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Abstract. Lake level elevation and variation are important indicators of regional and global climate and environmental change. Lake Qinghai, the largest saline lake in China, located in the joint area of the East Asian monsoon, Indian summer monsoon, and Westerly jet stream, is particularly sensitive to climate change. This study examines the lake's water level and temporal change using the ice, cloud, and land elevation satellite (ICESat) altimetry data and gauge measurements. Results show that the mean water level from ICESat rose 0.67 m from 2003 to 2009 with an increase rate of 0.11 m/yr and that the ICESat data correlates well ($r^2 = 0.90$, root mean square difference 0.08 m) with gauge measurements. Envisat altimetry data show a similar change rate of 0.10 m/yr, but with ∼0.52 m higher, primarily due to different referencing systems. Detailed examination of three sets of crossover ICESat tracks reveals that the lake level increase from 2004 to 2006 was 3 times that from 2006 to 2008, with the largest water level increase of 0.58 m from Feb. 2005 to Feb. 2006. Combined analyses with *in situ* precipitation, evaporation, and runoff measurements from 1956 to 2009 show that an overall decreasing trend of lake level (-0.07 m/yr) correlated with an overall increasing trend ($+0.03^\circ$C/yr) of temperature, with three major interannual peaks of lake level increases. The longest period of lake level increase from 2004 to 2009 could partly be due to accelerated glacier/perennial snow cover melt in the region during recent decades. Future missions of ICESat type, with possible increased repeatability, would be an invaluable asset for continuously monitoring lake level and change worldwide, besides its primary applications to polar regions. © *2011 Society of Photo-Optical Instrumentation Engineers (SPIE)*. [DOI: 10.1117/1.3601363]

Keywords: ICESat; Lake Qinghai; lake level; *in situ* measurements; climate change.

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1 Introduction

The hydrological cycles of major lakes and rivers are of great importance for studies of local response on regional and global climate change. Lake level and temporal change can reflect water mass balance of a basin, and is closely related with climate parameters of precipitation,

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temperature, evaporation, humidity, wind, etc. Lake level variations also affect bottom sediment characteristics, ecological consequences, circulation pattern, and wind-driven waves.[1–3]

Lake level data, one of the most important and fundamental datasets used in hydrologic analysis, are traditionally obtained through gauge measurements. However, in many cases, limited spatial distribution of hydrological gauges is often not able to provide adequate or continuous observations due to economic and political reasons. There is even a decrease of globally gauging networks during the last decade.[4] Many studies show that satellite radar and/or laser altimetry provide effective and powerful data for many potential applications in oceans, rivers, lakes, wetlands, and floodplains. For example, water level variations are monitored using Topex/Poseidon with a precision of several tens of centimeters.[5–8] Lake wetland hydrologic variation, lake level fluctuations, and volume variations are examined with Envisat RA-2.[1,9,10] Water surface changes are studied with high precision ICESat (the ice, cloud, and land elevation satellite) altimetry data.[11–16]

Previous studies of Lake Qinghai have primarily focused on lake level variation, chemical budget, and hydrological change using *in situ* gauge data.[17–21] This paper uses ICESat data in retrieving water level and change of Lake Qinghai over the period of 2003 to 2009, the life span of ICESat. Comparisons of *in situ* measurements with ICESat and Envisat altimeter datasets are also presented. In addition, ICESat elevation profiles, relative lake level change, and relation between lake level change and *in situ* measurements of weather and hydrological variables are examined in detail.

2 Background of Lake Qinghai

Lake Qinghai, the largest brackish-saline lake in China, was formed in an intermontane tectonic depression of the northeast margin of the Tibetan Plateau. It extends from 36°32′ to 37°15′ N and 99°36′ to 100°47′ E (Fig. 1), with an altitude of ∼3193 m, an area of 4317.69 km^2, and a water volume of $\sim 7.16 \times 10^{10}$ m^3 (2008). The mean depth of the lake is 21 m and the maximum depth is 25.5 m (recorded in 1985).[18] The maximum length and width of the lake are approximately 106 and 67 km, respectively.

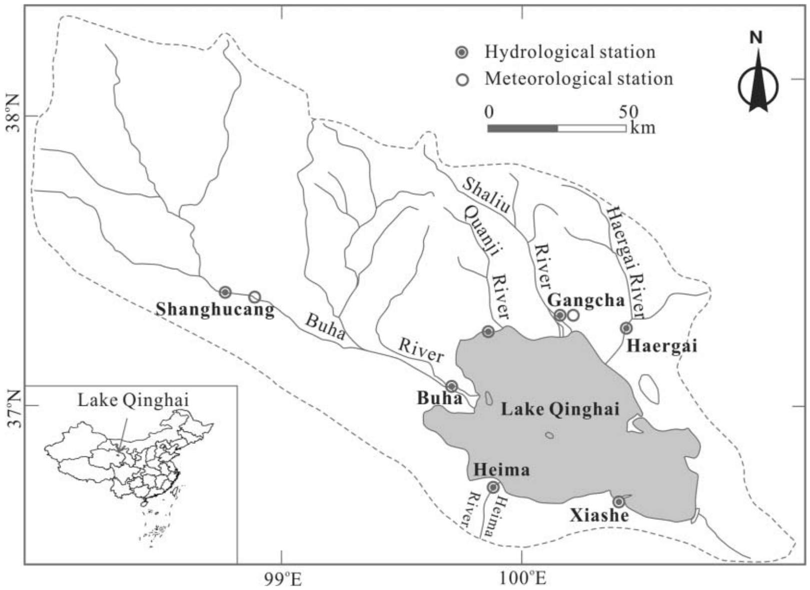

Fig. 1 Location of Lake Qinghai in China. Rivers, hydrological, and meteorological station sites are shown in Lake Qinghai basin.

The lake is a closed, slightly saline lake (salinity 12.5 g/l)[22] with no surface water outflow. The water is fed mainly from direct precipitation and runoff through more than 50 intermittent rivers or streams.[19] The drainage basin covers a total catchment area of about 29,660 km^2 (Fig. 1). The sub-basin areas of five major rivers in Lake Qinghai basin are 14,337 km^2 for the Buha River basin, 1442 km^2 for the Shaliu River basin, 1425 km^2 for the Haergai River basin, 567 km^2 for the Quanji River basin, and 107 km^2 for the Heima River basin.[18,23] The Buha River is the longest and largest river, which contributes almost half of the total runoff to the lake.[24] The runoff together from the five largest rivers in the basin counts for 83% of the total runoff to the lake; 75% of the total runoff occurs from June to September.[25]

The annual mean air temperature (1951 to 2007) is 1.2°C,[19] the annual mean precipitation (1959–2000) is 357 ± 10 mm, and the annual mean evaporation is 924 ± 10 mm,[18] nearly 3 times that of precipitation. The rainfall from May through September accounts for 90% of a full year precipitation.[26] The East Asian monsoon, Indian summer monsoon, and Westerly jet stream cover the area, and hence it is one of the most sensitive regions for studying climate change.[17,25] The qualitative knowledge of Lake Qinghai level variations is of great importance to climate and environmental research, as well as evolution of the ecological environment and economical benefit to the region.

3 Data Used and Methodology

3.1 *In situ* Dataset

The *in situ* lake level measurements of hydrologic and meteorological parameters have been conducted since 1959 by the Bureau of Hydrology and Water Resources of Qinghai Province. The annual mean *in situ* measurements of water level (elevation) from 1959 to 2009 at Station Xiashe, $36^\circ 35' 16.0''$ N/$100^\circ 29' 28.4''$ E, southeastern part of Lake Qinghai (Fig. 1), the daily corresponding observations of *in situ* measurements (at Station Xiashe), and ICESat altimetry data during 2003 to 2009, are obtained for this study. The geodetic reference system of the *in situ* data is Chinese National Datum (i.e., the Yellow Sea Datum, created in 1965 and renewed in 1985). The datum origin lies in Dagang tide gauge in Qingdao City, China. Guo[27] noted that the 1985 datum is 35.7 cm higher than the WGS84 datum. By combination of the datum mark and gauge measurements, the difference between the Chinese 1985 datum and the WGS84 datum is about 40 cm in the Lake Qinghai area.[27,28] Therefore, the *in situ* measurements are transformed into the WGS84 datum for comparison with ICESat altimetry data.

Although measurements of temperature, precipitation, evaporation, and runoff data for the lake have been started since 1956, only some of the data are available for this study, including the annual mean temperature from Station Gangcha for the period of 1958 to 2009, and annual mean precipitation, annual mean evaporation, and annual mean runoff from both Stations Gangcha and Buha for the period of 1956 to 2009.

3.2 ICESat Data

The Geoscience Laser Altimeter System (GLAS) onboard the ICESat satellite was launched into a 600 km altitude orbit with a 94° inclination on January 13, 2003. The primary objective of ICESat was to measure changes in elevation of Greenland and Antarctic ice sheets and elevation of polar sea ice,[29–33] while it has shown wide application to hydrology, land topography, cloud and aerosol heights, and vegetation canopy heights with unprecedented accuracy.[32,34] The GLAS sensor had a 1064 nm laser beam for measuring surface elevation and dense clouds heights, and a 532 nm laser beam for measuring backscatter profiles of clouds and aerosols.[35] With a beam width of $\sim 110\ \mu$rad and a pulse rate of 40/s, ICESat samples the Earth's surface with a sample footprint of ~70 m diameter spaced at 170 m intervals and ~2 cm precision for a flat surface.[31,33] The level 2 altimetry product (GLA14) provides surface elevation for land

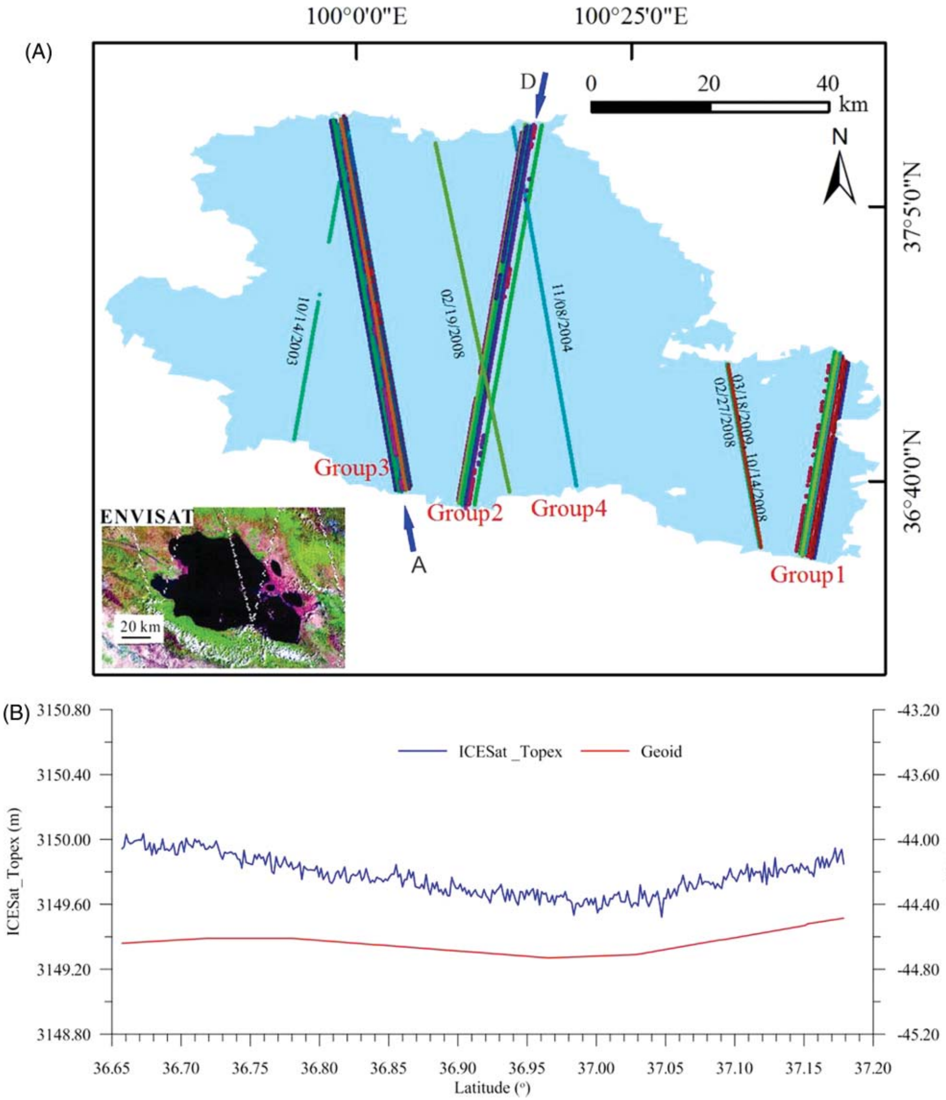

Fig. 2 (a) The 47 ICESat descending (D) and ascending (A) tracks overpass Lake Qinghai. The tracks are grouped into four subgroups according to their spatial distribution (discussed in Sec. 4.2). The inset map shows a sample of Envisat ground tracks. (b) Example of ICESat_Topex elevation and EGM96 geoid profiles on October 6, 2008.

with a 91 day repeat track. ICESat elevation over water surfaces, such as oceans, lakes, rivers and wetlands, and continental coasts have been examined in numerous studies with successful performance.[11,12,14–16,36–38] In addition, ICESat elevation profiles have been used to calculate lake and river surface slope, shown better than 1 cm km^{-1} and 0.001° precision, respectively.[11,39] A total of 47 ICESat tracks crossing Lake Qinghai from the period of 2003 to 2009 are available for this study (Fig. 2).

3.3 ICESat Data Processing

Detailed data processing of ICESat/GLA14 is documented in Zhang et al.[16] and includes the following steps: i. Use NSIDC's GLAS altimetry elevation extractor tool (NGAT, version 0.11) to extract information (.txt) from scaled GLAS binary format files; ii. convert the data into .mdb file in Microsoft Access; iii. extract data when ICESat tracks intersect with Lake Qinghai; and iv. convert those qualified data (ICESat_elevation_Topex) to the orthometric height (ICESat_elevation_Ortho) using Eq. (1).

$$\text{ICESat\_elevation\_Ortho} = \text{ICESat\_elevation\_Topex} - \text{EGM96\_geoid} - 0.7 \tag{1}$$

where ICESat_elevation_Topex and EGM96_geoid are directly provided from the ICESat data, and 0.7 m is the offset from Topex ellipsoid to WGS84 ellipsoid.[13]

Figure 2 also shows an example of the EGM96 geoid profile provided with the ICESat data on October 6, 2008, and the associated ICEsat_elevation_Topex profile of the date. The derived and outliers-removed data of ICESat orthometric height (or ICESat elevation thereafter) are used for comparison and analysis in the study.

3.4 Envisat Data

With the aim of studying and monitoring the Earth and its environment from space, the European Space Agency launched Envisat in 2002. Envisat, in a 35 day repeat orbit, provides observations of the Earth's surface from 82.4° N to 82.4° S, with an equatorial ground-track spacing of about 85 km.[40] The radar altimeter (RA-2) onboard Envisat is to provide a global scale collection of radar echoes over ocean, land, and ice to measure ocean topography, water level variations over the large river basin, land surface elevation, and to monitor sea ice and polar ice caps.[41] Many studies show Envisat radar altimeter (RA-2) has high accuracy in monitoring inland lake level changes.[1,10,40,42] Laboratoire d'Etude en Géophysique et Océanographie Spatiale (LEGOS) provides orthometric heights, using the GGM02c geopotential field combination model that differs from the WGS84/EGM96 referencing system that ICESat elevation data used, for 150 lakes and reservoirs globally, freely available at http://www.legos.obs-mip.fr/en/soa/hydrologie/hydroweb/.[43] ENVISAT data from LEGOS over Lake Qinghai during 2003 to 2009 are used in this study for comparison purpose. The inset map in Fig. 2 shows a sample of Envisat tracks through Lake Qinghai.

4 Results

4.1 Lake Level Change

Figure 3 shows annual mean lake level change from 1959 to 2009 as measured at Station Xiashe. It is clear that, from 1959 to 2009, the water level has experienced a general decreasing trend

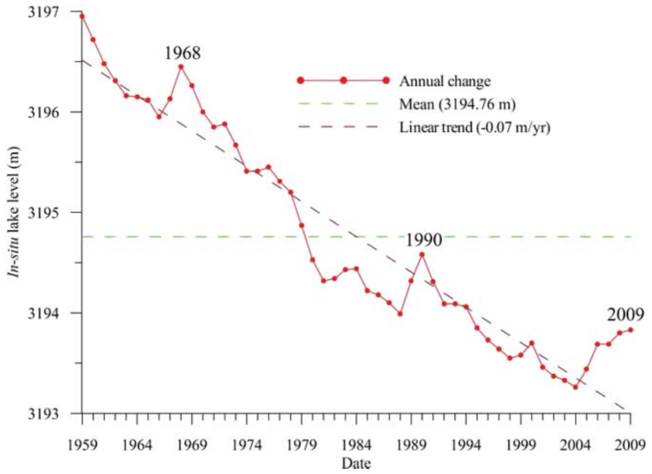

Fig. 3 Mean annual lake level change from gauge station Xiashe over the 1959 to 2009 period.

with the exception of several interannual peaks (years 1968, 1990, and 2009). Over the whole time span from 1959 to 2009, the water level decreased 3.11 m from 3196.95 m of 1959 to 3193.84 m of 2009, with a change rate of −0.07 m/yr. The mean lake level elevation in the period is 3194.76 m.

Table 1 shows the elevation information extracted, including date, mean elevation of all footprint elevations of the date, standard deviation of all footprint elevations, minimum of all footprint elevations, maximum of all footprint elevations, and footprint counts. The daily mean *in situ* measurements on the corresponding date with ICESat data from Station Xiashe are also provided in Table 1 for comparison. The lake level indicates an increase tendency, from

Table 1 Lake Qinghai elevation derived from ICESat altimetry data during the period of 2003 to 2009. *in situ* measurements of water level at Station Xiashe are also included. The elevation unit is in meters (m).

Date	ICESat elevation	Standard deviation	Minimum	Maximum	Counts	*in situ* measurement
10/14/2003	3193.35	0.12	3193.03	3193.66	183	3193.42
10/18/2003	3193.44	0.13	3192.79	3193.85	312	3193.42
10/22/2003	3193.39	0.18	3193.07	3193.68	157	3193.41
11/16/2003	3193.35	0.19	3193.16	3194.62	366	3193.33
02/19/2004	3193.19	0.12	3193.00	3193.55	278	3193.27
02/22/2004	3193.21	0.12	3193.00	3193.58	88	3193.27
03/18/2004	3193.12	0.12	3193.00	3193.91	115	3193.21
05/20/2004	3193.27	0.18	3193.00	3193.73	125	3193.20
06/17/2004	3193.30	0.12	3193.04	3193.93	352	3193.25
10/06/2004	3193.38	0.13	3193.07	3193.80	356	3193.40
11/03/2004	3193.35	0.12	3193.01	3193.73	361	3193.33
11/08/2004	3193.33	0.08	3193.12	3193.86	330	3193.32
02/20/2005	3193.18	0.15	3193.00	3193.62	291	3193.20
02/24/2005	3193.15	0.27	3192.65	3193.97	150	3193.19
05/22/2005	3193.15	0.08	3193.00	3193.47	162	3193.22
05/26/2005	3193.43	0.08	3193.22	3193.62	107	3193.24
10/23/2005	3193.81	0.06	3193.64	3193.98	316	3193.79
10/27/2005	3193.82	0.14	3193.36	3193.99	135	3193.79
11/21/2005	3193.64	0.12	3193.34	3194.57	357	3193.72
02/24/2006	3193.73	0.09	3193.56	3193.99	340	3193.63
02/27/2006	3193.72	0.06	3193.58	3193.89	169	3193.63
03/24/2006	3193.67	0.10	3193.21	3193.98	330	3193.63
05/26/2006	3193.57	0.14	3193.36	3193.99	354	3193.61
05/29/2006	3193.74	0.10	3193.27	3193.98	174	3193.62
06/23/2006	3193.71	0.14	3193.31	3194.84	367	3193.67
10/27/2006	3193.63	0.10	3193.31	3193.99	198	3193.75
10/30/2006	3193.86	0.08	3193.56	3193.98	80	3193.75
11/24/2006	3193.65	0.17	3193.22	3194.56	323	3193.69
03/13/2007	3193.64	0.12	3193.23	3193.97	66	3193.60
03/17/2007	3193.77	0.08	3193.59	3193.98	148	3193.60
04/11/2007	3193.64	0.23	3193.21	3193.99	49	3193.62
10/04/2007	3193.76	0.14	3193.11	3194.15	161	3193.83
10/08/2007	3193.74	0.24	3193.11	3194.53	39	3193.84
11/02/2007	3193.86	0.13	3193.53	3194.51	366	3193.87
02/19/2008	3193.72	0.11	3193.50	3194.78	343	3193.74
02/22/2008	3193.84	0.06	3193.48	3193.99	161	3193.74
02/27/2008	3193.95	0.03	3193.88	3193.99	37	3193.74
03/18/2008	3193.72	0.14	3193.42	3194.66	341	3193.74
10/06/2008	3193.93	0.13	3193.63	3194.37	361	3193.92
10/09/2008	3193.93	0.13	3193.47	3194.94	163	3193.93
10/14/2008	3193.76	0.14	3193.39	3194.18	99	3193.92
12/14/2008	3193.77	0.18	3193.04	3194.73	364	3193.76
03/10/2009	3193.64	0.10	3193.40	3193.78	19	3193.73
03/14/2009	3193.81	0.09	3193.54	3193.99	146	3193.73
03/18/2009	3193.80	0.16	3193.40	3194.23	176	3193.73
04/08/2009	3193.62	0.17	3193.32	3193.93	23	3193.74
10/02/2009	3194.02	0.15	3193.47	3194.45	266	3194.09

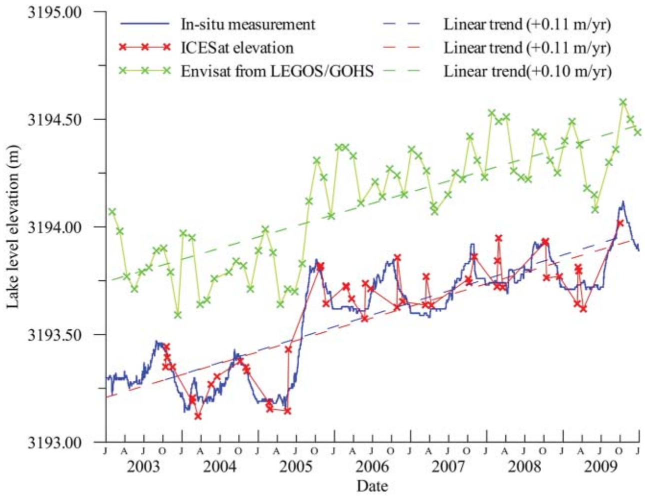

Fig. 4 Time series of ICESat elevation and in situ measurements from Station Xiashe in the bottom and ENVISAT elevation from LEGOS/GOHS in the top, from 2003 to 2009. The dashed lines are the change trends of each datasets.

3193.35 m on October 14, 2003 to 3194.02 m on October 2, 2009. The difference of lake level for the 6 year period is around 0.67 m. The rate of increase is 0.11 m/yr. The mean standard deviation of all footprint elevations used in the 6 year period and footprint counts are 0.13 m and 217 (range 19 to 367), respectively.

Figure 4 shows the lake level/elevation time series from three different data sources: daily *in situ* measurements from Station Xiashe, available daily mean elevation from ICESat footprints, and available daily Envisat data from LEGOS/GOHS. Surprisingly, all datasets show the same (or very similar) increasing trend of 0.10 to 0.11 m/yr for the period. This indicates that both satellite datasets have a similar quality in monitoring change trend of lake level, although the absolute elevation values of Envisat are consistently ∼0.52 m higher than ICESat elevations, primarily due to different referencing systems of Envisat and ICESat. The bias could also be partly due to the tracking algorithm selected at the LEGOS to construct the ranges. ICESat elevations, however, agree well with *in situ* measurements (the same referencing system). Figure 5 presents a scatter plot of the two elevations, showing a very good correlation ($r^2 = 0.90$). The absolute average difference and root-mean-square-difference (RMSD)between the two elevations are 0.06 and 0.08 m, respectively. This supports that the absolute error of ICESat elevation is better than 10 cm. The biggest water level increase, 0.68 m, was from April 2005 to October 2005, based on *in situ* measurements.

4.2 ICESat Elevation Profiles

As shown in Fig. 2, the 47 ICESat tracks are grouped into 4 subgroups according to their spatial distribution, with examples of elevation profiles in groups 2 and 3 shown in Fig. 6.

Group 1, on the eastern side of the lake, consists of 13 ICESat tracks. They show a mean lake level increase of 0.42 from 3193.39 m on 10/22/2003 to 3193.81 m on 03/14/2009. The rate of increase and the elevation standard deviation (std) are 0.12 m/yr and 0.13m, respectively. All 12 continuous tracks together shows a mean northward slope of 0.0010° (range 0.0010°).

Group 2 includes 13 ICESat tracks. They show a mean lake level increase of 0.27 m from 3193.35 m on 11/16/2003 to 3193.62 m on 04/08/2009. The increase rate and std are 0.10 m/yr and 0.15 m, respectively. The 10 continuous tracks show a mean northward slope of 0.0015° (range 0.0011°).

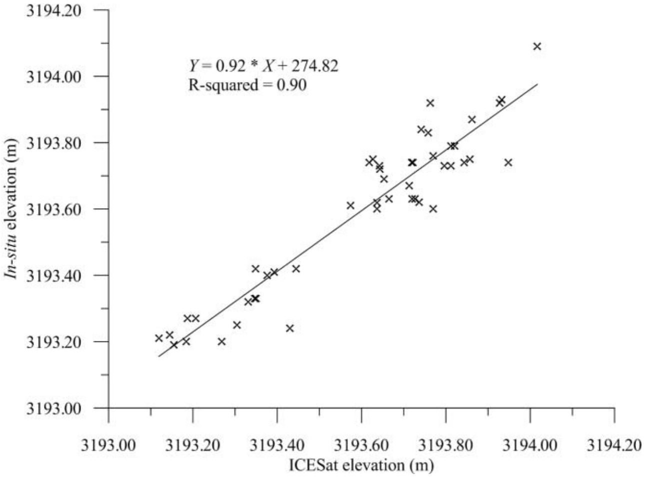

Fig. 5 Lake level at *in situ* station versus lake level derived from ICESat.

Group 3 includes 15 ICESat tracks. They show a mean lake level increase of 0.58 m from 3193.44 m on 10/18/2003 to 3194.02 m on 10/02/2009. The increase rate and std are 0.12 m/yr and 0.12 m, respectively. The 14 continuous tracks show a mean northward slope of 0.0011$^{\mathrm{o}}$ (range 0.0013 $^{\mathrm{o}}$).

Other scattered tracks are grouped into Group 4. This group includes 6 tracks. Most of them are short profiles, since bad elevations due to environmental contaminations are removed for further analysis.

4.3 Relative Lake Level Change

ICESat tracks with overlapping footprints (<1 pixel distance, or 70 m) within closing dates of different years can provide a more accurate lake level change. A total of 3 sets of such ICESat tracks (A, B, C) are found and whose overlapping footprints are extracted for comparison (Table 2). Therefore, those overlapping footprints are, of course, less than the total counts for corresponding dates shown in Table 1.

Figure 7 shows these three sets of ICESat profiles and elevation differences. The three datasets of A, B, and C are part of Group 2, Group 1, and Group 3, respectively. Comparing A

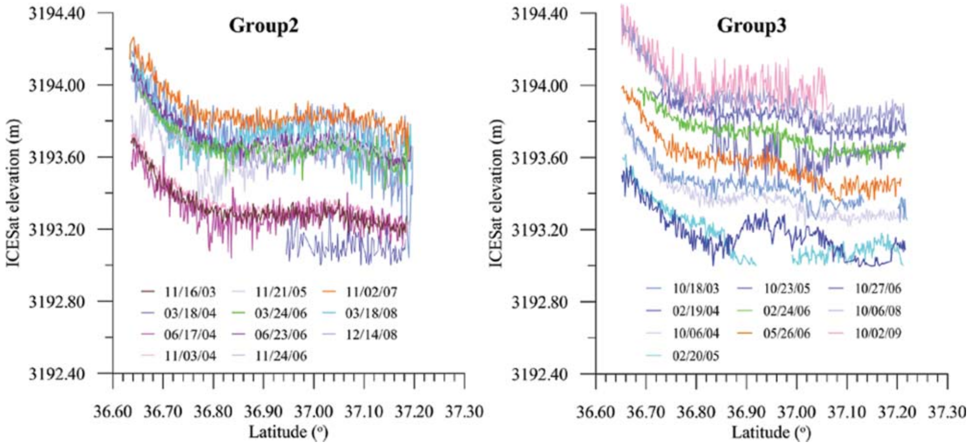

Fig. 6 Examples of ICESat elevation profiles in groups 2 and 3.

Table 2 Relative lake level change of ICEsat track groups.

Group tracks	Number of footprints	Elevation profile (South to North)	Elevation difference (m)
A: 06/17/2004, 06/23/2006	328	decrease, flat, decrease	0.41
B: 02/27/2006, 02/22/2008	155	decrease, increase	0.14
C: 02/19/2004, 02/20/2005, 02/24/2006	234	decrease, flat, decrease, flat	0.58

and B, it suggests that the overall lake level increase from 2004 to 2006 is 3 times that from 2006 to 2008 (Table 2). This is consistent with Figs. 3 and 4, a big jump from 2004 to 2006, while only a small jump from 2006 to 2008. Figure 7(c) shows the water level profile on 02/19/2004 is close to the one on 02/20/2005, while the water level profile on 02/24/2006 is much higher. Given that there is not much difference between 02/19/2004 and 02/20/2005, it suggests that the 0.58 m mean water level increase should mostly come from Feb. 2005 to Feb. 2006. This is consistent with Fig. 4. Repeated footprints of similar dates, but different years, can provide significant information about lake level and change with high accuracy.

5 Discussion

Water level in Lake Qinghai has shown an overall decreasing trend during 1956 to 2009. There were several interannual water level increases, particularly, the three water level peaks in the years 1968, 1990, and 2009. The most recent one is the water level increase from 2004 to 2009, which is also observed from the available ICESat altimetry data from 2003 to 2009. The ICESat and gauge data agree very well, and an increase rate of 0.11 m/year is found. Continuous profiles of the 47 ICESat tracks show an overall northward slope, with mean slope of $\sim 0.001^\circ$, i.e., 0.017 m/km (very small slope). The slope is most likely due to the EGM96 geoid error. Averaging all elevations along such a profile to get a mean elevation for the profile should have automatically removed this small slope effect, i.e., geoid error. This is the basis for our comparison of mean elevation from each profile over the period from 2003 to 2009 (Fig. 4). Near crossover footprints (short than 70 m) along three sets of profiles (Fig. 7) clearly show that the elevation difference profiles are overall flat, i.e., the geoid error is generally removed. The mean value of each difference profile as shown in Table 2 should be a more accurate comparison of lake level change. These sets of profiles, however, are not easily available from ICESat data for an area outside the polar regions. In our case, we only get 3 sets (or 7 profiles) out of the total 47 profiles overpass the lake for the 7 years. The lake level changes derived from those three sets of profiles, however, are similar as (or very close to) what is shown in Fig. 4. This indicates that 1. the averaging of all ICESat footprint elevations along a profile indeed removed the geoid error; 2. the mean elevation from each profile can effectively/accurately represent the actual lake level in that moment when the orbit overpasses the lake; and 3. the change from those mean elevations can reflect the actual lake level change, as shown in Fig. 4.

The overall decrease in water level caused some ecological environmental problems in the lake basin such as grassland degradation, desertification of land, and destruction of biological diversity. The reasons for water level decrease are mainly due to two factors: human (anthropogenic) activities and climate change. However, the water consumption by human activities (domestic, livestock, agriculture, and industrial water) accounts for only a small portion of the river runoff to the lake. For example, Li[18] reported from 1959 to 2000 that water consumption of human activities (0.77×10^8 m^3) only accounts for 4.8% of the total river runoff (16.03×10^8 m^3), and that evaporation from the lake surface (924 ± 10 mm) is three times of the precipitation over the lake (357 ± 10 mm) or river runoff to the lake (348 ± 21 mm). This suggests that water consumption by human activities has little effect on lake level decline. Therefore, the lake level change should mainly be due to the climate change, i.e., precipitation, runoff, and evaporation.

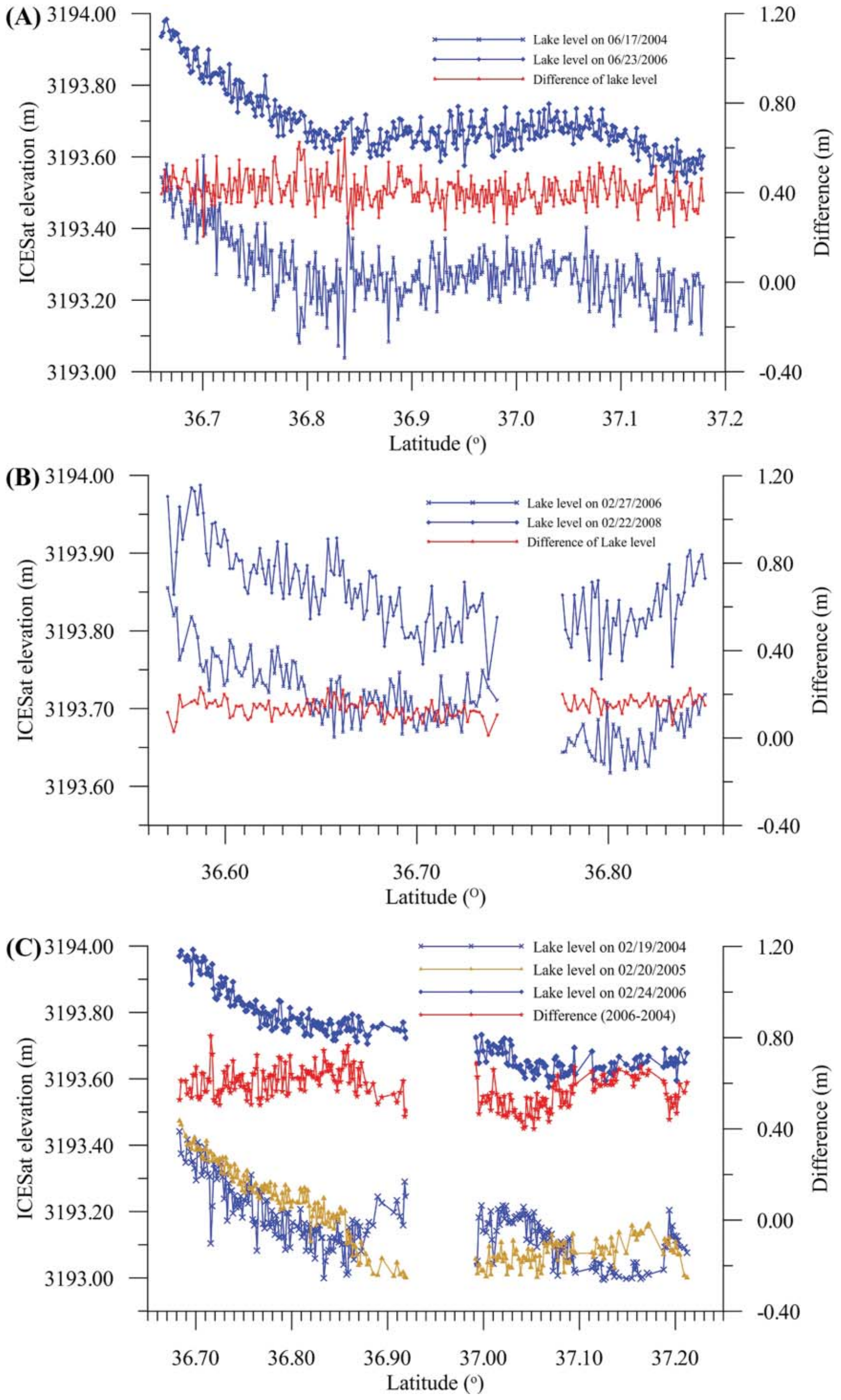

Fig. 7 Three sets of near crossover ICESat profiles and difference profiles. The discrete profiles indicate ICESat footprint gaps (removed due to contamination of clouds) along these tracks.

Figure 8 shows the temperature, precipitation, and evaporation time series from the two Stations Buha and Gangcha during the past 53 years (from 1956 to 2009). Since only Station Gangcha has available temperature data and the two stations are close, the temperature at Station Buha is assumed to be similar as Station Gangcha as shown in Fig. 8 for comparison purposes. The annual mean, maximum, and minimum temperatures are −0.26, 1.73, and −1.51°C, respectively. The annual mean temperature increased 1.82°C from −0.09°C in 1958 to 1.73°C

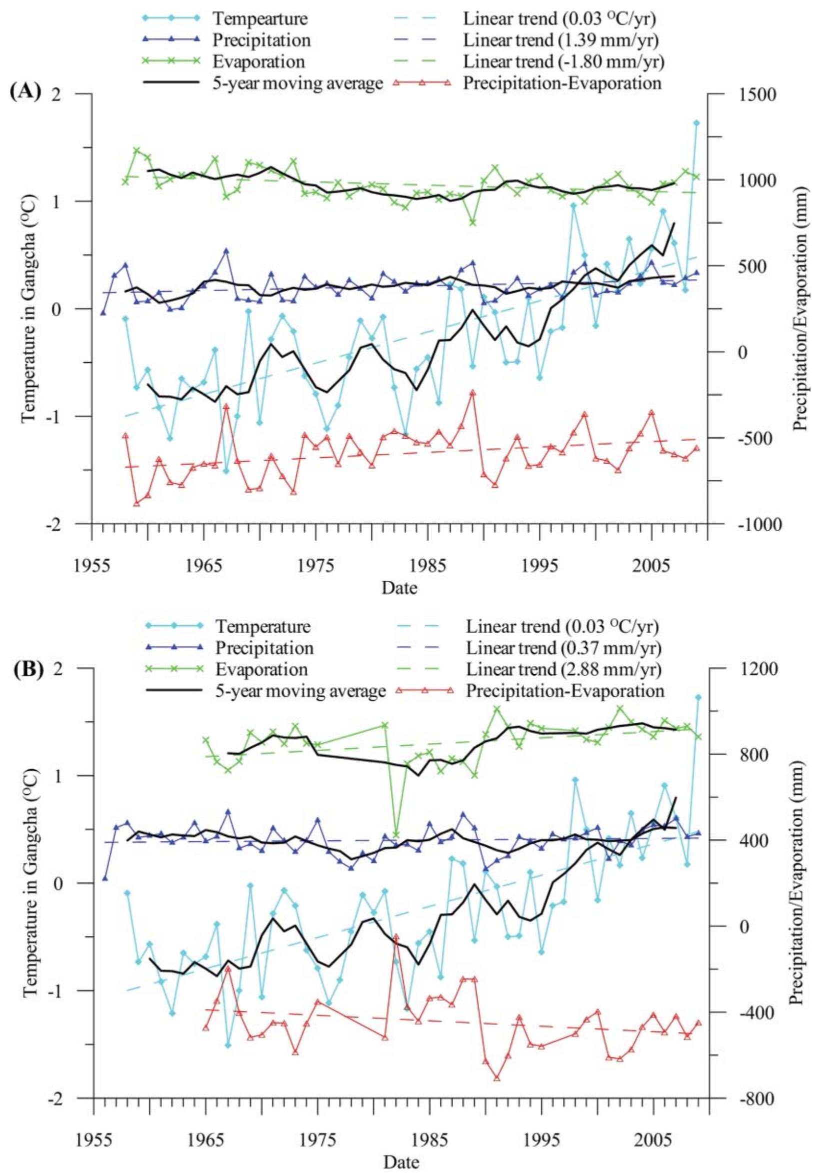

Fig. 8 Change trend of annual mean temperature, precipitation, evaporation, and the P-E difference at Stations Buha (A) and Gangcha (B), in Lake Qinghai basin from 1956 to 2009.

in 2009, with an increase rate of 0.03°C/yr. The annual mean precipitation and evaporation are 380.31 and 973.12 mm at Station Buha, and 399.52 and 852.66 mm at Station Gangcha, respectively. Although there is a slight increase trend of precipitation (1.39 mm/yr for Station Buha and 0.37 mm/yr for Station Gangcha), the evaporation shows a mixed phenomenon, decrease trend (−1.80 mm/yr) for Buha and increase trend (2.88 mm/yr) for Gangcha. Since the evaporation is often 2 times larger than the precipitation, the differences between precipitation and evaporation (P-E) are big negative numbers as shown in Fig. 8, a slight increased trend for Buha and decrease trend for Gangcha. Three peaks of P-E difference (1967, 1989, and 2005) for Buha station, matched well with the three lake level increase peaks (1968, 1990, and 2009) as shown in Fig. 3. The 2009 lake level peak is the longest lake level increase and started in 2004. There is another P-E difference peak in 1999, resulting in a small lake level increase peak in year 2000 (Fig. 3). The sub-basin through Buha station is the largest sub-basin contributing runoff to the lake as shown in Fig. 9. Three of the four largest runoff peaks (1964, 1967, 1989, and

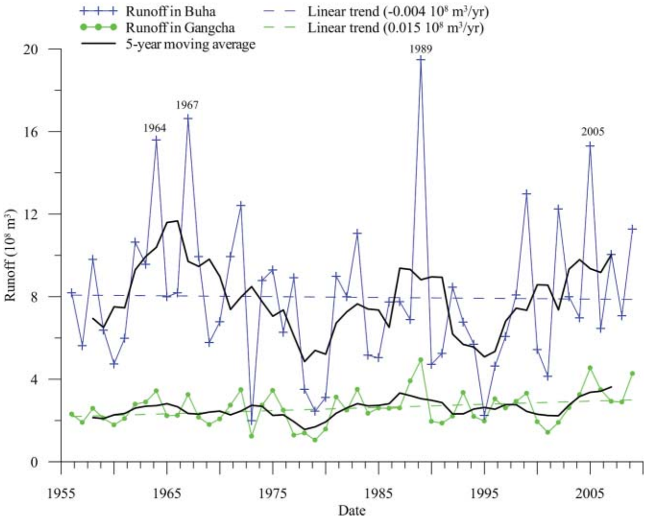

Fig. 9 Annual mean river runoff at Stations Buha and Gangcha during the period of 1956 to 2009.

2005) match well with the three P-E difference peaks (1967, 1989, and 2005) for Buha station. This suggests that the high precipitation in the region indeed contributes more river runoff to the basin, and significantly increases the lake level. The 1964 runoff peak, however, does not have any match with high precipitation, high P-E difference, or increased lake level. Therefore, this number cannot be explained by the current data available. Since the sub-basin through Station Gangcha is a small basin, the runoff contribution from this sub-basin to the lake level should be limited.

The longest period of lake level increase from 2004 to 2009 could partly be due to the significant or accelerated glacier/perennial snow cover melting in the region during the recent decades due to the global warming.[16] Although the area of perennial snow/glaciers cover in the entire Lake Qinghai basin is less than 300 km^2, only accounting for 1% of the entire watershed,[26] the runoff from snow/ice melt could have significantly contributed to the continuous lake level increase as shown in many other lakes in the Tibetan Plateau.[16] The mean annual temperature for the region was changed from overall negative to overall positive from 1956 to 2009, in particular, the five-year running mean became positive since 1996 (Fig. 8). This could be a tipping point that could have accelerated the glacier/perennial snow cover melting in the region. This is clearly seen in the runoff time series from Station Buha where the five-year running mean has been significantly increasing since 1996 (Fig. 9). It is expected that the current lake level increase trend would continue for a certain period to another tipping point, when the glacier/perennial snow cover melting will not be able to offset the runoff loss due to other factors, such as, precipitation decrease, evaporation increase, and/or increase consumption of human activities. Without knowing the ground water discharge to the lake, river runoff from each sub-basin, and lake area when each lake elevation changed (from either gauge measurements or satellite altimetry data), it is still impossible to calculate the total water balance of the lake and its change. This, however, is out of the scope of this paper.

6 Conclusion

In this study, Lake Qinghai water level elevation and change from 2003 to 2009 are examined using ICESat data. ICESat laser altimetry exhibits a strong capability for the monitoring of the lake level. ICESat data, *in situ* measurements, and Envisat data from LEGOS/GOHS show the same (similar) increase rate of 0.10 to 0.11 m/yr for the period of 2003 to 2009. ICESat elevation are strongly correlated with *in situ* lake level measurements ($r^2 = 0.90$, RMSD $= 0.08$ m).

The absolute difference of Envisat and ICESat elevations (∼0.52 m) is primarily due to their different referencing systems. ICESat indicated lake surface slope (∼0.001°, i.e., 0.017 m/km) is quite small and is most likely due to the EGM96 geoid error. Averaging of all elevations along an ICESat profile can effectively remove the geoid error. The relative lake level changes with overlapping footprints within closing days of different years can provide a more accurate measurement of lake level change. The lake level difference profiles between 6/17/2004 and 6/23/2006, between 2/19/2004, 2/20/2005, and 2/24/2006, and between 2/27/2006 and 2/22/2008 are overall flat and positive, i.e., lake level increase. The time series and precision of lake level elevation and changes worldwide would be greatly improved with increased repeatability of ICESat2.

The temperature in Lake Qinghai observed from Station Gangcha shows an increase trend, which is consistent with the overall decrease trend of lake level from 1959 to 2009, although the precipitation and evaporation do not present a clearly positive relationship with temperature. The major runoff peaks from the largest sub-basin passing through Station Buha match well with the P-E difference peaks and the lake level increase peaks. This suggests that the Buha sub-basin indeed makes the largest contribution to the lake level change: decrease or increase. The longest period of lake level increase from 2004 to 2009 could be partly due to the significant or accelerated glacier/perennial snow cover melting in the region during recent decades. However, without knowing the ground water discharge to the lake, runoff information from other sub-basins, exact ice mass loss from glaciers/perennial snow cover, and exact water surface areas of corresponding dates with ICESat elevations, it is still impossible to calculate the total water balance of the lake and its change.

The year 1996, when the five-year running mean temperature for the region became positive, could have been the tipping point, resulted in transpose glacier/perennial snow cover melting in the region. It is expected that the current lake level increase trend would continue for a certain period to another tipping point, when the glacier/perennial snow cover melting will not be able to offset the runoff loss due to other factors, such as precipitation decrease, evaporation increase, and/or increase consumption of human activities.

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Biographies and photographs of the authors not available.