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Performance evaluation of combining ICESat-2 and GEDI laser altimetry missions for inland lake level retrievals

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Abstract

Monitoring lake water levels is important to fully understand the characteristics and mechanism of lake dynamic change, the impact of climate change and human activities on lakes, etc. This paper first individually evaluated the performance of the newly released Global Ecosystem Dynamics Investigation (GEDI) and the successor of the Ice, Cloud, and Land Elevation Satellite mission (ICESat-2) for inland lake level retrieval over four typical lakes (Chaohu Lake, Hongze Lake, Gaoyou Lake and Taihu Lake) using in situ gauge data, then the lake levels of the two missions were combined to derive long time-series lake water levels. A comparison of the mission results with in situ water levels validated the accuracy of the ICESat-2 with R varying from 0.957 to 0.995, MAE 0.03 m-0.10 m and RMSE 0.04 m-0.13 m; however, larger bias occurred in GEDI results with R spanning from 0.560 to 0.952, MAE 0.31 m-0.38 m and RMSE 0.35 m-0.46 m. Before the lake levels were combined, GEDI bias correction was carried out. The correlation coefficients and annual change rate differences between the combined and the in situ data were 0.964 and 0.06 m/yr, 0.852 and 0.05 m/yr, 0.888 and 0.05 m/yr, and 0.899 and 0.02 m/yr for Lake Chaohu, Hongze, Gaoyou and Taihu, respectively. Except for individual months and seasonal differences caused by GEDI estimations, the general trend of monthly, seasonal, and annual dynamics of inland lake water levels captured by combined GEDI and ICESat-2 missions were consistent with measurements from hydrological stations. These encouraging results demonstrate that combining the two missions has great potential for frequent and accurate lake level monitoring and could be a valuable resource for the study of hydrological and climatic change.

Keywords: Satellite laser altimetry, ICESat-2 ATL13, GEDI L2A, Inland lake monitoring, Performance evaluation

Introduction

A full understanding of lake level dynamics is vital to study the impact of climate change and human activities on lakes and can also provide a scientific basis for regional ecological environment protection (Frappart et al. 2018). In recent years, satellite altimetry technology has been developed to extensively monitor lake water levels. Radar satellites can quickly obtain lake surface elevations over large scales and under all weather conditions; these satellites include Topex/Poseidon, Envisat, and Cryosat-2 (Busker et al. 2019; Crétaux et al. 2011; Velpuri et al. 2012). However, the accuracy of these observations may be influenced by their larger footprints and different retracking methods towards waveforms (Gao et al. 2013; Wang et al. 2019). Compared with radar altimeters, laser altimeters have smaller footprints and higher sampling densities, which are more appropriate for the observation of small lakes or reservoirs (Li et al. 2020).

The first laser altimetry satellite for Earth observation, ICESat was widely used to retrieve lake water levels (Hwang et al. 2019; Wang et al. 2016, 2013). For example, Srivastava et al. (2013), using ICESat data, analysed lake levels in Himalaya–Karakoram from 2003 to 2009

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and found that 10 lakes displayed different increasing trends, while another 3 lakes presented decreasing trends. Phan et al. (2012) investigated 154 lakes over the Tibetan Plateau and found that the average increase rate was 0.20 m/yr. As the second generation of ICESat, ICESat-2, launched in September 2018, adopted a new single photon counting system that can detect the earth's surface at a photon level (Tian and Shan 2021). The new laser instrument transmits six beams at the same time with a diameter of approximately 14 m for each shot, with an interval between the two laser footprints along the track of approximately 0.7 m. Compared with ICESat, ICESat-2 has a much denser sampling and higher spatial resolution. Zhang et al. (2019) found that the lake coverage of ICESat-2 was approximately twice that of ICESat over the Qinghai-Tibetan Plateau. Dandabathula and Rao (2020) selected and validated the ATL13 product with 46 near real-time measurements, which showed that the maximum uncertainty was several centimetres. Yuan et al. (2020) studied reservoirs and large lakes in China using ATL13, the results of which demonstrated that the relative altimetric error was 0.06 m. However, the uncertainty of some lakes in mountainous areas tended to be larger than that of flat lakes. Similarly, Xu et al. (2021) investigated the dynamics of global lakes and reservoirs and found that the variations in monthly water level had a high accuracy (RMSE = 0.08 m, $r = 0.999$) when compared with data from 33 stations.

Similar to ICESat, GEDI, launched in December 2018, is a full-waveform system whose main mission is to observe the forest canopy height and canopy vertical structure to characterize important carbon cycling (Adam et al. 2020). Data were collected in March 2019. Its product L2A was validated by in situ data using 8 lakes in Switzerland, which found that the mean difference between the elevations and that of hydrological stations varied from -13.8 cm to + 9.8 cm with standard deviations ranging from 14.5 to 31.6 cm (Fayad et al. 2020). In addition, Xiang et al. (2021) compared ICESat-2, ICESat, and GEDI over the Great Lakes and lower Mississippi River using in situ data from 22 gauge stations. The comparison revealed that the root mean square error was 0.06 m, 0.10 m, and 0.28 m in turn for the three altimeters, indicating an inferior accuracy of GEDI compared to ICESat-2 and ICESat. Similar results also appeared in Frappart et al. (2021)'s study, which showed that the results obtained by ICESat-2 had high accuracy; however, more results were contrasted for GEDI in the mountainous area. In regard to combining multiple satellites for long time-series retrievals of lake levels, Wang et al. (2019) constructed the time-series of Ngangzi Co Lake using TOPEX/Poseidon-family altimeter data from 1992 to 2017. The accuracy was approximately 0.17 m for TOPEX and 0.10 m for Jason 1/2/3. Using ICESat, Envisat, and CryoSat-2, Li et al. (2020) studied lake level changes in the middle and lower Yangtze River Basin from 2002 to 2017, which showed that the average biases of ICESat and Cryosat-2 compared with Envisat were 6.7 cm and 3.1 cm, respectively. Luo et al. (2021) combined ICESat with ICESat-2 datasets during 2003–2019 to monitor lake level and storage changes on the Tibetan Plateau; the results presented a mean water level change rate of 0.20 ± 0.04 m/yr.

Generally, there were a few performance evaluations solely for ICESat-2 or GEDI data, especially for ICESat-2. However, performance evaluations for a combination of these data for long time-series water level monitoring is very limited. Therefore, the objective of this study is to evaluate the performance of combining ICESat-2 and GEDI for inland water level retrieval and to analyse the main factors that influence the accuracy.

Data and methods

Study area

Four typical inland lakes, Lake Chaohu, Hongze, Gaoyou and Lake Taihu, were utilized for the performance evaluation. These four lakes were selected because they have relatively larger lengths (48–393 km) and widths (25–56 km) to cover sufficient ground tracks (Zhang et al. 2016). The area of the four lakes spans from 650 km^2 to 2427 km^2 under their normal water levels (Table 1) (Fang et al. 2017). In addition, the hydrological stations that recorded the water levels were accessible and could provide sufficient in situ gauge data for validation.

Table 1 Study lakes and the observation distributions of ICESat-2 and GEDI satellites

Lakes	Lats (N)	Lons (E)	Area (km^2)	ICESat-2 observations	Total days (d)	GEDI observations	Total days (d)
Chaohu Lake	31.41°–31.80°	117.26°–117.96°	770	2018/12–2021/06	31	2019/06–2021/08	42
Hongze Lake	33.00°–33.67°	118.17°–118.90°	2069	2018/10–2021/07	36	2019/07–2021/08	48
Gaoyou Lake	32.65°–33.16°	119.10°–119.50°	650	2018/11–2020/12	17	2019/07–2020/10	35
Taihu Lake	30.92°–31.55°	119.92°–120.57°	2427	2018/10–2021/07	35	2019/05–2021/06	25

Notes: the water surface area of each lake is under its normal water level

Data acquisition

In this study, the ICESat-2 inland surface water product ATL13 and the GEDI Level 2A product were adopted. The available data for ICESat-2 and GEDI spanned from October 2018 to July 2021 and May 2019 to August 2021, respectively, when the draft was in progress. These datasets can be downloaded from the Earth Data Center (https://search.earthdata.nasa.gov/). Among the current available products, the higher version 4 of ICESat-2 and version 2 of GEDI were used. The total available days of ICESat-2 and GEDI observations for each lake are listed in Table 1. Some example tracks of the two laser altimetry missions over the four lakes are illustrated in Fig. 1.

ICESat-2 ATL13 product

ICESat-2 adopts a single photon counting system with 10 kHz repetitions, which significantly improves the spatial resolution. There are six ground tracks that can be divided into three pairs (1 L and 1R, 2 L and 2R and 3 L and 3R). The energy ratio between strong and weak beams is approximately 4:1 (Neumann et al. 2020). The relative strength of the left and right beams depends on the orientation of the ICESat-2 observatory, which is adjusted approximately twice per year. ATL13 developed from the ATL03 geolocated photon product. It is segmented, with a minimum length of 100 signal photons to monitor small lakes. It provides along-track water surface heights, including the surface water height statistics (mean, standard deviation, slope), significant wave height, subsurface attenuation, and shallow bathymetry (when water clarity permits) (Jasinski et al. 2020). The orthometric heights, which were referenced in Earth Gravitational Model 2008 (EGM2008), were chosen to express the water level heights.

GEDI L2A product

The GEDI instrument is a full-waveform lidar. It includes three lasers. The "coverage" laser splits into two ground

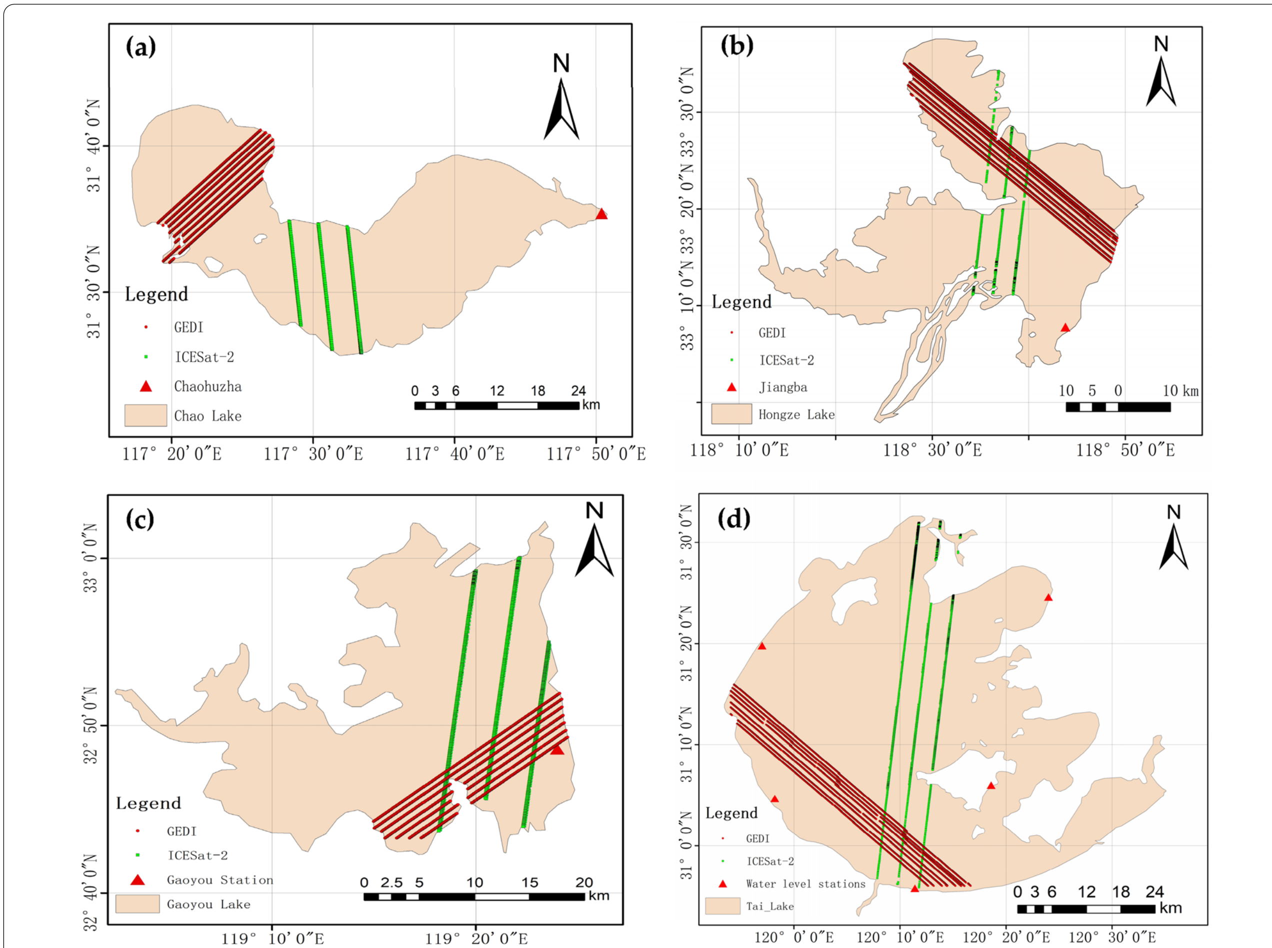

Fig. 1 Samples of ICESat-2 and GEDI over the four lakes and their hydrological stations: **a** Chaohu Lake (8 November 2020 for ICESat-2; 3 May 2020 for GEDI); **b** Hongze Lake (8 March 2019 for ICESat-2; 20 July 2020 for GEDI); **c** Gaoyou Lake (23 December 2018 for ICESat-2; 2 December 2019 for GEDI); **d** Taihu Lake (18 April 2019 for ICESat-2; 5 July 2020 for GEDI)

tracks, each of which then scatters, producing two ground transects. For the other two "full power" lasers, each produces two ground transects, thus producing 8 ground beams on the Earth's surface. The L2A geolocated elevations are derived from L1B products, which provides waveform processing results from multiple algorithms (Hofton et al. 2020). The surface height is referenced to the WGS84 ellipsoid. In addition, the product contains a preliminary set of quality flags and metrics that can be used to filter shots with poor geolocation performance and waveforms of low signal quality (Roy et al. 2021). According to the parameter settings in the data processing algorithm theory document (Fayad et al. 2020), the width of the second Gaussian filter (Smoothwidth_zcross) determines the position of the last detected peak (ground echo). Algorithms 1 and 4 were fixed to 6.5 ns, and the remaining Algorithms 2, 3, 5 and 6 were set to 3.5 ns. Thus, Algorithm 1 and Algorithm 2 can represent the remaining algorithms. In addition, we further tested whether the effective beams obtained by Algorithm 2 were more than those obtained by Algorithm 1. Therefore, only the parameter 'elev_lowestmode_a2' from Algorithm 2 was adopted in our study.

In situ data

The in situ data with reference to the Wusong elevation datum were used to evaluate the derived water levels from satellite laser altimetry. For Chao Lake, Chaohuzha Station monitors lake water levels at one-hour intervals. Gauge data were collected from the Ma'anshan water management system (http://www.masswj.net:9009/ahwater/website/index.html). The data for Hongze Lake, Gaoyou Lake and Taihu Lake are available from the Website of Jiangsu Provincial Department of water resources (http://jssslt.jiangsu.gov.cn/). The gauge data for Taihu Lake are the average from five stations; therefore, in the following description, the mean value will no longer be marked with specific station names, such as other lakes, but will be replaced by general water level stations. The detailed distribution of gauge stations at each lake (boundaries of the lakes were based on 2018) is shown in Fig. 1. To eliminate the near-shore footprint interference, the boundary of each lake was retracted inward by 50 m.

Methodology

The quality control strategy and the accuracy assessment metrics were proposed according to the characteristics of each mission as described below. The combined water level extraction can be divided into five steps: (1) screen laser footprints on each lake surface; (2) remove the outliers; (3) calculate the average of each track using the remaining laser footprints; (4) average all the effective tracks as the final water level of an individual date; and (5) adjust the bias between the two missions.

Outlier removal

Not all observations were valid due to the effects of atmospheric conditions and clouds. Referring to reference Xiang et al. (2021), several steps were implemented to remove the outliers. For both data, the first step was to estimate the elevation bin whose step size was set to be 1 m, which was large enough for various water surface slopes. Then, those heights within the maximum bin (mode) that possessed the highest frequency were preserved. The rest outside the 1 m interval from the mode were discarded as outliers. In the second step, the mean water level was calculated based on the remaining heights, and the root mean square (RMS) of residuals between the heights and the mean water level was estimated. Those values were considered outliers if the absolute differences between the observations and the mean water level were greater than 3 RMS.

Furthermore, stricter criteria were carried out for GEDI L2A. Parameters including the quality flag and waveform number flag were employed to remove the low-quality and nonwater surface footprints. First, the above useful data were screened by a quality flag that equals 1, which means that the L1B waveforms met certain criteria based on energy, sensitivity, amplitude, and real-time surface tracking. Hence, they could be further processed (Fayad et al. 2020). Subsequently, the waveform number flag that equals 1 was selected to guarantee waveform returning from the lake surface. Finally, the 3 RMS criterion was implemented again to further remove outliers. In the fourth step, even if the single beam met the above criteria, the mean value of the beams of the specific day was removed if the differences between the beams of the same day were larger than 1 m. In addition, for direct comparison and combining with ICESat-2, the surface elevations of the GEDI were transformed to orthometric heights using the EMG2008 $2.5' \times 2.5'$ resolution geoid model using the software tool (https://geographiclib.sourceforge.io/html/geoid.html).

Accuracy assessment metrics

Lake water levels retrieved by individual missions were validated directly through in situ gauge data. The statistical metrics include Person's correlation coefficient (R) and the P value of the regression Model (P), the mean relative bias (MRB) calculated from repeated tracks of different phases and the corresponding in situ *data*, the mean absolute error (MAE) after normalizing the vertical datum, and the root mean square error (RMSE) of the differences between altimetric and hydrological station data, which can be calculated by Eqs. 1, 2, 3, 4. In addition, to remove the influence of a few large values on the mean, the boxplot was used to show the lower and upper limits, median, and the first and third quantiles of the absolute error. The MRB, MAE, and RMSE were calculated for the four lakes based on all the effective observations of this study. For the evaluation of the combined results, visual and quantitative comparisons of monthly and yearly mean and increase (change) rates were used:

$$R = \sqrt{1 - \frac{\sum_{i=1}^{N}(hs_i - hg_i)^2}{\sum_{i=1}^{N}\left(hg_i - \overline{hg_i}\right)^2}}, \tag{1}$$

$$MRB = \Delta(hs_i - hs_j) - \Delta(hg_i - hg_j), \tag{2}$$

$$MAE = \frac{1}{N}\sum_{i=1}^{N}\left|hs_i - hg_i\right|, \tag{3}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(hs_i - hg_i\right)^2}, \tag{4}$$

where hs is the satellite lake water height derived from the ICESat-2 or GEDI; hg is the gauge lake water height from hydrological stations; $\overline{hg_i}$ is the average of the gauge data; and $\Delta(hs_i - hs_j)$ is the difference between hs_i and hs_j, which represents the heights of adjacent repeated tracks i and j.

Results and analysis

To examine the accuracy of the water level acquired by each mission, the errors of individual satellites were analysed first. Then, the absolute bias of the GEDI was corrected, and the combined long time-series lake levels were generated. In addition, the influencing factors on the accuracy of the observations were investigated.

Lake levels retrieved by individual missions

Consistency and relevance evaluation

Figure 2 displays the consistency and correlation between the estimated water levels and the in situ gauge data. This result indicated that there was a high consistency between the variation trend of the estimated and observed water levels of ICESat-2, and the difference between them was mainly caused by the inconsistency of the water level height datum. However, compared with ICESat-2, the consistency between the variation trend of the estimated and observed water levels of the GEDI was lower. Figure 3 shows that even though the effective ICESat-2 monitoring days were different, high correlations between altimetry and gauge data were found for the four lakes. There were up to 36 most effective monitoring days for Hongze Lake, and the highest correlation of Gaoyou Lake was up to 0.995 with $P<0.001$. Based on their high consistency and correlation, these offsets were considered to be the systematic bias between EGM2008 and Wusong elevation.

The effective days of the GEDI were 18, 22, 17, and 10 days for Lake Chaohu, Hongze, Gaoyou, and Taihu, respectively, and the R spanned from 0.560 to 0.952, which demonstrated that the efficiency of the data and the accuracy of the GEDI were relatively low and inferior to those of ICESat-2. Among them, Chaohu Lake had the highest correlation ($R=0.952$, $P<0.001$), while Taihu Lake had the lowest correlation ($R=0.560$, $P>0.05$) and the fewest effective data. Compared to the total observation days, the number of effective days indicated that the GEDI had more outliers or data that could not be used due to the large error.

Relative and absolute accuracy evaluation

To remove the systematic bias and errors caused by the differences in geographical locations and observation times of laser footprints, we first chose the repeated tracks and their corresponding water levels measured at nearly the same time for relative accuracy evaluation. The differences derived from Eq. 2 indicate the height difference of two adjacent dates from the observations of the repeated tracks or the corresponding measurement difference from hydrological stations. The difference comparison for Lake Taihu is visually illustrated in Fig. 4. Except for several pairs, most of the pairs had small differences. The quantitative MRBs of the four lakes are tabulated in Table 2. The MRB ranged from 0.01 m to 0.05 m with the standard derivation of 0.07–0.20 m, which revealed that the relative error of water level estimation by ICESat-2 was within 0.05 m.

For direct comparison, the vertical datum of the in situ data was adjusted to the EGM2008 datum by subtracting the mean system offsets. The MAE of the four lakes spanned from 0.03–0.10 m, with RMSE ranging from 0.04 m to 0.13 m (Table 2). In addition, the boxplot of MAE is detailed in Fig. 5, which illustrates that the medians of the four lakes were all under 0.08 m. Among them, Gaoyou Lake had the highest accuracy with minimum MAE and RMSE. Lake Taihu had relatively smaller MAE and RMSE values. However, several outliers (abnormally large errors) appeared on Lake Chaohu and Hongze. Lake Hongze had the largest MAE and RMSE and relatively large outliers, which indicated that there was a relatively large difference between ICESat-2 estimations and the measured water levels.

In addition, the influence of strong and weak beams on the accuracy of water level extraction was further analysed. The MAE of the four lakes' strong beam observations versus that of weak beams improved within 0.01 m, which indicated that the performance of strong beams

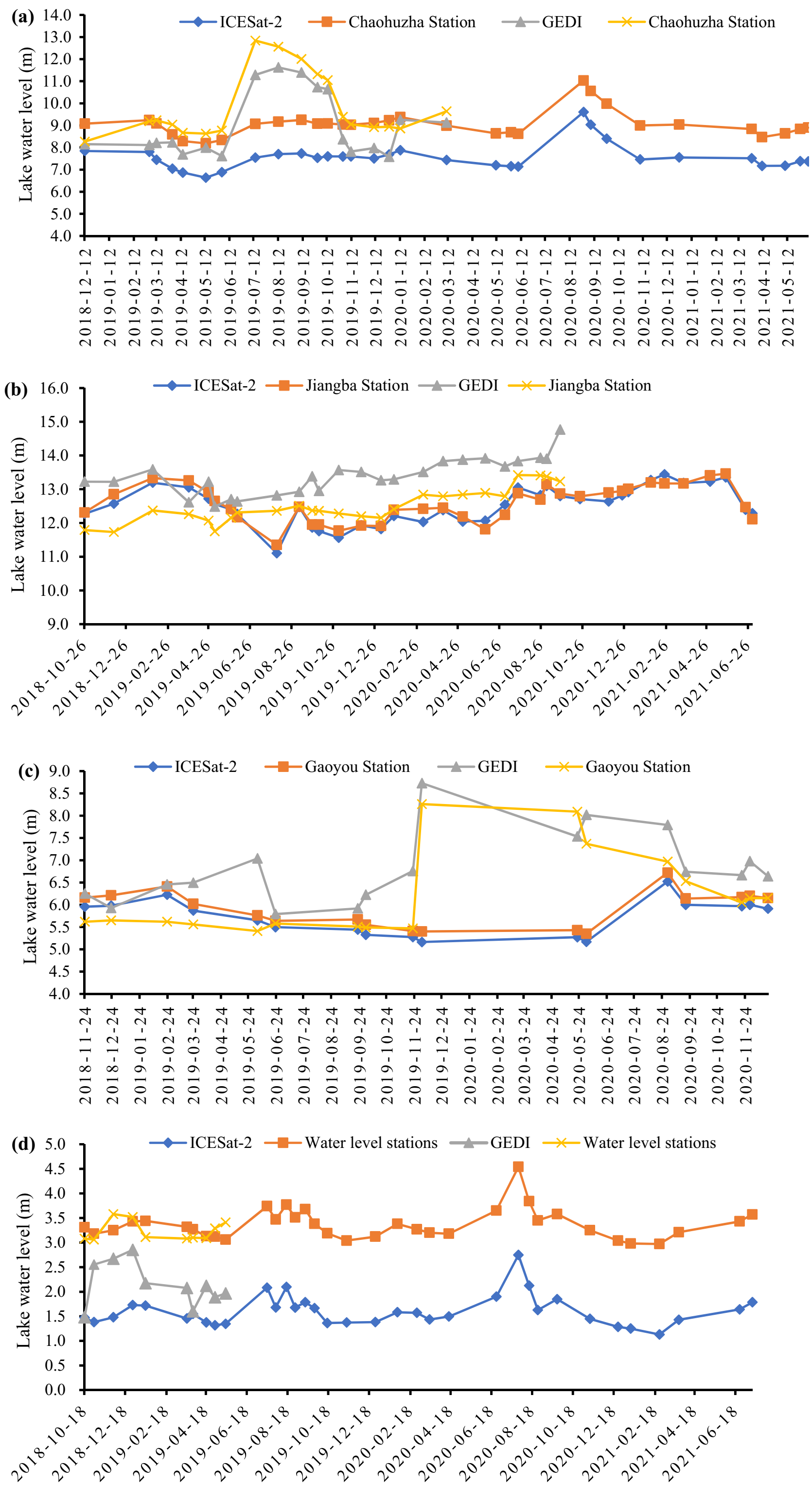

Fig. 2 Consistency evaluation of ICESat-2 and GEDI estimated lake levels (the timeline is based on ICESat-2 acquisition dates) with in situ measurements for **a** Chaohu Lake, **b** Hongze Lake, **c** Gaoyou Lake, and **d** Taihu Lake

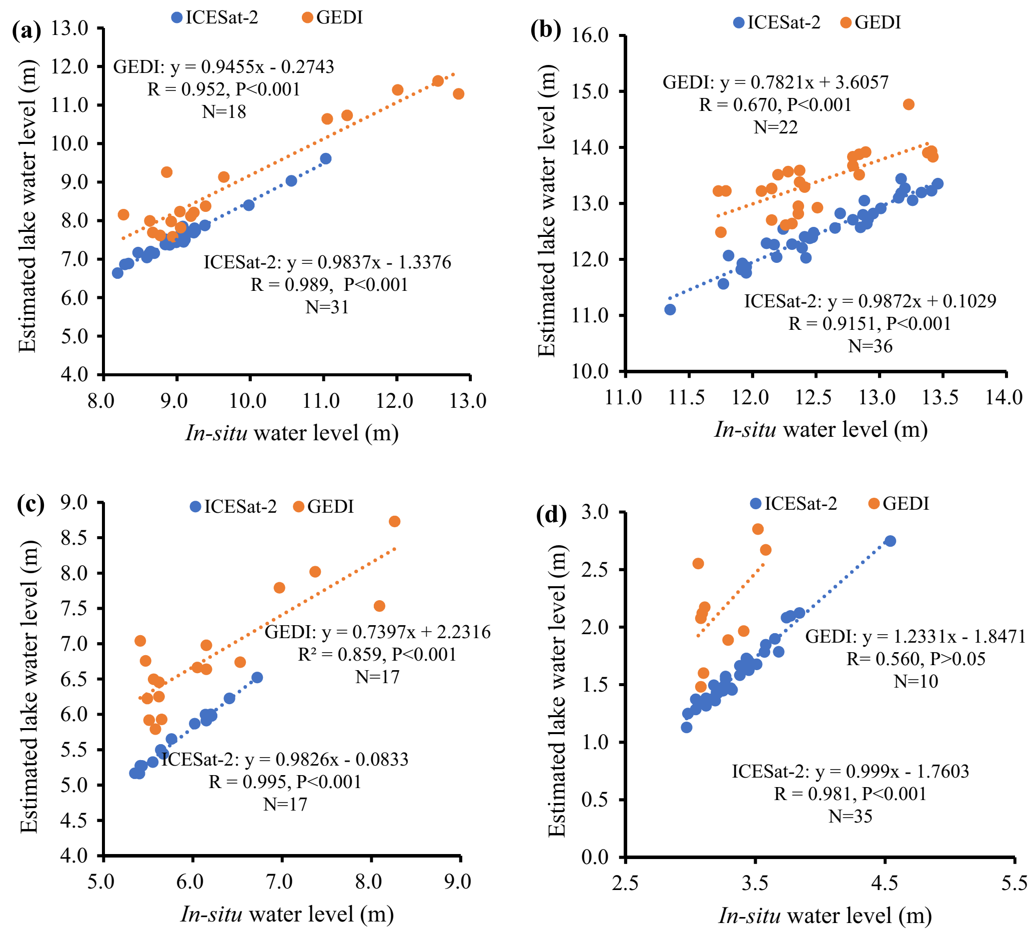

Fig. 3 Correlation evaluation of ICESat-2 and GEDI estimated lake levels with in-situ measurements for **a** Chaohu Lake, **b** Hongze Lake, **c** Gaoyou Lake, and **d** Taihu Lake

was slightly better than that of weak beams for lake water level estimation.

The indirect accuracy of repeated orbits of the GEDI was not evaluated due to fewer valid data, and there were no repeated tracks among the effective data. Table 2 lists the MAE and RMSE as the direct comparison results, which ranged from 0.31 m to 0.38 m and 0.35 m to 0.46 m for the four lakes. Obviously, the larger positive bias indicated that the GEDI overestimated the water levels with lower accuracy.

Figure 5 further depicts the boxplot of the MAE for the GEDI. The medians were 0.24 m, 0.37 m, 0.21 m, and 0.33 m for Lake Chaohu, Hongze, Gaoyou and Taihu, respectively. The MAE of Hongze Lake was larger than that of the other three lakes, whether based on ICESat-2 or GEDI. This was perhaps because the water velocity in the subareas of Hongze Lake was more sensitive to the change in wind speed resulting from wind-driven circulation. Moreover, the conversion of the vertical datum introduced additional errors.

To examine the influence of beam strength on the accuracy of water level measurements, mean water levels were computed first from coverage beams (beam 0000, beam 0001, beam 0010, and beam 0011) and full power beams (beam 0101, beam 0110, beam 1000, and beam 1011). Then, the bias between different beams and the in situ data was analysed. The mean errors of coverage and full power beams between observations and in situ water levels were 0.84 m and 0.72 m, 1.14 m and 1.06 m, 0.89 m and 0.64 m, and 0.68 m and 0.65 m for Chao Lake, Hongze Lake, Gaoyou Lake and Tai Lake, respectively. The accuracies were correspondingly improved by 0.12 m (14.3%), 0.08 m (7.0%), 0.25 m (28.1%), and 0.03 m (4.4%), which proved that full power beams could yield a higher accuracy in comparison to the coverage beams. Therefore, full power beams of the GEDI are recommended for water level retrieval.

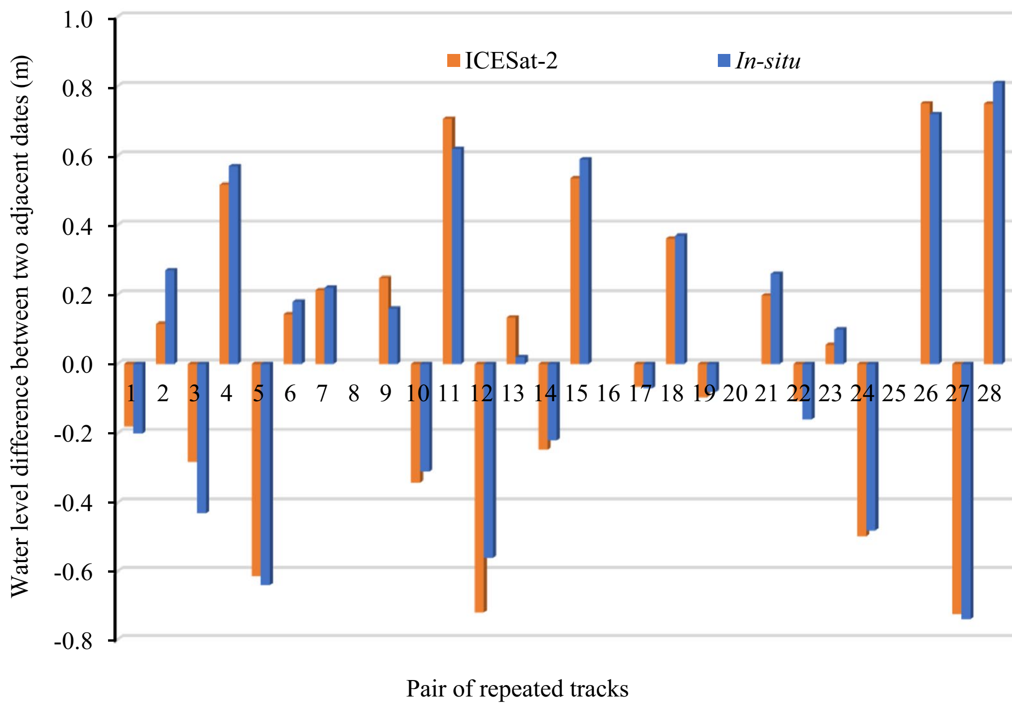

Fig. 4 The relative difference between two adjacent dates of repeated tracks and the corresponding in situ gauge data of Taihu Lake

Table 2 The evaluation of ICESat-2 and GEDI versus the in situ water levels acquired at nearly the same time

Lakes	ICESat-2			GEDI	
	MRB (m)	MAE (m)	RMSE (m)	MAE (m)	RMSE (m)
Chaohu Lake	− 0.02 ± 0.14	0.06 ± 0.05	0.08	0.35 ± 0.28	0.45
Hongze Lake	0.05 ± 0.20	0.10 ± 0.09	0.13	0.38 ± 0.20	0.43
Gaoyou Lake	0.01 ± 0.07	0.03 ± 0.02	0.04	0.33 ± 0.32	0.46
Taihu Lake	− 0.01 ± 0.07	0.05 ± 0.03	0.06	0.31 ± 0.16	0.35

Lake levels retrieved by combining two missions

After adjusting the GEDI results by subtracting the mean error between the in situ measurements of each lake, long time-series lake water levels were derived. Figure 6 illustrates the combined dynamics of Lake Hongze and their corresponding in situ measurements. Even after bias adjustment, the GEDI's overall water levels were higher or lower than those of Jiangba Station. For example, the water levels on October 8, 2020, and August 5, 2021, were obviously higher than those in the in situ data. Nevertheless, the general change trend from 2018 to 2021 of the two datasets was consistent. Both presented a declining trend in 2019, with the lowest water level of 11.35 m on August 4, 2019, and an increasing trend, which reached its maximum in September and then declined again. The correlation coefficients between the combined results and the in situ water levels of the four lakes were 0.964, 0.852, 0.888 and 0.899 for Lake Chaohu, Lake Hongze, Lake Gaoyou, and Lake Tai, respectively. Moreover, Fig. 7 further displays the monthly and annual changes. Except for only two months of records in 2018, the lake water levels in the synchronous months generally showed a similar downwards trend and then an upwards trend from 2019 to 2021. However, there were seasonal differences in each year. In 2019, the combined water levels for July and August were 12.11 m and 11.79 m, respectively, with an increase of − 0.32 m, and the lowest water level occurred in August. Those for the in situ water level were 11.76 m and 11.86 m, respectively, with an increase of 0.10 m. The lowest water level occurred in July. The difference can be reflected in the GEDI estimations on 4 July 2019 (Fig. 6), which also indicated that the GEDI overestimated the water levels. In 2020, they increased by − 0.06 m and + 0.26 m from August to September. In 2021, the changes from March to April were − 0.66 m and + 0.23 m, respectively.

For the intra-annual change in 2019, both the estimated and in situ data showed that the lake water levels fell after February until they reached the lowest water level

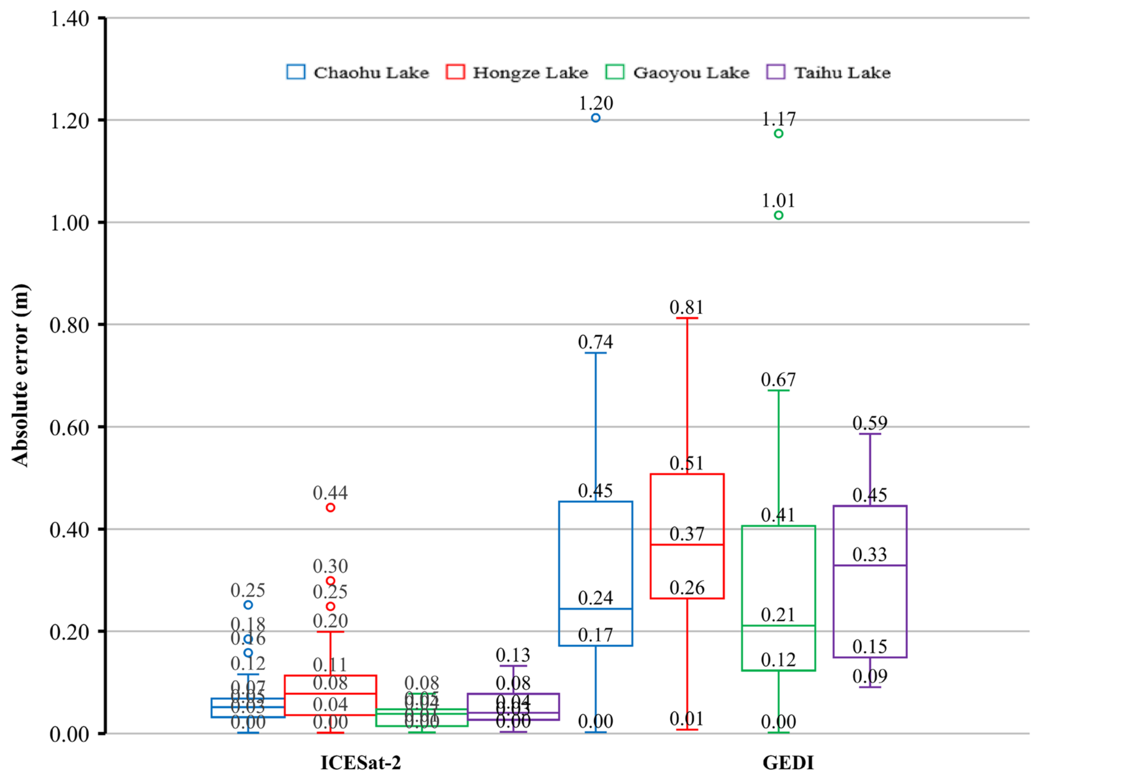

Fig. 5 Boxplot of MAE between ICESat-2 and GEDI observations and in situ water levels for the four lakes (the horizontal line numbers from bottom to top indicate the lower edge, first quantile, median, third quantile and upper edge in turn, and the discrete circulars represent the outliers)

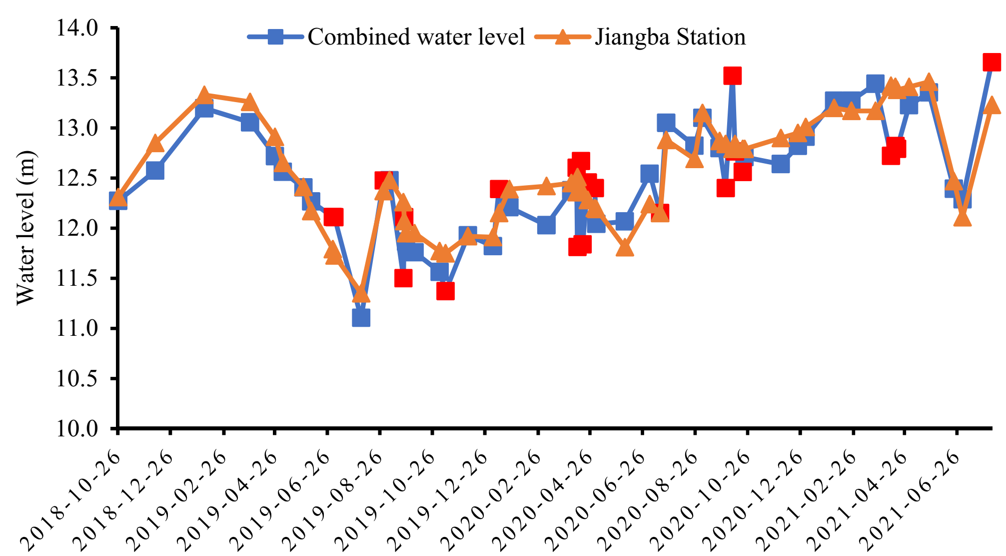

Fig. 6 Water levels retrieved by combining ICESat-2 (the blue squares) and adjusted GEDI (the red squares) for Hongze Lake

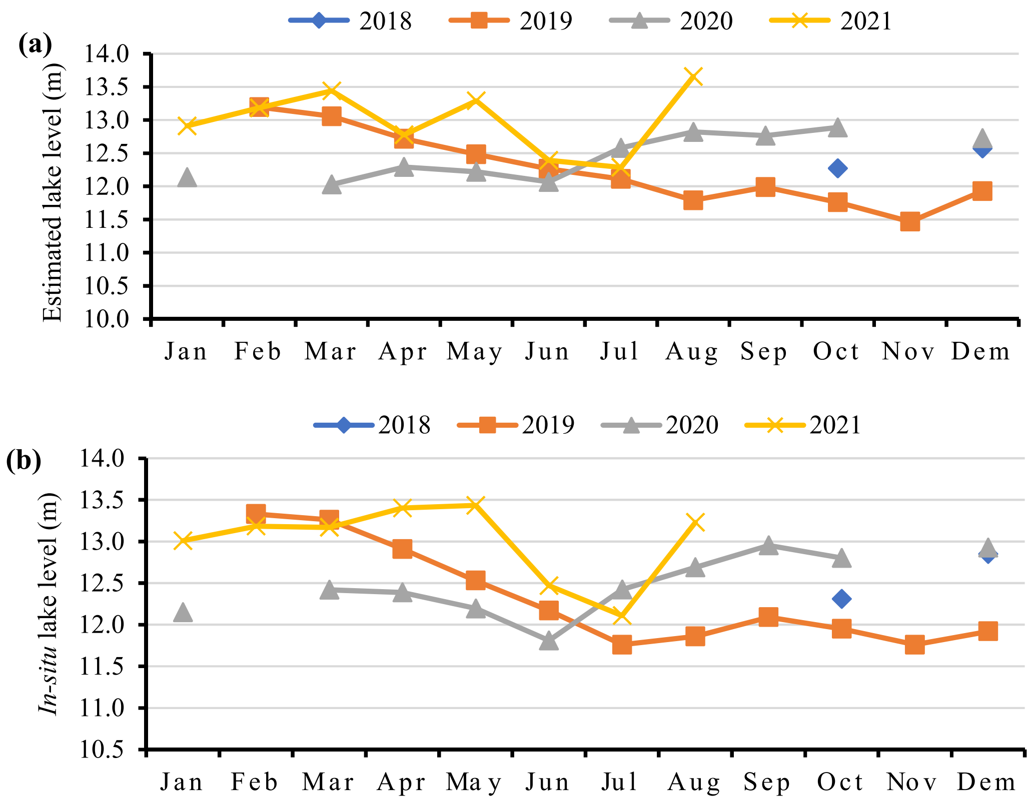

Fig. 7 Comparison of average water levels of each monthly and yearly variation of Hongze Lake: **a** estimated water levels; **b** in situ gauge water levels

in August or July. This condition was consistent with the news report that the average water level of Hongze Lake fell to 11.49 m (below the lowest navigable dead water level of 11.50 m) on July 17 due to the continuous drought and limited rain in the summer of 2019, the increase in agricultural irrigation water and the absence of passenger water upstream. The estimated water level (Fig. 7a) in August was slightly 0.07 m lower than that of the in situ gauge (Fig. 7b). Then, the water level rose to its highest value from August to September, began to decline from October to November, and finally increased again in December. For 2020, both presented a declining trend from March to June and then increased from June to October. The differences occurred in June, which was 0.16 m higher, and September, which was 0.18 m lower than that of the in situ measurements. For 2021, there was an upwards trend from January to May and a downwards trend from May to July. The combined estimated results in April were from GEDI observations and were much lower than those of in situ water levels, which can also be seen from the water level of individual days in Fig. 6.

For interannual change, assuming that the water level in 2018 can be expressed by the last two months, the annual average water levels for 2018, 2019, 2020 and 2021 were 12.42 m, 12.25 m, 12.45 m, and 12.99 m, respectively. Compared with the previous year, the annual increases (changes) were − 0.17 m/yr, 0.20 m/yr and 0.54 m/yr, with an average of 0.19 m/yr. The corresponding annual average water levels from Jiangba station were 12.58 m, 13.32 m, 12.43 m and 13.00 m. The water levels increased by − 0.26 m, 0.15 m, and 0.53 m year by year, with an average annual increase of 0.14 m/yr. The annual increase difference of the two datasets was 0.05 m/yr, which indicated that the combination of the ICESat-2 and GEDI missions had significant potential to monitor long time-series lake water levels. In addition to Hongze Lake, the comparisons of the other three lakes' annual changes retrieved by the combined results and the in situ measurements are tabulated in Table 3. The mean annual increases in the estimated and in situ water levels were − 0.11 m/yr and − 0.05 m/yr, − 0.11 m/yr and − 0.09 m/yr, and − 0.06 m/yr and − 0.04 m/yr for Chao Lake, Gaoyou Lake and Tai Lake, respectively. The annual differences between both datasets were 0.06 m/yr, 0.05 m/yr, 0.05 m/yr and 0.02 m/yr.

Table 3 Comparisons of yearly means and water level increases acquired by combining ICESat-2 and GEDI between in situ data for four lakes

Lakes	Yearly change	Estimated lake level (m)				In situ lake level (m)			
		2018	2019	2020	2021	2018	2019	2020	2021
Chaohu	Mean	7.85	7.38	7.86	7.50	9.08	8.90	9.42	8.93
	Increase		**− 0.47**	**0.48**	**− 0.35**		**− 0.19**	**0.53**	**− 0.50**
Hongze	Mean	12.42	12.25	12.45	12.99	12.58	12.32	12.43	13.00
	Increase		**− 0.17**	**0.20**	**0.54**		**− 0.26**	**0.15**	**0.53**
Gaoyou	Mean	5.97	5.58	5.76	/	6.19	5.71	6.01	/
	Increase		**− 0.39**	**0.18**	**/**		**− 0.47**	**0.30**	**/**
Taihu	Mean	1.54	1.56	1.72	1.36	3.32	3.31	3.47	3.20
	Increase		**0.02**	**0.16**	**− 0.36**		**− 0.01**	**0.16**	**− 0.27**

Discussion

Factors affecting combining lake level accuracy

The influence on lake level accuracy may come from several aspects. First, except for the area variation of each lake and the selection of the footprints over the water lake surface, as a single laser altimetry satellite, the product quality itself of each mission was important for the accurate extraction of lake water levels. For ICESat-2 ATL13, the error may be inherited from ATL03, which was the global geolocated ellipsoidal height product of each photon event. In addition, the water backscatter model used in ATL13 and the processing methods may influence the accuracy (Jasinski et al. 2020). Similarly, the GEDI L2A was derived from the L1B geolocated return waveforms, which were easily affected by cloud and algorithm settings (Hofton et al. 2020). Thus, the results from different algorithms would affect the accuracy of the final water levels. Second, the outlier removal method was implemented for the two missions, especially for the GEDI, which had more unqualified footprints. For example, the bin with the maximum frequency may filter out the wrong water level for a few beams when the bin frequency of the correct water level was lower. Additionally, applying the geoid transformation model or mean constant as offsets for vertical shifting between different height data would induce errors. Finally, the geophysical difference and observation time difference between the satellite tracks and hydrological stations would inevitably introduce errors. In our study, we assessed all observations for absolute validation. Selecting the laser footprints within a certain radius of hydrologic stations (such as 10 km) as the validation samples would weaken the influence of geographical location on errors. In addition, the water levels acquired within a laser footprint of the laser altimetric satellite represented an instantaneous value at a certain moment, while the water levels of hydrological stations were not the real-time water level at the corresponding time but the average water levels of a certain time interval. The above factors together led to the error of the combined water levels.

Implications for inland water level dynamics monitoring

In addition to the accuracy of water level estimation, the spatial and temporal resolutions of a laser satellite altimetry mission were critical for monitoring inland water level dynamics. Table 1 shows that compared with ICESat-2, the GEDI can obtain more observation data in a shorter time according to the total observation days of the two satellites. However, after the outliers were eliminated, the effective data showed that the abnormal rate of the GEDI was high, and more than half of the data were removed. The effective data rates of Chaohu Lake, Hongze Lake, Gaoyou Lake and Taihu Lake were 42.86% (18/42), 45.83% (22/48), 48.57% (17/35) and 40.00% (10/25), respectively. Nevertheless, compared with ICESat-2 alone, the temporal resolution of the four lakes can be improved by 58.06% (18/31), 66.11% (22/36), 100% (17/17) and 28.57% (10/35), which revealed that the combination of the two missions can significantly enhance the monitoring frequency and provide more detailed information on water level variations. Similarly, Shu et al. (2017) adopted the number of observations within the 30 km radius of a station to estimate the annual observation frequency for the Great Lakes and found that the GEDI had the highest frequency, with 14.80 observations per year, followed by ICESat-2 (10.43), which was approximately five and four times that of ICESat-1 (2.45). The spatial resolution determines the size of the water body that can be measured. Given that ICESat-2 and GEDI possess smaller footprints and operate simultaneously, the dynamics of inland lakes can be optimally retrieved once more products of both satellites are available.

Conclusions

Accurate lake levels are necessary to investigate the change in hydrological processes, related problems of water resources and ecosystems, etc. New laser altimetry satellites provide an opportunity for monitoring water level dynamics, especially in remote regions that lack water level stations. In this paper, the water levels retrieved from two satellite altimetry ICESat-2 and GEDI were evaluated and validated against ground-measured water levels from their gauge stations using four typical lakes. Accuracy assessment metrics indicated that the performance of ICESat-2 showed strong correlations (R ranging from 0.957 to 0.995) and high accuracy (RMSE 0.04 m-0.13 m). The quantitative results revealed that the accuracy of water level estimation by ICESat-2 can reach within 0.05 m, and strong beams have slightly better accuracy than weak beams. However, GEDI had relatively low correlations (R varying 0.560–0.952) and accuracy (RMSE spanning from 0.35 m to 0.46 m). The full power beams can better improve the accuracy of the retrieval results.

After bias adjustment between the two missions, the combined long time-series water levels illustrated a consistent change trend with the hydrological stations over the four lakes. The annual increase differences between the estimated and the in situ data were 0.06 m/yr, 0.05 m/yr, 0.05 m/yr and 0.02 m/yr for Lake Chaohu, Hongze, Gaoyou and Taihu, respectively. The encouraging results suggested that the combination of ICESat-2 and GEDI products could significantly advance our understanding of the monthly, seasonal, and yearly changes, which can provide a valuable reference for hydrological and climatic studies.

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Author contributions
Conceptualization, ZZ; methodology, ZZ and GC; software, ZZ, GC and XG; validation, YB, XG, and JB; formal analysis, ZZ and GC; data curation, XG and JB; writing—original draft preparation, ZZ; writing—review and editing, ZZ, YB; and GC; visualization, ZZ and XG. All the authors read and approved the final manuscript.

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Availability of data and materials
The data used in this work may be obtained from the paper indicated links in the manuscript.

Declarations

Competing interests
The authors declare no conflict of interest.

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