shown in figure c). (e): Elevation of lake water surface from selected GLA14 data. The two vertical lines with a downward arrow indicate the location of two ends for elevation interpolation. (f) Lake water-level change trend derivation of Maima Co Lake. Figure e and f have the same Y-axis.

effect or having highly saturated waveforms. The number of LWF depends on the width of water surface and ICESat/GLAS ground track settings. After LWF identification, available footprints may be sparse and not so continuous in space (Fig. 2c). Additionally, lake water surface is the gradient from GLAS altimetry data (Urban et al., 2008). Therefore for LWF from a specific campaign, we fitted an equation of water surface elevation versus geographical latitude coordinate (Eq. 1). The slope '*A*' and intercept '*B*' were derived as well. If

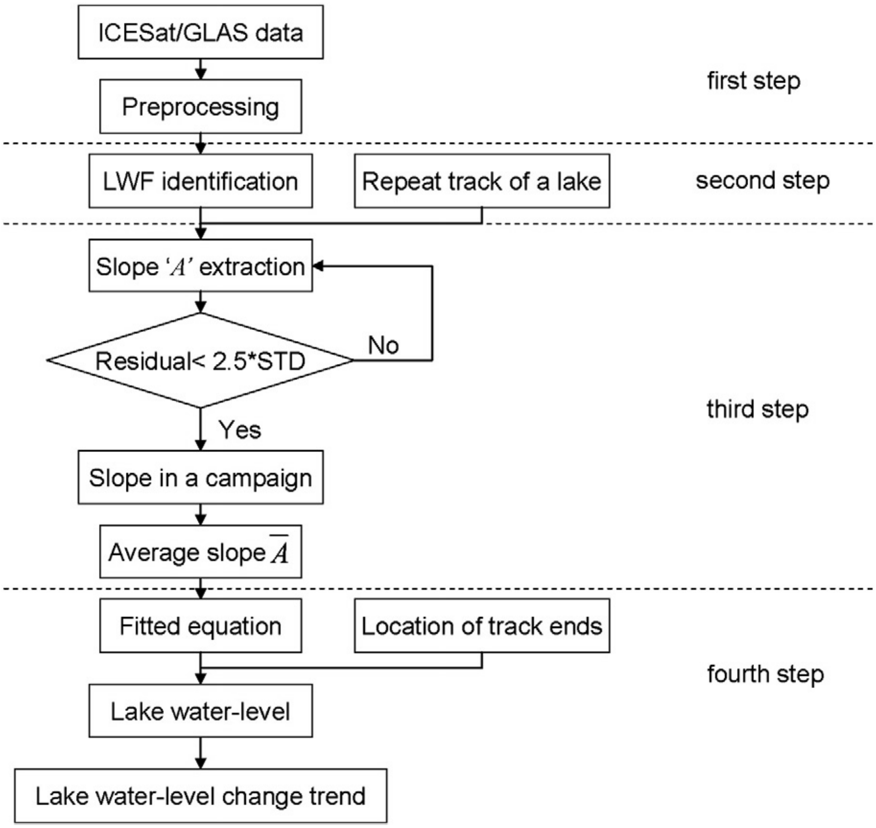

Fig. 3. Flowchart of water-level change trend calculation. STD is the standard deviation of the residuals. LWF is the acronym of Lake Water Footprint. Slope is '*A*' in Eq. (1).

there were GLAS observations from several repeat tracks, only data from tracks with more observation campaigns were used.

$$H = A \cdot \psi + B \quad (1)$$

where, '*H*' is the elevation of ICESat/GLAS, '*A*' is the slope, '*B*' is intercept, 'ψ' is latitude, '·' means multiplication.

Standard deviation of residual was calculated as well. Footprints with absolute value of residual exceeding 2.5 times of standard deviations were taken as abnormal data. Iterating calculation would not stop until all the residuals fulfilling our setting. Additionally, footprints from each track with a standard deviation of residual exceeding 0.20 m were abandoned. Fig. 2e shows the elevation of LWF covering Maima Co Lake from all available campaigns from 2003 to 2009. By iterative calculation, some misclassified LWF covering offshore land were

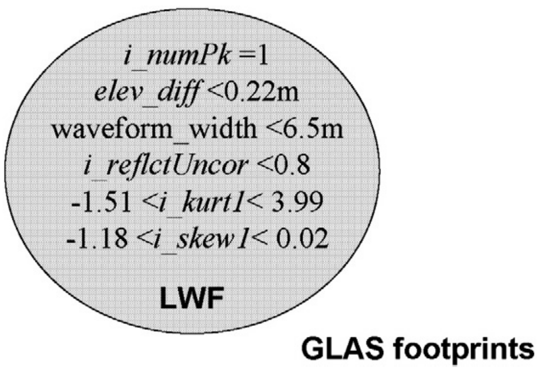

Fig. 4. Algorithm of lake water footprints (LWF) identification from all the footprints. '*elev_diff*' is the elevation difference between adjacent footprints along track. 'waveform_width' is calculated by subtracting *i_SigBegOff* from *i_SigEndOff* (Wang et al., 2012b).

excluded because of their greater elevation (the three misclassified footprints from offshore land from campaign L3h in Fig. 2c did not appear in Fig. 2e).

Finally, mean slope '$\overline{A}$' was derived (Fig. 3). Slope '*A*' and intercept '*B*' of water level were calculated with each track as a unit and the slopes should be almost the same for repeat tracks from different campaigns. Slope '*A*' is a small value close to zero. So we continued to calculate a mean slope '$\overline{A}$' as the final slope of Eq. (1).

3.4. Lake water-level trend calculation

Boundary in the latitude direction of LWF from different campaigns could be derived from statistics of all the footprints. The locations of both maximum and minimum were taken as ends (Fig. 2e). Elevation on both ends of repeat tracks was used to calculate an elevation according to the fitted slope '$\overline{A}$' in Eq. (1). The mean of the first and the second end values for each track was taken as the lake water level at a specific campaign.

The tendency of a specific lake was fitted as a linear trend of elevations versus time from different campaigns with the least squares method by Eq. (2). The dashed gray line in Fig. 2f shows the final fitted trend. R^2 is 0.968 for Maima Co Lake, which shows the lake water level was increasing almost linearly from 2003 to 2009.

$$E = trd \cdot date + b \quad (2)$$

where '*E*' is elevation of lakes, '*trd*' is the annual average trend of water-level changes, '*date*' is the observation time and '*b*' is the intercept.

4. Validation of ICESat/GLAS-derived result by lake gauge data

In order to validate our results, in situ gauge data from Qinghai Lake and Nam Co Lake were taken from Zhang et al. (2011b) and Zhang et al. (2011c) to make comparisons with the water-level results obtained from GLAS data. The locations of Qinghai Lake (36° 32′ N to 37° 15′ N, 99° 36′ E to 100° 47′ E) and Nam Co Lake (30° 30′ N to 30° 54′ N, 90° 16′ E to 91° 03′ E) are identified in Fig. 6. Gauge data are in different elevation systems with ICESat elevation. In order to compare the trend of water-level changes, an offset needs to be eliminated to make these data comparable. The offsets between ICESat derived water level and gauge data (water level from ICESat/GLAS subtracting gauge data) were calculated with the least squares method. For Qinghai Lake and Namco Lake the offsets are 44.020 m and −4690.20 m, respectively. After removing the offset, the water level data from ICESat/GLAS and gauge were plotted in Fig. 5. For Qinghai Lake, the difference varies from −0.13 m to 0.12 m with a standard deviation of 0.09 m. For Namco Lake it varies from −0.07 m to 0.06 m with a standard deviation of 0.07 m. These indicate good agreement between the trend of water level changes from ICESat/GLAS and that of gauge data. Although there are three campaigns at most for ICESat/GLAS each year, intra-annual trends of water-level changes could be reflected clearly, especially for Nam Co Lake. The fluctuation of water-level from ICESat/GLAS shows a clear and regular trend of intra-annual change trend.

5. Results

We initially tried to study water-level changes over the 100 largest lakes in China (Ma et al., 2010). Their distributions are shown in Fig. 6.

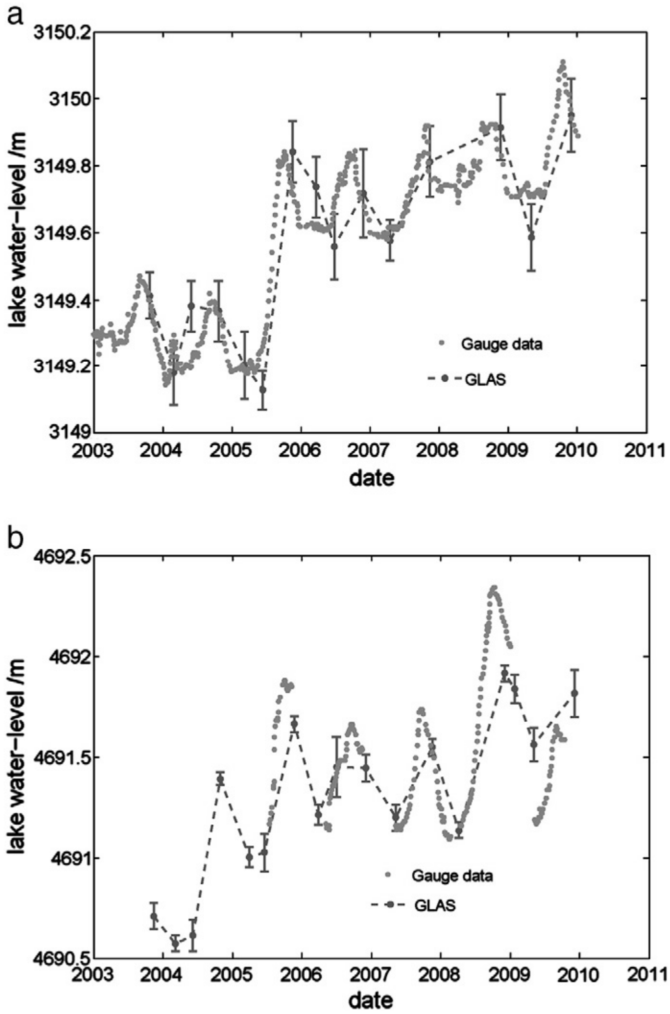

Fig. 5. Gauge data from Qinghai Lake (a) and Nam Co Lake (b). Gray dashed lines are water level from the ICESat/GLAS data and the black points or lines are in situ gauge data. Modified from Zhang et al., 2011b and Zhang et al., 2011c.

After data preprocessing and LWF identification, 44 of the lakes (Fig. 6) were excluded because of lack of GLAS data coverage. There were no ICESat/GLAS data for 37 lakes. Another seven lakes were excluded because of their number of GLAS campaigns being fewer than six. The remaining 56 of them had no less than seven campaigns and water-level trends were determined. The results are shown in Fig. 7 and Table 1.

From Fig. 7 and Table 1 we can see that China could be primarily divided into four parts according to geographical location and trends of water-level change. These are area A (all of Qinghai–Tibet Plateau (QTP) and south of Inner-Mongolia and Xinjiang Plateau (IXP)), area B (North part of China, including most of IXP, as well as NorthEast Plain (NEP)), area C (East China Plain (ECP)) and area D (Yunnan–Guizhou Plateau (YGP)). In area A, most lakes showed an increasing trend of water-level changes from 2003 to 2009. However, lakes in the southeast of QTP showed a decreasing trend. In area B, most lakes showed a decreasing trend. In area C, most lakes fluctuated with low magnitude of changes. In area D, fluctuations in water-level changes were also observed.

In area A, there are 34 lakes with 31 located in QTP and 3 located in IXP (Table 1). Seven lakes showed a decreasing trend while the remaining 27 showed an increasing trend. Among the seven lakes with decreasing trends, only two lakes, Yamzhog Yumco Lake and Peiku Co Lake, had R^2 greater than 0.6. Yamzhog Yumco Lake decreased most obviously with a water-level change of −2.52 m from 2004 to 2009. R^2 from the other five decreasing lakes were all lower than 0.2. These five lakes showed a lower rate of water-level drop (−3 to −6 cm/a).

Among the 27 lakes with increasing trends, only three lakes, Ngangla Ringco Lake, Ringqinyubu Co Lake and Qinghai Lake had R^2 lower than 0.6. Hoh Xil Lake had the most linear trend of water-level change, with R^2 of 0.99. Selin Co Lake had the greatest increase rate with +0.62 m/a. Its water level increased from 4507.00 m in 2004 to 4510.03 m in 2008 (Table 1).

Most of these 34 lakes had more than 10 ICESat/GLAS campaigns. Although the observation campaigns for Hoh Xil Lake and Tu Co Lake were not that many, their R^2 values were high. Generally speaking, most lakes showed an increasing rate of annual change (Table 1).

There are 11 lakes in area B, seven of which showed a decreasing trend with the remaining four showing an increasing trend. Hulun Lake showed the most dramatic decrease with an annual change of −0.396 m/a. Bosten Lake had the second most dramatic decrease. Dali Lake and Bel Lake showed decreasing trend with annual changes between −0.10 m/a and −0.20 m/a. Wuliangsu Hai had a small increasing trend, but the R^2 was 0.63. Those five lakes were with R^2 values greater than 0.60. The remaining seven lakes either decreased or increased with a low rate of annual change (Table 1). Generally speaking, most lakes in area B showed a decreasing trend, especially for those lakes located between 85°E and 125°E (Fig. 7).

In area C, there are 9 lakes which are located in ECP, the middle and lower reaches of Yangtze River. These lakes showed varying annual changes with relatively small R^2, less than 0.40. Poyang Lake had the greatest '$\overline{A}$'. When water level is high at Yangtze River, it takes up water from the river (Hui et al., 2008). Otherwise, it drains into Yangtze River. Meanwhile Poyang Lake had the greatest decreasing trend of annual water-level change. Longgan Lake took the second place. Both of them had an annual change rate of less than −0.20 m/a (Table 1). The annual change rate of water level in the remaining seven lakes was less than 10 cm/a. Their water levels seemed to be almost stable.

In area D, there are only two lakes, Dianchi Lake and Fuxian Lake, located in YGP. From Table 1, we could see that both of these two lakes showed a similar lake slope of along-track height. For Dianchi Lake, the average annual rate of water-level change was −0.02 m/a (Table 1). However, the change was accompanied with a low R^2. Compared with Dianchi Lake, Fuxian Lake showed an increasing trend with a rate of 0.19 m/a (Table 1).

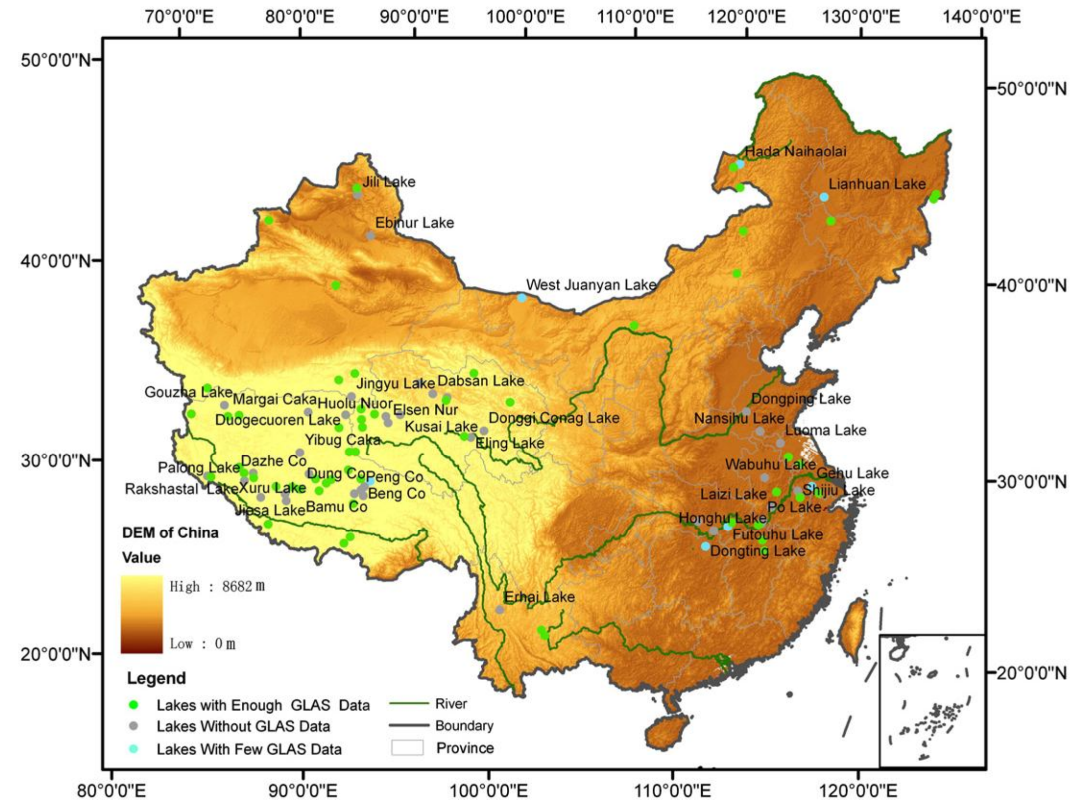

Fig. 6. Locations of the 100 largest lakes in China. The 56 lakes (names not labeled) with enough GLAS data coverage are indicated with green points. The remaining 44 lakes whose names labeled in the figure are not used to derive water-level change. The 37 lakes with no GLAS data coverage are colored in gray. The seven lakes with insufficient GLAS data coverage are colored in cyan.

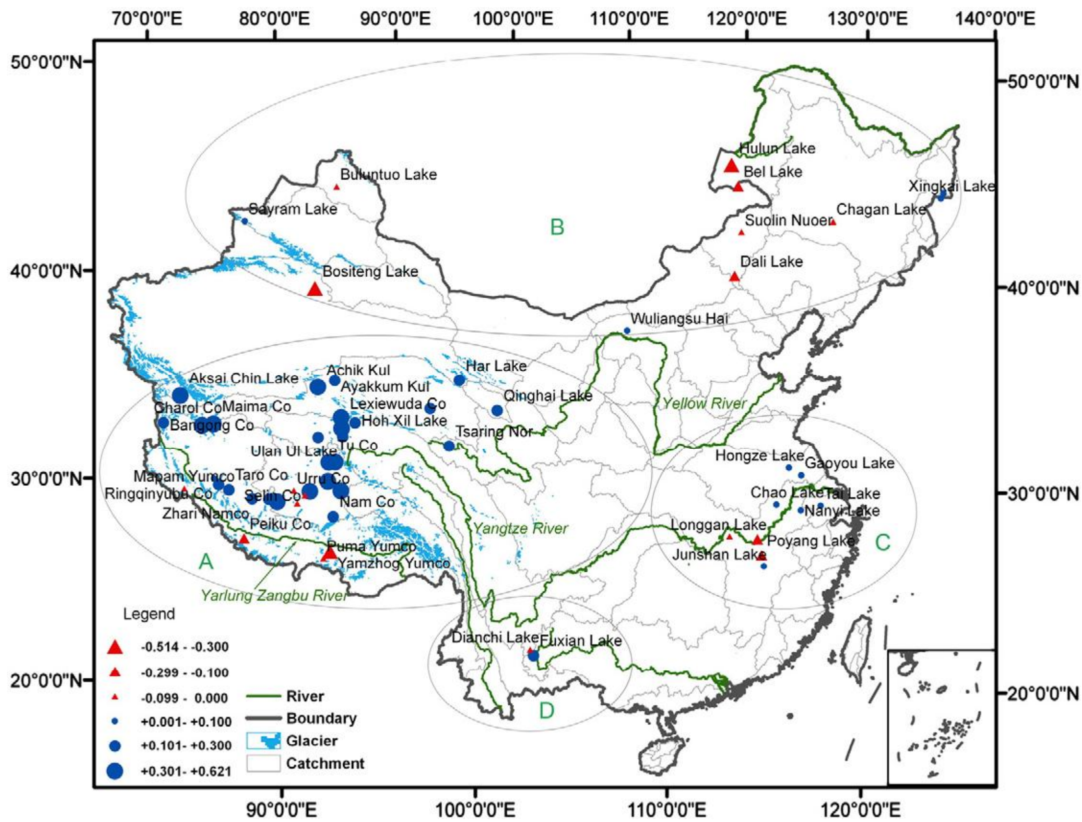

Fig. 7. Trends of water-level change of the 56 large lakes in China from 2003 to 2009 determined from ICESat/GLAS. The gray polygons are catchments. Four gray ellipses demonstrate the four areas (A, B, C and D) of division according to lakes' locations and trends.

Table 1
Result of 56 large lakes in China. The box with dashed line indicates the decreasing trends and other parts indicate increasing part. (QTP: Qinghai–Tibetan Plateau, IXP: Inter–Mongolia and Xinjiang Plateau, NEP: NorthEast Plain, ECP: East China Plain, YGP: Yunnan–Guizhou Plateau).

Area	Region	Lakes	Longitude (°)	Latitude (°)	Area (km^2)	Number of campaigns	Start_date (yyyymmdd)	End_date (yyyymmdd)	Start_elev (m)	End_elev (m)	Trend (m/a)	R^2	'$\overline{A}$' (m/°)
A	QTP	Yamzhog Yumco	90.71	28.96	650.478	14	20040225	20091009	4411.003	4408.481	−0.514	0.856	−5.191
A	QTP	Peiku Co	85.59	28.89	272.952	16	20030228	20090327	4553.01	4552.049	−0.153	0.662	−0.803
A	QTP	Mapam Yumco	81.47	30.69	409.899	17	200 30306	20090325	4563.032	4562.781	−0.056	0.125	−0.858
A	QTP	Puma Yumco	90.39	28.57	294.109	16	20031030	20090322	4983.02	4982.482	−0.04	0.084	−5.702
A	QTP	Nagtasang Co	88.72	31.58	333.753	13	20031116	20090408	4530.471	4530.186	−0.034	0.08	−2.93
A	QTP	Urru Co	88.00	31.71	362.517	13	20031108	20090331	4520.223	4519.565	−0.034	0.028	−1.544
A	QTP	Kyaring Co	88.34	31.12	477.979	15	20031108	20090331	4615.802	4615.158	−0.032	0.028	−4.805
A	QTP	Ngangla Ringco	83.08	31.54	542.889	12	20031105	20081203	4688.559	4688.9	0.081	0.13	−1.246
A	QTP	Ringqinyubu Co	83.45	31.28	188.357	15	20031024	20091008	4733.163	4733.43	0.103	0.442	−2.243
A	QTP	Bangong Co	79.25	33.68	627.187	15	20031021	20091005	4219.819	4220.274	0.106	0.792	0.734
A	QTP	Qinghai Lake	100.20	36.88	4254.900	15	20031018	20091002	3149.412	3149.951	0.107	0.546	−0.398
A	QTP	South Huoluxun Lake	95.83	36.74	167.439	11	20031105	20081204	2627.74	2628.312	0.134	0.83	−8.75
A	QTP	Zhari Namco	85.61	30.93	990.257	12	20030308	20070412	4582.81	4583.666	0.157	0.66	−0.227
A	QTP	Har Lake	97.59	38.29	596.390	13	20040618	20090409	4031.418	4032.069	0.175	0.835	0.811
A	QTP	Nam Co	90.61	30.74	2040.904	17	20031107	20091009	4690.71	4691.816	0.177	0.641	−1.61
A	QTP	Tsaring Nor	97.26	34.93	526.621	10	20031019	20091003	4252.374	4253.77	0.213	0.728	−2.534
A	QTP	Dogai Coring	88.95	34.59	431.355	14	20031026	20091010	4781.508	4782.68	0.234	0.83	−0.174
A	QTP	Tangra Yumco	86.61	31.07	840.825	14	20031023	20090315	4506.757	4508.091	0.277	0.714	−3.494
A	QTP	Hoh Xil Lake	91.14	35.59	315.953	6	20040620	20090411	4846.519	4847.82	0.286	0.994	−3.028
A	QTP	Ulan Ul Lake	90.48	34.81	566.959	13	20031107	20081206	4817.656	4819.054	0.286	0.844	−2.817
A	QTP	Taro Co	84.12	31.14	486.625	13	20031101	20090324	4538.862	4540.081	0.291	0.738	−2.077
A	QTP	Chibuzhang Co	90.26	33.46	515.681	13	20031111	20081209	4897.243	4898.635	0.314	0.807	−1.599
A	QTP	Charol Co	81.62	34.02	356.469	15	20031110	20090402	4786.548	4788.38	0.324	0.857	−1.781
A	QTP	Zige Tangco	90.86	32.08	225.554	13	20031107	20090330	4533.811	4535.675	0.364	0.802	−1.972
A	QTP	Ngangzi Co	87.14	31.02	445.476	12	20031031	20090323	4656.866	4658.989	0.379	0.821	−1.825
A	QTP	Lexiewuda Co	90.20	35.75	247.585	11	20031107	20081206	4830.644	4832.595	0.402	0.929	−2.588
A	QTP	Xijir Ulan Lake	90.34	35.21	373.870	12	20031111	20081209	4732.163	4733.921	0.414	0.845	−3.59
A	QTP	Qixiang Co	89.98	32.45	170.980	15	20031030	20090322	4580.884	4583.097	0.458	0.881	−0.794
A	QTP	Maima Co	82.31	34.22	145.219	13	20031118	20090410	4894.563	4897.509	0.529	0.968	−2.089
A	QTP	Tu Co	89.86	33.40	427.996	8	20040302	20090322	4895.954	4898.573	0.559	0.835	−1.63
A	QTP	Selin Co	88.99	31.81	2129.023	11	20040305	20081201	4507.003	4510.031	0.621	0.893	−1.579
A	IXP	Ayakkum Kul	89.42	37.55	797.010	11	20031026	20091010	3833.458	3834.797	0.251	0.804	2.121
A	IXP	Achik Kul	88.41	37.08	442.620	12	20031022	20090314	4211.747	4213.761	0.395	0.974	−3.868
A	IXP	Aksai Chin Lake	79.84	35.21	185.310	14	20031025	20090317	4824.511	4826.738	0.507	0.839	0.78
B	NEP	Chagan Lake	124.26	45.27	329.500	9	20030307	20090326	140.212	139.953	−0.047	0.436	−1.841
B	NEP	Small Xingkai Lake	132.57	45.34	185.610	9	20031019	20081007	95.046	95.149	0.028	0.197	−0.649
B	NEP	Xingkai Lake	132.29	45.13	1057.020	13	20031023	20091007	93.765	94.183	0.07	0.431	−1.597
B	IXP	Hulun Lake	117.40	48.94	2203.763	12	20040607	20090328	532.125	530.167	−0.396	0.951	−2.178
B	IXP	Bosten Lake	87.04	41.97	1004.330	12	20031116	20090408	986.969	984.994	−0.393	0.934	0.462
B	IXP	Dali Lake	116.64	43.29	202.271	14	20031114	20090406	1220.391	1219.732	−0.17	0.876	−1.77
B	IXP	Bel Lake	117.70	47.81	635.798	13	20031105	20090328	574.169	573.703	−0.12	0.623	−2.063
B	IXP	Buluntuo Lake	87.29	47.26	858.900	15	20031019	20091003	430.567	430.243	−0.081	0.219	3.916
B	IXP	Suolin Nuoer	117.52	45.48	430.808	13	20031028	20090320	816.916	816.786	−0.025	0.233	−9.902
B	IXP	Sayram Lake	81.17	44.60	462.630	12	20031024	20081012	2028.984	2029.241	0.044	0.264	4.256
B	IXP	Wuliangsu Hai	108.85	40.96	306.565	6	20031105	20081203	985.892	986.377	0.073	0.625	−0.719
C	ECP	Poyang Lake	116.28	29.11	3206.980	9	20031115	20090407	6.019	6.32	−0.237	0.113	−14.35
C	ECP	Longgan Lake	116.15	29.95	280.480	10	20031115	20090407	5.883	4.639	−0.206	0.323	0.144

(continued on next page)

Table 1 (*continued*)

Area	Region	Lakes	Longitude (°)	Latitude (°)	Area (km^2)	Number of campaigns	Start_date (yyyymmdd)	End_date (yyyymmdd)	Start_elev (m)	End_elev (m)	Trend (m/a)	R^2	‘$\overline{A}$’ (m/°)
C	ECP	Liangzi Lake	114.51	30.23	351.770	11	20031030	20081018	4.886	3.944	–0.061	0.019	–0.57
C	ECP	Gaoyou Lake	119.29	32.85	639.210	12	20031031	20090324	9.209	8.998	0.004	0.003	0.517
C	ECP	Hongze Lake	118.59	33.31	1663.320	14	20031023	20091008	12.953	13.757	0.03	0.026	0.084
C	ECP	Chao Lake	117.53	31.57	786.010	12	20030310	20 090410	5.109	5.384	0.048	0.053	–0.408
C	ECP	Nanyi Lake	118.96	31.11	197.830	10	20040303	20090324	9.146	10.483	0.05	0.048	2.386
C	ECP	Tai Lake	120.19	31.20	2537.170	11	20031014	20081126	9.257	9.056	0.075	0.153	–1.21
C	ECP	Junshan Lake	116.34	28.53	177.320	7	20031115	20090407	11.289	12.089	0.09	0.122	–1.263
D	YGP	Dianchi Lake	102.69	24.82	300.382	6	20041014	20091010	1855.572	1855.373	–0.022	0.119	–2.807
D	YGP	Fuxian Lake	102.89	24.52	214.539	11	20040227	20091010	1690.311	1691.046	0.193	0.588	–2.73

6. Discussion

6.1. About the method

Zhang et al. (2011c) derived lake water level as a mean elevation of footprints along each track after exclusion of abnormal data. We did not use such a method for the following reasons. First, for a specific campaign, after LWF identification using the method in Wang et al. (2012b), some footprints with poor quality, highly saturated or cloud influenced were excluded. Therefore available footprints covering a specific lake may not be so continuous. Second, slope ‘$\overline{A}$’ in Eq. (1) was a small value close to zero. Slope ‘$\overline{A}$’ could lead to an elevation-difference of several centimeters per kilometer along a GLAS track. Thus the mean elevation taken as water level of a lake may produce an error, particularly when only one half of the continuous footprints covering a lake were available. Under such circumstances, a bias greater or smaller than the actual value of water level would result. From Table 1 we could see that slope ‘$\overline{A}$’ varied from −14.35–+4.26 m/° which could result in an elevation difference of about −1.44–+0.43 m when two footprints are 10 km apart in the latitude direction. In this paper we did not use all the observations covering the specific lake, but only those from tracks with good data coverage. Additionally, iterative calculation in Section 3.3 may exclude some observations. Thus our resulting water level data may be fewer than those used in Zhang et al. (2011c).

After LWF identification, most data from some earlier campaign covering a specific lake, such as L1a, L2a, L3a were excluded because transmitted laser energy were high and highly saturated waveform were produced. Additionally, ICESat/GLAS may observe cloud layer above lakes, which is useless for our calculation. These are why for a specific lake, not all data from different campaigns are available.

6.2. Ratio of R^2 and trend of water-level change

From the 56 large lakes located in China, we can find some general phenomena. The relation between R^2 and trend of water-level change was plotted in Fig. 8. It (Ratio) was calculated by Eq. (3).

$$Ratio = \frac{R^2}{trd} \quad (3)$$

where ‘R^2’ is R^2, ‘*trd*’ is the trend of lake water-level change.

For the 18 lakes with decreasing trends, the average Ratio was −3.25 with a standard deviation of 2.71 (dashed lines in the left portion of Fig. 8). For the remaining 38 lakes with increasing trends, the average Ratio was 3.20 with a standard deviation of 1.96 (dashed line in the right portion of Fig. 8). We can see from Fig. 8, a great value of water-level change trend, increased or decreased, was always accompanied with a great R^2 value. A low magnitude in water-level change was always accompanied with a low R^2 value, i.e. fluctuating. This coincides with our common sense because for the time-series of water-level data, small annual changes can be caused by fluctuation in water elevation around a certain value. However, large annual changes are not dominated by fluctuation but a trend, with a large R^2.

6.3. Reasons for water-level changes

6.3.1. Area A

Area A covers all the QTP and the south part of IXP. According to the Chinese glacier inventory, there are 36,793 existing glaciers with a total area of about 49873.44 km^2 and ice volume of 4561.3857 km^3 (Chen et al., 2011). QTP is the greatest existing glaciation area in low-mid latitude of the world and a gigantic reservoir of fresh water, which can provide 504×10^8 m^3 of water to river runoffs (Liu et al., 2000; Shi, 2005; Yao et al., 2004, 2007). The distribution of these glaciers is shown in Fig. 7. Precipitation, temperature, evaporation, glacier melting and permafrost melting are vital factors influencing water levels of lakes in this region (Lee et al., 2011; Lu et al., 2005).

Most studies showed that the QTP was getting warmer under the background of global warming (Wu et al., 2005). Most lakes in this area are recharged with snow or glacier melts. Therefore, the warming trend in temperature could probably result in more melting of glacier and snow, subsequently leading to rise of water level in lakes. More detailed analysis had been discussed by Zhang et al. (2011a), Zhang et al. (2011b), Zhang et al. (2011c), Shao et al. (2007) and Phan et al. (2012).

Most lakes on QTP show an increasing trend of water-level change. In the Yarlung Zangbu River catchment, all lakes (Mapangyong Co Lake, Peiku Co Lake, Yamzhog Yumco Lake and Puma Yumco Lake in the southeast of QTP in Fig. 7, close to the border of China) showed a decreasing trend of water-level change (Fig. 9). Yarlung Zangbo River, with 14 large branches, is an exorheic river with 10,814 glaciers in its upstream, the greatest number of glaciers over TP (Zhou, 2009). Although there are so many glaciers, most glacier melt may not be kept in the basin but discharged to downstreams. Both Peiku Co and Yamzhog Yumco are salt lakes indicating no direct water injection. The same trend of water from glacier melting caused by continuous warming as the runoff of Yarlung Zangbu River (Liu et al., 2007) demonstrates its contribution to downstreams. Although Mapangyong Co and Puma Yumco are fresh water lakes, glacier and snow melting water may not play an influencing role as primary as those lakes in central QTP. For Mapangyong Co Lake, the precipitation and evaporation are primary factors influencing water level (Ye et al., 2008).

The averaged temperature in this basin increased by about 0.205 °C/10a (Liu et al., 2007). The temperature indices (regional average frequency of cold days, cold nights, coldest day temperature and coldest night temperature) in eastern TP decreased based on weather

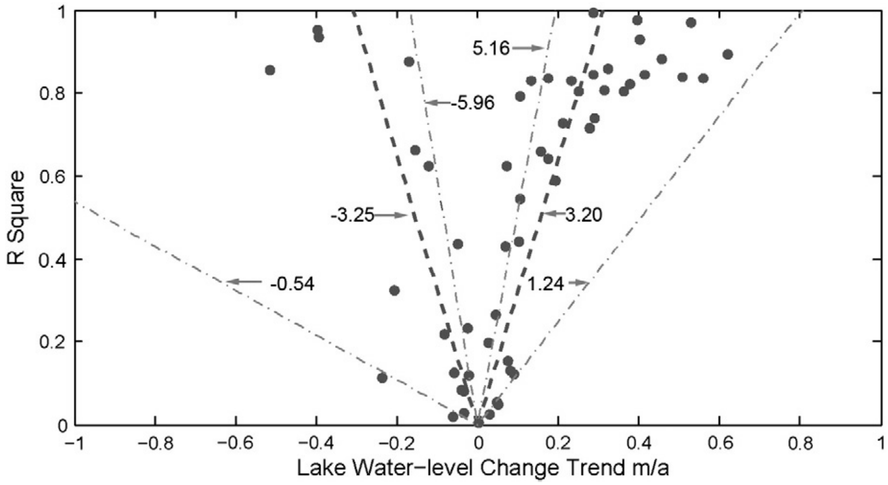

Fig. 8. Ratio between R^2 and trend of water-level changes. The average 'Ratio' of both increasing and decreasing trends is indicated with a dashed black line respectively. The point dashed line mark the location of one standard of mean value respectively.

station data from 1961 to 2008 (Z.X. Li et al., 2011b), indicating continuous warming in this area. The mass balance of glaciers in this area was negative from 2005 to 2008 (Yao et al., 2010). The smaller the glacier was, the more serious was the glacier mass loss. In the long run, glacier melting will decrease as a result of reduced availability in glacier mass (Yao et al., 2010). It was predicted that the snow and glacier melts will come to a peak value in 2040 then decrease in the Yarlung Zangbu River Basin (Zhou, 2009). From Fig. 9 we can see that four lakes in this basin show the same intra-annual patterns while a multi-annual decreasing trend undergoes. Several reasons

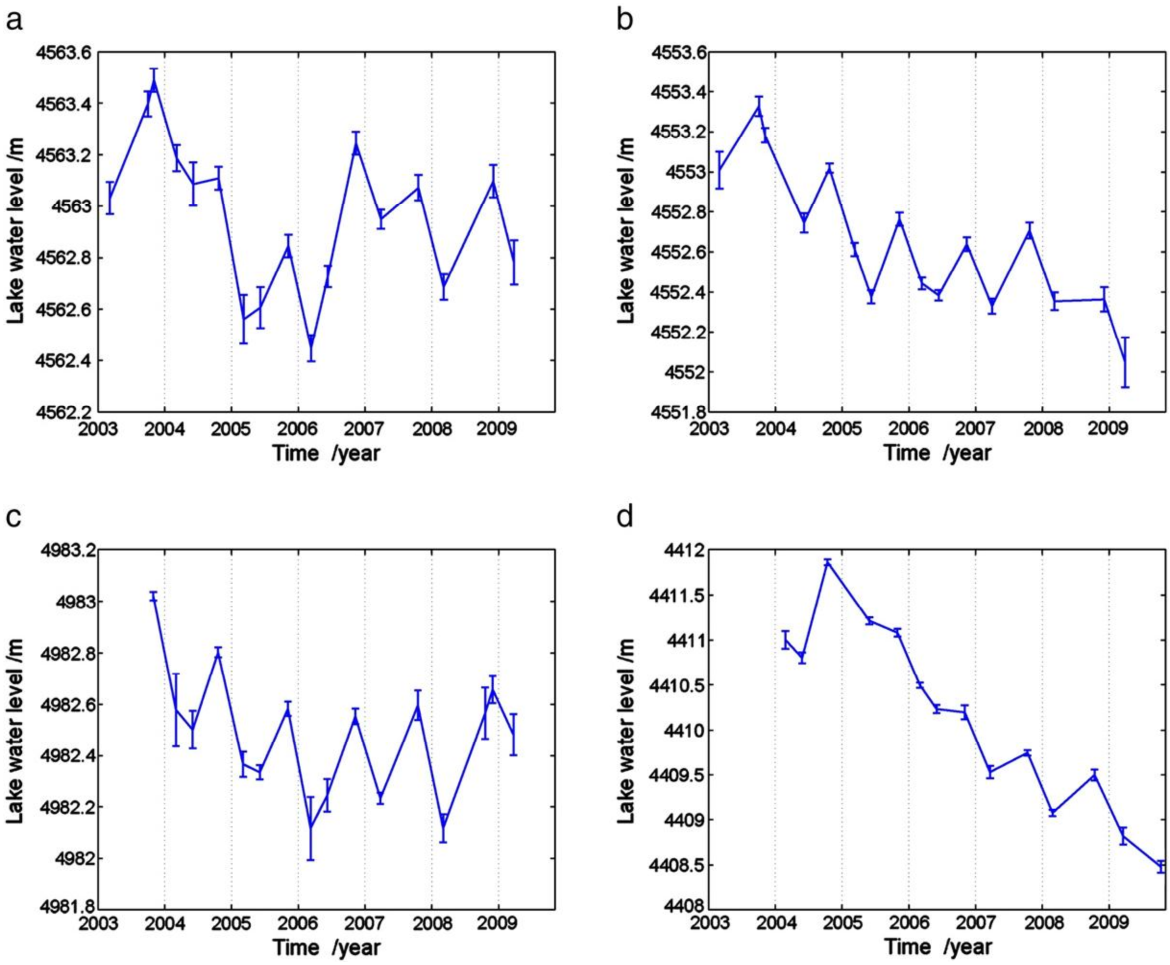

Fig. 9. Water-level change in the Yarlung Zangbu River basin. (a), (b), (c) and (d) correspond to Mapangyong Co Lake, Peiku Co Lake, Puma Yumco Lake and Yamzhog Yumco Lake respectively.

may contribute to the intra-annual pattern and decreasing trend of these four lakes.

(1) Westerly wind circulation: In the winter, QTP was controlled by westerly wind circulation, less precipitation, prevailing westerly wind (Zhou, 2009). The increasing temperature may strengthen evaporation in the winter.
(2) Monsoon: The precipitation was speculated as the major water source for these lakes (Bian et al., 2009; Ye et al., 2008). Yarlung Zangbo River basin was dominated by India southwest monsoon in summer. The rainfall concentrated in summer with river runoff increase in the same time. So rainfall from monsoon could recharge these lakes in the summer. The precipitation varied not as significant as the temperature in east TP from 1961 to 2008 (Z.X. Li et al., 2011b). Therefore, the increase of water level in the summer should not vary much, especially for Peiku Co Lake and Puma Yumco Lake in Fig. 9(b) and (c).
(3) Desertification and aggravated soil erosion: Because of high-cold climate and severely retarding vegetative restoration, Tibet was sensitive to desertification (Yang et al., 2006). From 1999 to 2004, the desertification area expanded by 64,725 km^2 (Wang & Xu, 2007). From 2000 to 2010, the South Tibet was one of the most serious regions in greenness decrease (desertification) from MODIS data (Liu & Gong, 2012). According to Wang (2009), traditional use of biomass had accelerated soil erosion especially in the Yijianglianghe Region (middle area of the Yarlung Zangbo River). The eco-environment in this region did not help to maintain water level but contribute to water-level decrease.
(4) Temperature increases: Although climate warming could produce more melt water from glacier or snow, those melts may not recharge these lakes as described above. Strong evaporation caused by warming temperature contributed to water level decrease. Long sunshine time (Wang, 2009) could make it even worse.

In summary, the trend of water-level increase for most lakes in area A was probably caused by more water recharge from glacier and snow melting and also permafrost degradation (Jin et al., 2000) under climate warming. In Yarlung Zangbo River Basin, the intra-annual decreasing trend of water level in the winter was presumably caused by serious evaporation induced by the warming weather and westerly wind. The intra-annual increase trend of water level in the summer might be caused by rainfall from southwest monsoon. The decreasing trend of water level from 2003 to 2009 might be caused by strong evaporation for warming climate and strong west wind in winter, with desertification and aggravated soil erosion in this region as the local factors. Additionally, the operation of Yamzhog Yumco Pump Storage Power Station might contribute to water-level drop (Zhang et al., 2011c).

6.3.2. Area B

In area B, Hulun Lake showed the greatest decreasing trend in water-level change (Figs. 7 and 10a, Table 1) and there was an intra-annual pattern of water-level decrease in summer and increase in winter, different from findings by Hwang et al. (2005). This could be owing to several reasons as follows.

(1) Less precipitation: The annually averaged precipitation around Hulun Lake was about 247–319 mm/a (Wang et al., 2012c). Based on weather station data from 1960 to 2009 (Fig. 10c), we could see that the monthly average precipitation had a decreasing trend in the warm season (April to October) although it increased slightly after 2000. A decreasing trend of precipitation could contribute to water-level decrease (Shen et al., 2006; Zhao et al., 2007). The monthly averaged precipitation had an increasing trend but with a flat slope (Fig. 10c), in the cold season (November to March). In the cold season, the lake was covered by ice because of low temperature (Fig. 10e). More precipitation in that time could contribute to water-level increase which coincided with the result from ICESat/GLAS.
(2) Temperature: From Fig. 10e, we can also see that the monthly averaged temperature had an increasing trend not only in the warm season but also in the cold season. Strong evaporation caused by temperature increase (Vincent, 2009) could cause water-level decrease (Zhao et al., 2007). The annually averaged evaporation was about 1500 mm/a (Wang et al., 2012c). Evaporation was much serious in the warm season than in the cold season because of a higher temperature. This could contribute to water-level decrease in the summer.
(3) Overgrazing and agriculture: The grass land degraded around Hulun Lake because of overgrazing (Shen et al., 2006). The livestock number in 2009 was 15,514,500, about twice that of 2003 in Hulunbeier City (http://www.hulunbeier.gov.cn/zwgk/index.asp). From 2002 to 2006, the degraded grass land occupied about 53% of available grass land around Hulun Lake (Zhao et al., 2008). The function of water reserve and weather adjustment of the wetlands was degraded in Hulun Lake. Although the population in Hulunbeier City kept stable, the number of wells for underground irrigation in 2009 was 24,534, about twice that of 2003. The effective irrigation area in 2009 was about 190,000 ha, up by 10% than 2007. Therefore, human activities could be another factor for the shrinkage of Hulun Lake.
(4) Runoff recharge decrease: The runoff recharging Hulun Lake decreased greatly from 1998 to 2009 (Wang et al., 2012c; Zhao et al., 2007), from more than 1.7×10^9 m^3/a to less than 2.5×10^8 m^3/a. After 2003, the runoff also showed a decreasing trend, at a low level of less than 5×10^8 m^3/a. Runoff recharge decrease was another reason for water level decrease of Hulun Lake.

In summary, for Hulun Lake, precipitation increase in the cold season could be the reason of intra-annual water-level increase in winter. Stronger evaporation caused by warming climate and human factors, such as agriculture water consumption and grass land degradation due to overgrazing were most probable factors for water-level decrease in Hulun Lake. The decrease of water recharge from runoffs also contributes to the water-level decrease.

As can be seen in Fig. 10b, Bosten Lake, located in the arid zone of west China (Wang et al., 2003; Xia et al., 2003), had the same decreasing trend from 2003 to 2009 as Hulun Lake. Several reasons can lead to the water-level decrease:

(1) Agriculture: Water consumption for agriculture is important reason (Li et al., 2003; Wan et al., 2006; Wang et al., 2003) because it had a negative correlation with water-level change. In 2008, the population in the basin was more than 4×10^5, three times of that in 1949 and the farming land was 2.5×10^5 km^2, about five times of that in 1949 (Wang et al., 2012a). Water consumption for agriculture increased from 1966 to 1985, then maintained stable from 1986 to 1995, and decreased from 1995 to 2000, at a level of about 10.53×10^8 m^3/a. This trend demonstrates that much water was used for agriculture, not recharging Bosten Lake. Thus this was the most probable reason for water-level decrease.
(2) Runoff recharge decrease: Although there are more than ten branches recharging Bosten Lake, Kaidu River contributes more than 80% (Wan et al., 2006; Wang et al., 2003). From the hydrological data around Bosten Lake from 1955 to 2002, variation of lake changes was primarily caused by runoff change of Kaidu River (Wan et al., 2006). According to reports (http://news.h2o-china.com/information/china/209601062551280_1.shtml), runoff of Kaidu River decreased from an averaged 179.79 m^3/s to 151.4 m^3/s in September, 2003. In 2010, the runoff of Kaidu River decreased by 3% to 8% (http://www.gov.cn/jrzg/2010-03/28/content_1566836.htm). Runoff decrease was another reason for the shrinking of Bosten Lake.

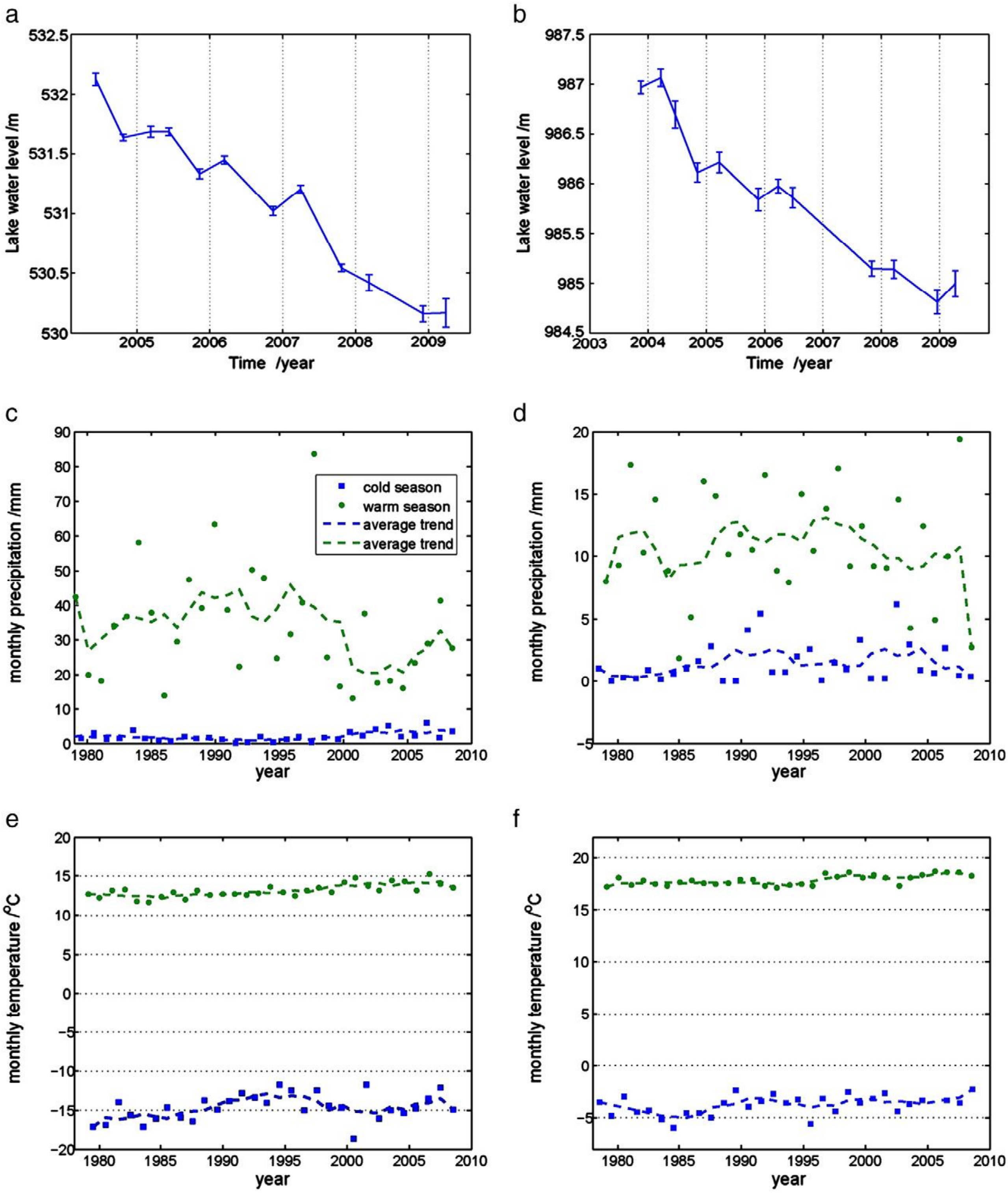

Fig. 10. Water-level changes, precipitation and temperature changes around Hulun Lake and Bosten Lake. Panels (a) and (b) correspond to water-level changes around Hulun Lake and Bosten Lake derived from ICESat/GLAS data respectively. Panels (c) and (d) correspond to monthly precipitation around Hulun Lake and Bosten Lake based on weather station data respectively. Panels (e) and (f) correspond to monthly temperature around Hulun Lake and Bosten Lake respectively. Panels (c), (d), (e) and (f) share the same legend.

(3) Precipitation decrease: From Fig. 10d, monthly precipitation showed a decreasing trend from 2000 to 2010 in the warm season, relative stable in the cold season, which could be another reason. The annual average precipitation was only about 68.2 mm/a (Sun et al., 2010). In the cold season, Bosten Lake was covered by ice for low temperature (Fig. 10f). Precipitation in this period could contribute to water-level increase slightly.

(4) High temperature in warm season: From Fig. 10f, we could see that the temperature in the warm season was about 17–18 °C, strong evaporation caused by high temperature could lead to water-level decrease. The annual average evaporation was 2000–2500 mm/a (Sun et al., 2010.)

(5) Drought: Strong evaporation was caused by continuous drought from 2007 to 2010, especially in 2009 (http://www.gov.cn/jrzg/

2010-03/28/content_1566836.htm). Water loss in surface water, ground water, soil moisture, snow or glacier cannot help Bosten Lake maintains a stable water level but contribute to the water-level decrease.

In summary, for Bosten Lake, the intra-annual increase in the cold season could primarily be caused by precipitation in winter. Agriculture water consumption, runoff recharge decrease, less precipitation, strong evaporation caused by high temperature and drought in warmer seasons were the most probable reasons for the water-level decrease.

Based on the above analysis, possible reasons for most lakes showing decreasing trends from 2003 to 2009 in area B could be as follows. (1) Climate warming: In the northeast of Inner-Mongolia, there was a consistent increasing trend of temperature. Data from weather stations around Dali Lake and Bel Lake also indicated a warming trend (Shen et al., 2006). Intensified evaporation caused by warming climate could result in water level decrease. (2) Drought: in recent 10 years, drought caused by climate warming or less precipitation could not help lakes maintain a stable water level but decrease. (3) Human activities: Northeast of China is one of the largest commodity grain bases in China (Jin & Zhu., 2008). In the recent 30 years (1978–2008), wetland in Inner-Mongolia and the Northeast Plain of China degraded dramatically (Gong et al., 2010; Niu et al., 2009, 2012). Niu et al. (2012) concluded that the wetland changes in northeast of China was caused by water consumption for agriculture because farm land continued to expand from 1990 to 2000. Water consumption for anthropogenic activities could contribute to water-level drop in this area.

6.3.3. Area C

Most lakes in this area fluctuated. This area is located in the middle and lower reaches of Yangtze River and influenced by the river runoff, as well as the East Asian monsoon climate and anthropogenic activities. From ICESat/GLAS data, we cannot find credible trends (with small R^2) because of large fluctuation amplitude of water level.

Poyang Lake, as the largest freshwater lake in China (Ye et al., 2011), the inter-annual water-level change was greater than several meters (Dronova et al., 2011). Basin discharge played a primary role in water-level change of Poyang Lake. Yangtze River played a complementary role of blocking outflows from the lake (Guo et al., 2008; Hu et al., 2007). Additionally, the operation of the Three Gorges Dam had affected the Yangtze River discharge and water level (Guo et al., 2011, 2012). During the period from Sep 15 to Oct 31 each year, the Three Gorge Reservoir stores water leading to reduction of water recharge for Poyang Lake. During the period from Dec 1 to Mar 31, the Three Gorge Reservoir drains water downstream causing an increase in water recharge to Poyang Lake (Qian & Zhan., 2012). This was partly the reason for large fluctuation of water level in Poyang Lake.

Natural factors, such as precipitation and evaporation, also affected water level changes of Poyang Lake. From 2001 to 2011, Jiang Xi Province suffered from continuous drought, with 2003, 2007 and 2009 the most serious. The annual average precipitation in these 3 years was about 1300 mm/a, decreased by 300 mm/a than the multi-year annual average of 1600 mm/a (Shen et al., 2012). Precipitation changes in Jiang Xi Province could have direct influence to Poyang Lake. However, without obvious climate warming here, the strong evaporation did not change much.

Additionally, sand excavation in Poyang Lake influenced water level directly and a hollow place with about 100 m in width was left by bucket dredger each time. Increase of forest cover after the "grain for green" reduced streamflow in the wet season and increases it in the dry season (Guo et al., 2008; Min, 2004). Thus, factors either natural or anthropogenic could affect water-level change at Poyang Lake.

Lakes in area C is located downstream of Yangtze River with which most lakes have direct and controlled indirect water exchange. After 2003, the Three Gorge Reservoir had direct influence in flow control of Yangtze River. Besides precipitation and evaporation, the Three Gorge Reservoir played an important role in water level changes. Also, a large number of people are settled here. Human factors such as agriculture water consumption, sand excavation also affected water level changes. Much human influence to lakes in this area might be possible reasons for small R^2 of water level changes.

6.3.4. Area D

Dianchi Lake, known for water quality degradation (Chen et al., 2009; Li et al., 2007) and Fuxian Lake are both popular tourism destinations. Every year they attract a large number of tourists (Zeng & Wu, 2009). Additionally, although there was a warming trend of temperature in YGP from 1961 to 2008, the magnitude was not as great as that of QTP (Z.X. Li et al., 2011b). The precipitation did not show a monotonic trend because different precipitation indices show different trends (Z.X. Li et al., 2011b). Therefore, these changes of natural factors could not lead to large fluctuation of Fuxian Lake and Dianchi Lake.

7. Conclusions

ICESat/GLAS data have already played a vital role in water-level change studies, especially for those lakes with steep lakeshore, which may not be so obvious in change of areas (J.L. Li et al., 2011a; Shao et al., 2007). In this study, based on ICESat/GLAS data, an automatic method to determining the trend of water-level changes had been proposed. Water level derived from ICESat/GLAS coincided with gauge data. Finally, trends of water-level change from the 56 large lakes in China during 2003 and 2009 were shown and possible reasons were given to the four areas.

Most lakes in area A (QTP and south part of IXP) was sensitive to climate warming, with water-level increase probably caused by increased melting of snow and glacier. Natural factors played a vital role in the QTP. However, regional differences did appear in area A, especially in the Yarlung Zangbo River Basin, where most lakes showed a decreasing trend of water-level changes.

Most lakes in area B (north of IXP and NEP) showing a decreasing trend of water-level change were probably caused by precipitation reduction and strong evaporation caused by climate warming. Continuous drought made the situation in North Xinjiang even worse. Water consumption for agriculture and environmental degradation contributed to the decrease. In area C, lake water-level might be affected by human activities so much that we did not further study the specific contribution of each factor. In area D, there are only two lakes whose water level changes might be caused by natural factors like temperature. However precipitation did not change so much in this area.

Because of the limited observations from ICESat/GLAS, some intra-annual fluctuations of water level cannot be detected. Thus bias in water level trends may be inevitable for limited campaigns. In addition, possible reasons for water-level changes were only given qualitatively. More research needs to be done on the contribution of different factors to water-level changes for a specific lake.

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