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 lakes' dynamic change, the impact of climate change and human activities on lakes, etc. This paper first individually evaluated the performance of newly released Global Ecosystem Dynamics Investigation (GEDI) and the successor of 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 lake levels of the two missions were combined to derive long time-series lake water levels. Compared with *in-situ* water levels, the validations revealed that very accurate results were obtained by ICESat-2 with R varing 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 combination, the bias correction of GEDI was carried out. The annual change rate differences between the combined 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 monthly, seasonal and annual dynamics of inland lake water levels captured by combined GEDI and ICESat-2 missions agree well with measuremnts from hydrological stations. These encouraging results demonstrate the great potential for frequent and accurate lake level monitoring, which could be a valuable resource for the studies of hydrological and climatic change.

Introduction

A full understanding of lake level dynamics is vital to study the impact of climate change and human activities on lakes, and provide scientific basis for regional ecological environment protection (Frappart et al., 2018). In recent years, satellite altimetry technology has developed into an extensive way to monitor lake water levels. Radar satellites can quickly obtain lake surface elevations over large-scale and under all-weather conditions, such as Topex/Poseidon, Envisat, and Cryosat-2 (Busker et al., 2019; Crétaux et al., 2011; Velpuri et al., 2012). However, the accuracy of the observations could be influenced by their larger size of 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 feasible for the observation of small lakes or reservoirs (Li et al., 2020a).

As 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; Wang et al., 2013). Such as, Srivastava et al. (2013) analyzed lake levels in Himalaya–Karakoram from 2003 to 2009, which found that 10 lakes displayed different increasing trend, while the other 3 lakes presented decreasing trend. Besides, Phan et al. (2012) investigated Tibetan plateau 154 lakes and found that the average increase rate was 0.20 m/yr. As the second generation satellite of ICESat, ICESat-2, launched in September 2018, adopted new single photon counting system that can detect at a photon level (Tian et al., 2021). The new laser instrument transmits six beams at the same time with a diameter about 14 m of each shot and the interval between two laser footprints along the track is about 0.7 m. Compared with ICESat, ICESat-2 has a much higher spatial resolution and denser sampling. Zhang et al. (2019) found that the lake coverage of ICESat-2 was about twice that of the ICESat over Qinghai Tibet Plateau. Dandabathula and Rao (2020) selected validated the ATL13 data product with 46 observations with near real-time measurements, which showed maximum uncertainty with several centimeters. Yuan et al. (2020) studied reservoirs and large lakes in China, the results of ATL13 demonstrated the relative altimetric error was 0.06 m, but the uncertainty of some lakes in mountainous areas tended to be larger than the flat ones. Xu et al. (2021) investigated the dynamics of global lakes and reservoirs using ATL13, and found that the variations in monthly water level with a high accuracy (RMSE = 0.08 m, r = 0.999), when compared with data from 33 stations.

Similar to ICESat, GEDI is full waveform system, launched in December, 2018, whose main mission is to observe the forest canopy height, canopy vertical structure to characterize important carbon cycling, etc (Adam et al., 2020). It began to collect data 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 varying 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 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 were obtained by ICESat-2 with high accuracy, however, more results were contrasted for GEDI in the mountainous area. In regards to long time-series retrieving of lake levels by combining multi-satellite, 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 about 0.17 m for TOPEX and 0.10 m for Jason 1/2/3. Using ICESat, Envisat, and CryoSat-2, Li et al. (2020b) 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 comparing 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 lakes level and storage changes on Tibetan Plateau, whose results presented a mean water level change rate with 0.20 ± 0.04 m/yr.

Generally, although there were a few performance evaluations on ICESat-2 or GEDI data alone, especially for ICESat-2, the performance of combining both for the long-term water level monitoring is very limited. Therefore, the objective of this study is to evaluate the performance of the combined ICESat-2 and GEDI for inland water level retrieval, and analyze main factors that influence the accuracy.

Data And Methods

Study area

Four inland typical lakes including Lake Chaohu, Hongze, Gaoyou and Lake Taihu were utilized for the performance evaluation. These four lakes were selected because they have relatively larger length (48 km-393 km) and width (25 km-56 km) to cover sufficient ground tracks (Zhang et al., 2016). The area of the four lakes spans from 650 km^2-2427 km^2 under their normal water levels (Table 1) (Fang et al., 2017).

Besides, the hydrological stations that record the water levels were more accessible, which can provide sufficient *in-situ* gauge data for the validation.

Data acquisition

In this study, ICESat-2 inland surface water product ATL13 and GEDI Level 2A were adopted. The available ICESat-2 and GEDI spanned from October 2018 to July 2021 and May 2019 to August 2021, respectively, when the draft was writing. These datasets could 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 utilized. The total available days of ICESat-2 and GEDI observations for each lake were listed in Table 1. Some example tracks of the two laser altimetry missions over the four lakes were illustrated in Fig.1.

ICESat-2 ATL13 product

ICESat-2 adopts single photon counting system with 10khz repetitions, which significantly improves spatial resolution. There are six ground tracks that can be divided into three pairs (1L and 1R, 2L and 2R and 3L and 3R). The energy ratio between strong and weak beams of approximately 4:1 (Neumann et al., 2020). Relative strength of left and right beams depends on the orientation of the ICESat-2 observatory, which was adjusted about twice per year. ATL13 developed from the ATL03 geolocated photons product. It was 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., 2019). The orthometric heights which are reference to Earth Gravitational Model 2008 (EGM2008) were chose to express water level heights.

GEDI L2A product

GEDI instrument is a full-waveform lidar. It includes three lasers. The “coverage” laser splits into two ground tracks that then each scatters producing two ground transects. For the other two “full power” lasers, each produces two ground transects, thus, totally, producing 8 ground beams on the Earth’s surface. The L2A geolocated elevations were derived from L1B products, which provided waveform processing results for multiple algorithms (Hofton et al., 2020). The surface height was referenced to WGS 84 ellipsoid. Besides, 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 setting in data processing algorithm theory document (Fayad et al., 2020), only the results from algorithm 2 were adopted in our study.

Table 1

Study lakes and the observations distribution 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.

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, the Chaohuzha Station monitored lake water levels at one hour interval. Gauge data were collected from Ma'anshan water management system (http://www.masswj.net:9009/ahwater/website/index.html). The data for Hongze Lake, Gaoyou Lake and Taihu Lake were available from the Website of Jiangsu Provincial Department of water resources (http://jsslt.jiangsu.gov.cn/). The detailed distribution of gauge stations at each lake (boundaries of the lakes were based on year 2018) was shown in Fig.1. In order to eliminate the near shore footprints' interference, the boundary of each lake was retracted inward by 50m.

Methodology

We put forward the quality control strategy according to the characteristic of each mission as described below, and the accuracy assessment metrics. The combined water level extraction can be divided into five steps: 1) screening laser footprints on each lake surface, 2) outliers' removal, 3) average the remaining laser footprints of each track, 4) average all the effective tracks as the final water level of an individual date. 5) bias adjustment between the two missions.

Outlier removal

Not all obervations were valid due to the affection of atmospheric conditions and clouds . Refered to the reference Xiang et al. (2021), several steps were implemted to remove the outliers. For both data, the first step was to estimate elevation bin whose step size was set to be 1 m that was large enough for various water surface slopes. Then, those heights within the maximum mode that possessed the highest frequency were preserved, the rest outside the 1m 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 as outliers if the absolute differences between the observations and the mean water level were greater than 3 RMS.

Furthermore, more stricter criteria were carried out for GEDI L2A, the parameters including the quality flag and waveform number flag were employed to remove the low quality and non-water surface footprints. Firstly, the above useful data were screened by quality flag whose value was equal to 1 means that the L1B waveforms met certain criteria based on energy, sensitivity, amplitude, and real-time surface tracking, hence could be further processed. Subsequently, the waveform number flag with 1 was selected for guaranteeing waveform returned from lake surface. Finally, the 3 RMS criterion was implemented again for further removing outliers. In the fourth step, even if the single beam met the above criteria, if the differences between the beams of the same day were larger than 1m, the mean value of the beams of the specific day was removed for its large uncertainty. Besides, for direct comparison and combining with ICESat-2, the surface elevations of GEDI were transformed to the orthometric heights using EMG2008 2.5'x2.5' resolution geoid model using the software tool (https://geographiclib.sourceforge.io/html/geoid.html)

Accuracy assessment metrics

Lake water levels retrieved by individual mission were validated directly through *in-situ* data. The statistical metrics include Person's correlation coefficient (R) and P value of regression model (P), mean relative bias (MRB) calculated from repeated tracks of different phases and the corresponding *in-situ data*, the absolute mean error (AME) after normalizing vertical datum, and Root Mean Square Error (RMSE) of the differences between hydrological station and altimetric data, which can be calculated as formulas (1)-(4). Besides, to remove the influence of a few large values on the mean, the boxplot was used to show the lower and upper limits, median, the first and third quantiles of the absolute error. The MRB, AME, and RMSE were calculated for the four Lakes based on all the observations of this study. For the evaluation of the combined results, visual and quantitative comparison of monthly and yearly mean and increase (change) rates were used.

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

$$MRB = \Delta(hs_i - hs_j) - \Delta(hg_i - hg_j) \#(2)$$

$$MAE = \frac{1}{N}\sum_{i=1}^{N}\left|hs_i - hg_i\right| \#(3)$$

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

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; $\bar{hg_i}$ is the average of the gauge data; $\Delta(hs_i - hs_j)$ means the difference of hs_i and hs_j, which represent the heights of adjacent repeated tracks.

Results And Analysis

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

Lake levels retrieved by ICESat-2

Consistency and relevance evaluation

Fig. 2 displayed the consistency and correlation between the estimated water levels and the *in-situ* gauge data. It indicated that there was a high consistency between the variation trend of estimated and observed water levels, and the difference between them was mainly caused by the inconsistency of water level height datum. Fig. 3 presented that even though the effective monitoring days are different, high correlations between altimetry and gauge data were found for four lakes. The most effective days of Hongze Lake were up to 36 days, and the highest correlation of Gaoyou Lake was up to 0.995 with $P<0.001$. Based on their high consistency and correlation, the offsets were considered to be the systematic bias between EGM2008 and Wusong elevation.

Relative and absolute accuracy evaluation

In order to remove the systematic bias, errors caused by the differences of geographical locations and observation time of laser footprints, we firstly chose the repeated tracks and the corresponding water levels measured nearly at the same time for relative accuracy evaluation. The differences derived from Eq. (2) mean the height difference of two adjacent dates from the observations of the repeated tracks, or the corresponding measurements difference of two dates' water levels from the hydrological stations. The difference comparison of Lake Taihu was visually illustrated in Fig. 4. It can be seen that except for several pairs, most of the pairs had small differences. The quantitative MRBs of the four lakes were tabulated in Table 2. The MRB ranged from 0.01 m-0.05 m with the standard derivation of 0.07 m-0.20 m, which revealed that the relative error of water level estimation by ICESat-2 can reach 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. From Table 2, it can be seen that the MAE of four lakes spanned from 0.03 m-0.10 m with RMSE ranging from 0.04 m-0.13 m. Besides, the boxplot of MAE was detailed in Fig.5, which illustrated that the medians of four lakes were all under 0.08 m. Among them, Gaoyou Lake had the highest accuracy with minimum MAE and RMSE, then was Lake Taihu. However, several outliers (abnormally large errors) appeared on Lake Chaohu and Hongze. Lake Hongze had the largest MAE, RMSE, and relative larger outliers, which indicated that there was a relatively large difference between ICESat-2 estimations and the measured water levels.

Besides, the influence of strong and weak beams on the accuracy of water level extraction was also further analyzed. The MAE of four lakes' strong beams observations versus that of weak beams improved within 0.01 m, which indicated that the performance of strong beams was slightly better than the weak beams for lake water levels' estimation.

Table 2

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

Lakes	MRB(m)	MAE(m)	RMSE(m)
Chaohu Lake	-0.02±0.14	0.06±0.05	0.08
Hongze Lake	0.05±0.20	0.10±0.09	0.13
Gaoyou Lake	0.01±0.07	0.03±0.02	0.04
Taihu Lake	-0.01±0.07	0.05±0.03	0.06

Lake level retrieved by GEDI

Relevance and absolute accuracy evaluation

Fig. 6 showed the correlation between the GEDI estimated water levels and the *in-situ* measurements. The sub-figures illustrated that the effective days of GEDI were 18, 22, 17, and 10 days for Lake Chaohu, Hongze, Gaoyou, and Taihu, respectively, and the R spanned from 0.560-0.952, which demonstrated that the efficiency of data and the accuracy of GEDI were relatively lower and inferior to that of ICESat-2. Among them, Chaohu Lake had the highest correlation ($R=0.952$, $P < 0.001$), while the 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 indiccated that GEDI had more outliers or data that could not be used due to the large uncertainty. We did not evaluate GEDI through indirect accuracy of repeated orbits due to fewer valid data and there were no repeated tracks among the effetive data. The MAE and RMSE as the direct comparision results were listed in Table 3, 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 postive bias turned out that GEDI overestimated the water levels with lower accuacy.

Fig.7 further dicpicted the boxplot of the MAE. The medians were 0.24 m, 0.37 m, 0.21 m and 0.33 m for Lake Chaohu, Hongze, Gaoyou and Taihu, respectively. And the MAE of Hongze Lake was larger than that of the other three lakes whether based on ICESat-2 or GEDI. This was perhaps due to that the the water velocity in the sub-areas of Hongze Lake was more sensitive to the change of wind speed resulting from wind-driven circulation that was absent in other lakes. Moreover, the conversion of vertical datum introduced additional errors.

Table 3

The evaluation of GEDI versus the *in-situ* water levels acquired nearly at the same time

Lakes	MAE (m)	RMSE (m)
Chaohu Lake	0.35±0.28	0.45
Hongze Lake	0.38±0.20	0.43
Gaoyou Lake	0.33±0.32	0.46
Taihu Lake	0.31±0.16	0.35

Coverage beams versus full power beams

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 biases between different beams and the *in-situ* data were analyzed. The mean error between observations from coverage and power beams 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, 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 power beams can yield a higher accuracy in comparison to the coverage ones. Therefore, the power beam measurements were recommended for water level retrieval.

Time-series lake levels by combining ICESat-2 and adjusted GEDI

After adjusting GEDI's results by subtracting the mean error between the *in-situ* measurements of each lake, long time-series lake water levels were derived. Fig. 8 illustrated the combined dynamics of Lake Hongze, and their corresponding *in-situ* measurements. It can be seen that even after bias adjustment, GEDI's overall water levels were higher or lower than that of Jiangba Station. For example, the water level of days on October 8, 2020, and August 5, 2021 were obviously higher than in-situ measuring data. Nevertheless, the overall change trend of the two was consistent. Both presented a decline trend in 2019 with the lowest water level 11.35 m on August 4, 2019, and an increase trend in 2020.

Moreover, Fig. 9 further displayed the monthly and annual changes. Except that there were only two months records in 2018, from the view of inter-annual change, it displayed that the water levels in the synchronous months of Hongze Lake showed a downward and then an upward trend from year 2019 to 2021. From the intra-annual change of 2019, both the estimated and *in-situ* data showed that the lake water levels were falling since February, until it reached the lowest water level in 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 little rain in the summer of 2019, the increase of agricultural irrigation water and the absence of passenger water in the upstream. The estimated water level (Fig.9 (a)) in August was slightly 0.07 m lower than that of *in-situ* gauge (Fig.9 (b)). Then, the water level rose to its highest from August to September, and began to decline from October to November, finally, increased again in December. For the year 2020, both presented a decline trend from March to June, and then increased from June to October, the differences occurred in

June with 0.16 m higher and September with 0.18 m lower than that of *in-situ* measurements. For year 2021, there was an upward trend from January to May and a downward trend from May to July. The combined estimated results in April were from GEDI observations and were much lower than that of *in- situ* water levels, which can also be seen from the water level of individual day in the above Fig.8.

Assuming that the water level in 2018 can be expressed by the last two months, and 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 change were -0.17 m/yr, 0.20 m/yr and 0.54 m/yr with an average 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. It increased -0.26 m, 0.15 m and 0.53 m year by year with average annual increase 0.14 m/yr. The annual increase difference of two datasets was 0.05 m/yr, which turned out the combining of ICESat-2 and GEDI missions has a great potential to monitor long time-series lake water levels. Besides the Hongze Lake, the comparisons of the other three lakes' annual change retrieved by the combined results and the *in-situ* measurements was tabulated in Table 4. The mean annual increase of the estimated and the *in-situ* water levels was -0.11 m/yr and -0.05m/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 4

The comparison of yearly mean and increase of water level 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 the lakes 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, whose error may inherit from ATL03 that was the global geolocated ellipsoidal height product of each photon event. Besides, the water backscatter model that used in ATL13 and processing methods may also influence the accuracy (Jasinski et al., 2020). Similarly, the GEDI L2A was derived from the L1B geolocated GEDI return waveforms, which were easily affected by cloud and processed by algorithm settings (Hofton et al., 2020). Thus, results for different algorithms would affect the accuracy of final water levels. Then was the outlier removal method implemented in this study for two missions, especially for GEDI which had more unqualified footprints. For example, the bin with the maximum frequency may filter out the wrong water level for few beams, when the bin frequency of the correct water level was lesser. Third, vertical shifting between different height datum, whether applying the geoid transformation model or mean constant offsets 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 took all observations for absolute validation, while if selecting the laser footprints within a certain radius of hydrologic stations, such as 10km, as the validation samples will weaken the influence of geographical location error; Besides, the water levels acquired by the laser footprints of 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 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 also critical for monitoring inland water level dynamics. Table 1 showed that comparing with ICESat-2, GEDI can obtain more observation data in shorter time according to the total observation days of the two satellites. However, after the outliers were eliminated, the effective data in the 3.2 section of the results showed that the abnormal rate of 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 time 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), respectively, which revealed that the combining of the two missions can significantly enhance the monitoring frequency and provide more detailed information of water level variations. Similarly, Shu et al. (2017) adopted the number of observations within the 30 km radius of a station was used to estimate the annual observation frequency for the Great Lakes and found that GEDI had the highest frequency with 14.80 observations per year, followed by ICESat-2 (10.43), which were about five and four times that of ICESat-1 (2.45). The spatial resolution decided the size of water body that can be measured. Given ICESat-2 and GEDI possessing smaller footprints and operating simultaneously, the dynamics of inland waters can be optimally retrieved once the more products of both satellites are available.

Conclusions

Accurate lake levels are necessary to investigate the change of hydrological processes, and related problems of water resource and ecosystem, etc. New laser altimetry satellites provide an opportunity for monitoring water level dynamics, especially in remote regions that lack water level monitoring stations. In this paper, four typical lakes were selected as the study area, and the water level retrieved from two satellite altimetry ICESat-2 and GEDI were evaluated and validated against ground measured water levels from their gauge stations. Accuracy assessment metrics indicated that the performance of ICESat-2 showed strong correlations with R ranging from 0.957–0.995 and the RMSE 0.04 m-0.13 m, whereas that of GEDI was relatively low with R varying 0.560–0.952 and RMSE spanning from 0.35 m to 0.46 m, respectively. Besides, the factors affecting the accuracy were analyzed and the potentials for monitoring inland water dynamics were explored.

After bias adjustment, the estimated water levels of the combined long time-series illustrated consistent change trend with the hydrological stations over the four lakes. The annual increase difference 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. 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 accuray than weak beams; however, GEDI obviously overestimated the water level according to the water level estimation results and the fullpower beams can better improve the accuracy of the retrival results. The encouraging results suggested that the combination of ICESat-2 and GEDI products can significantly advance our understanding of the monthly, seasonal and yearly changes, which can provide a valuable reference for hydrological and climatic studies.

Declarations

Author Contributions: Conceptualization, Z.Z., methodology, Z.Z. and G.C, software, Z.Z, G.C and X.G, validation, Y.B, X.G, and J.B., formal analysis, Z.Z. and G.C, data curation, X.G and J. B, writing—original draft preparation, Z.Z., writing—review and editing, Z.Z, Y.B, and G.C., visualization, Z.Z and X.G".

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

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Conflicts of Interest: The authors declare no conflict of interest.

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Figures

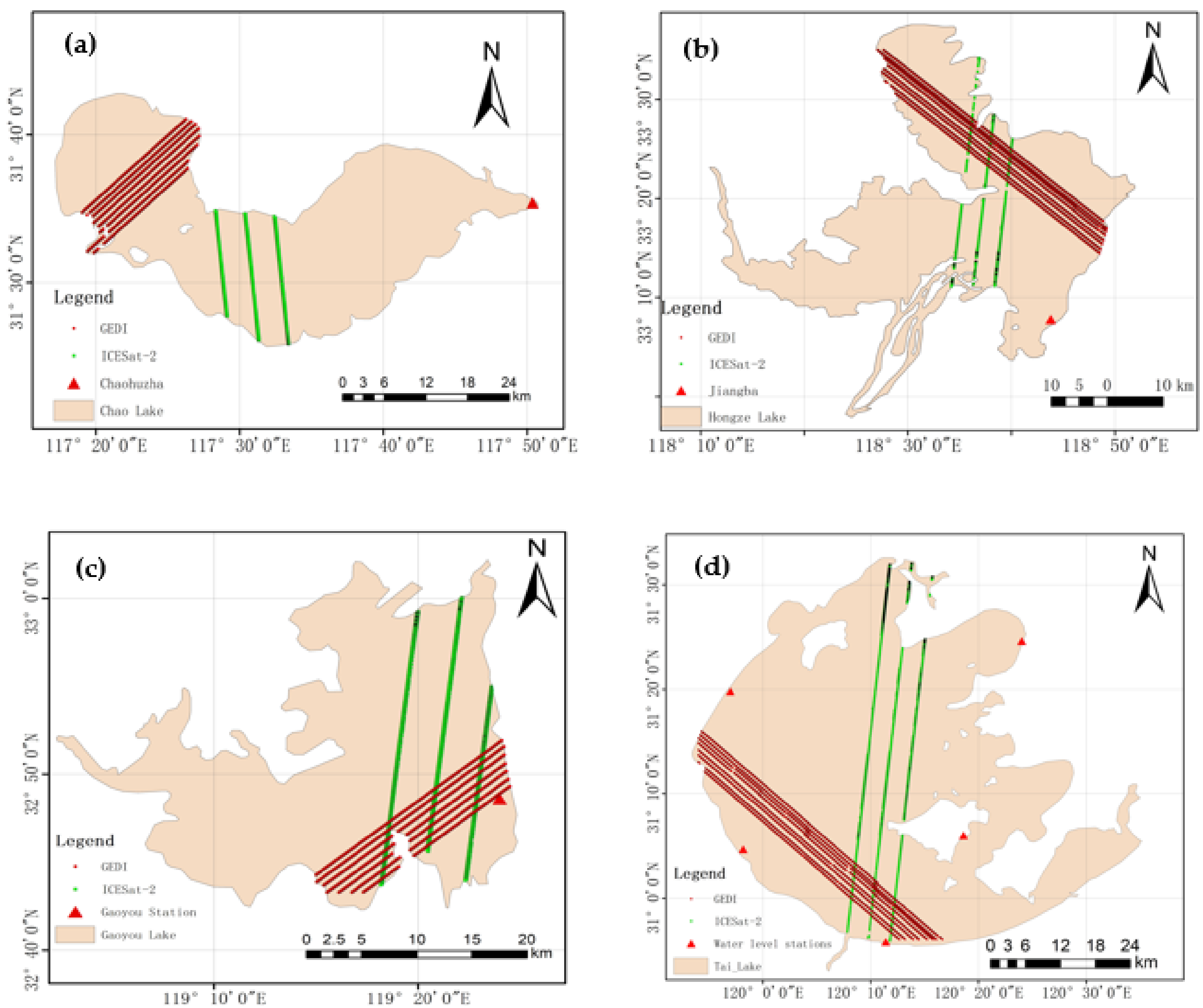

Figure 1

Samples of ICESat-2 and GEDI over the four lakes and their hydrological stations: **a** Chaohu Lake, **b** Hongze Lake, **c** Gaoyou Lake, **d** Taihu Lake

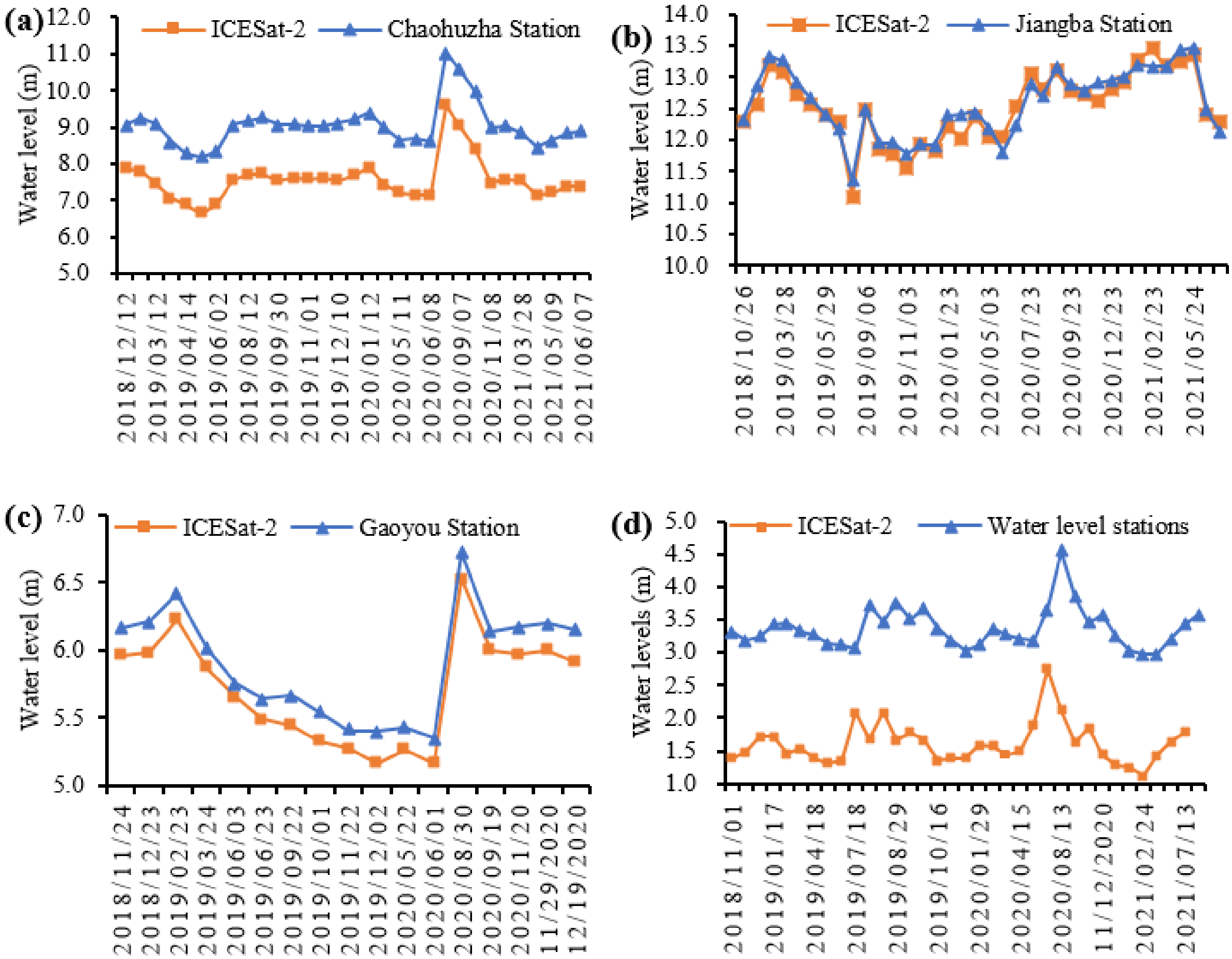

Figure 2

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

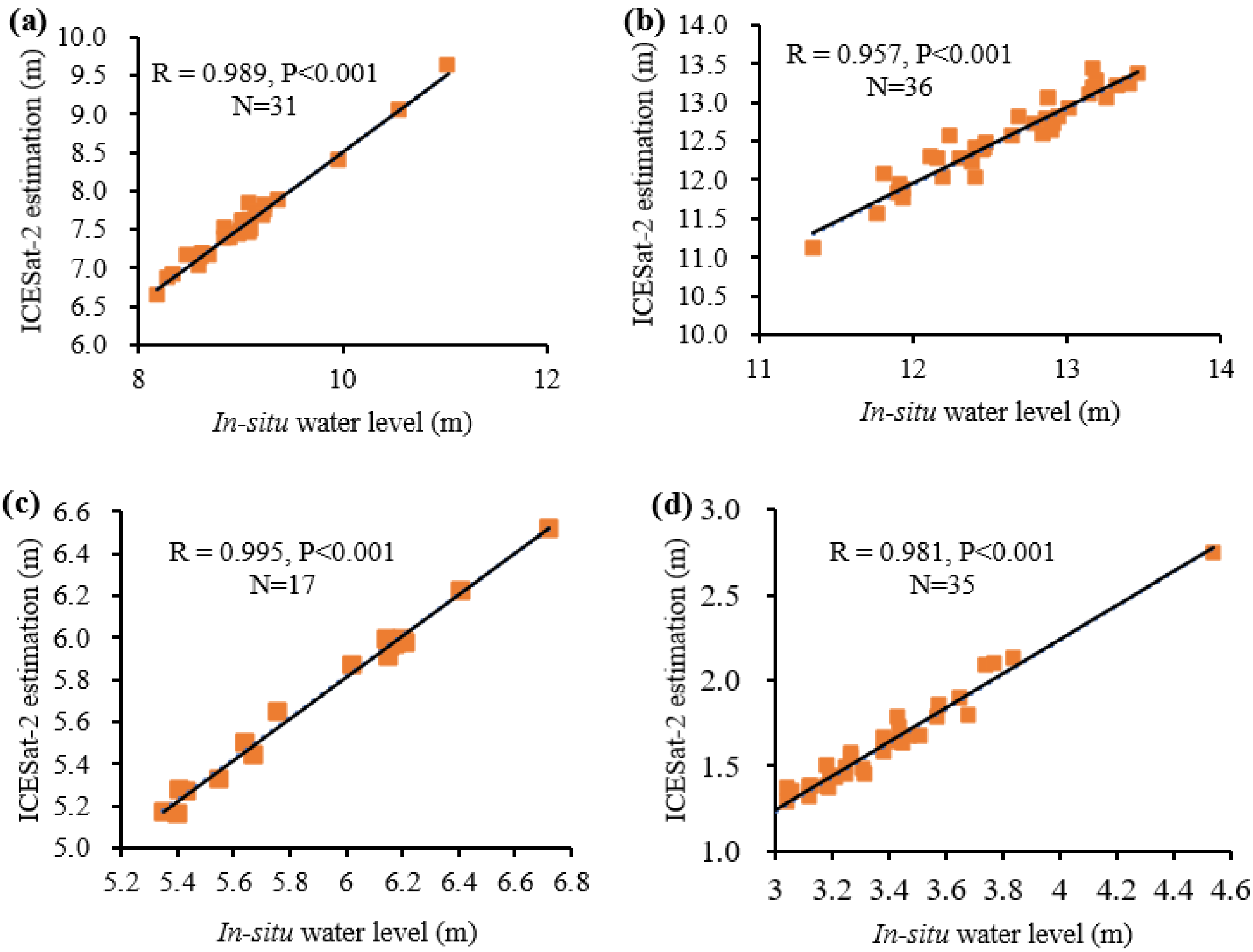

Figure 3

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

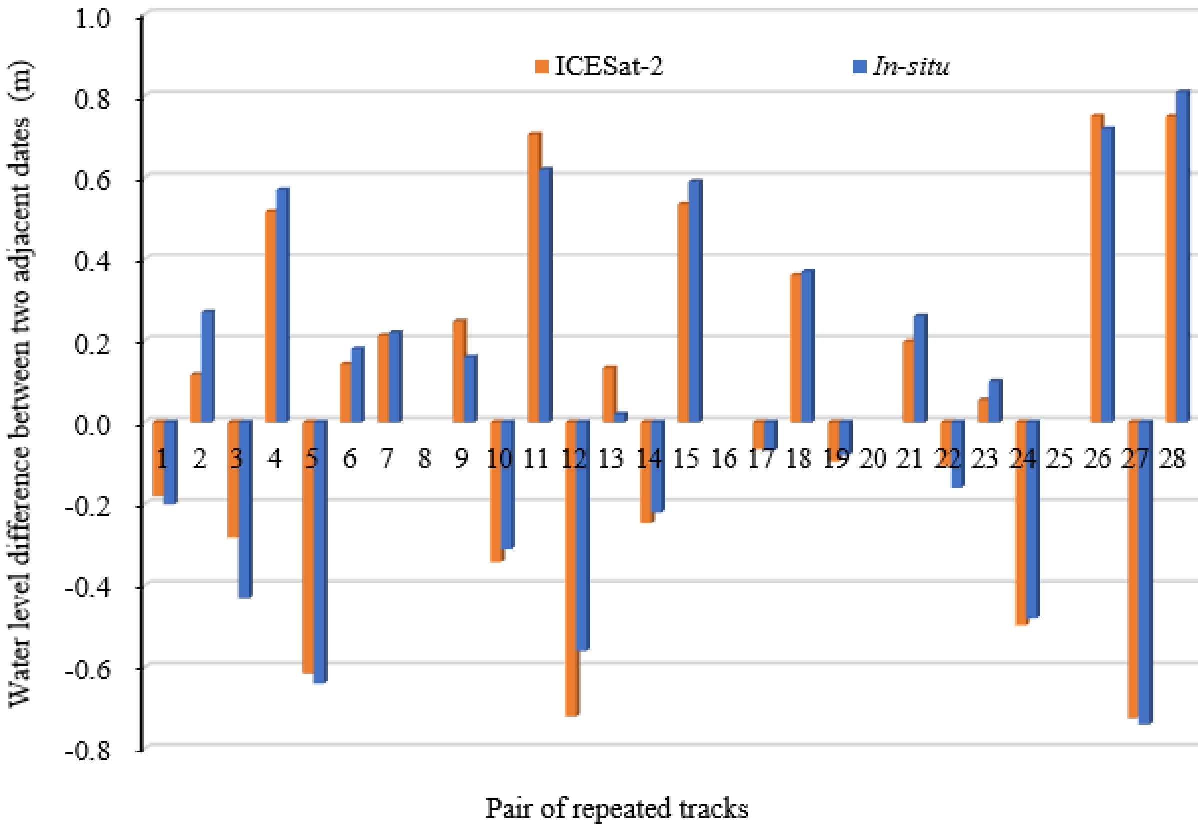

Figure 4

The relative difference between two adjacent dates of repeated tracks and the corresponding *in-situ* gauge data of Taihu Lake

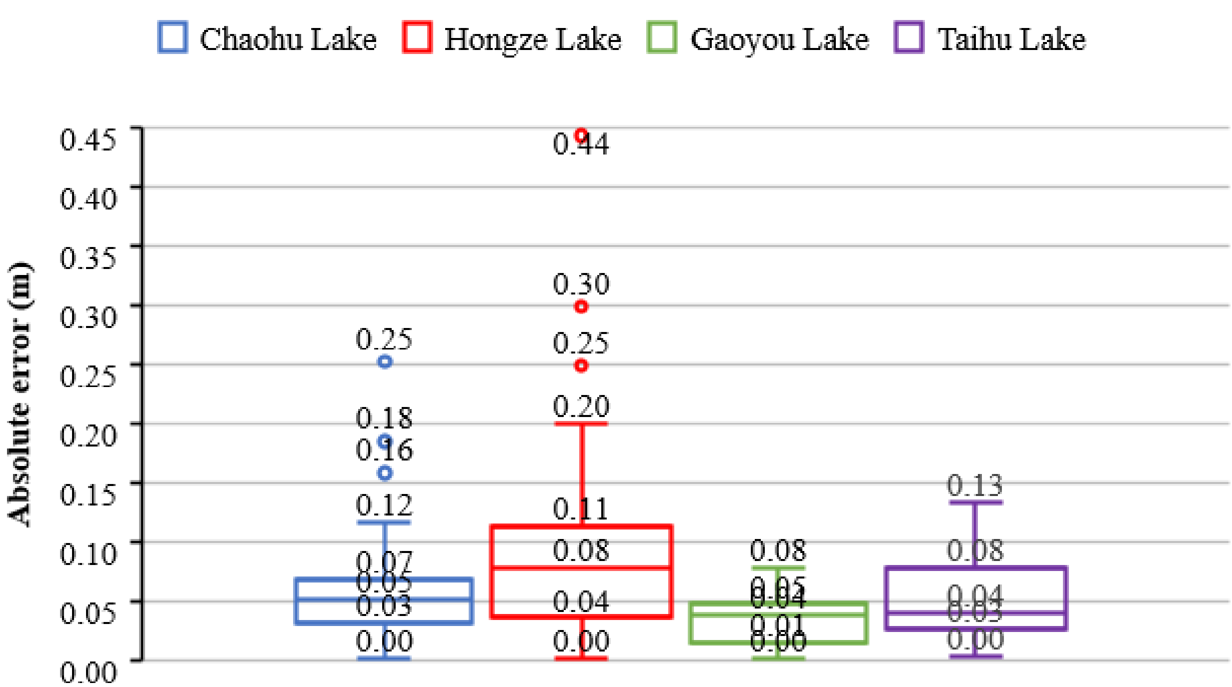

Figure 5

Boxplot of MAE between ICESat-2 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).

Figure 6

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

Figure 7

Boxplot of MAE between GEDI measurements and *in-situ* water levels for the four lakes (The horizontal line numbers from bottom to top are the lower edge, first quantile, median, third quantile and upper edge in turn, and the discrete circles are outliers).

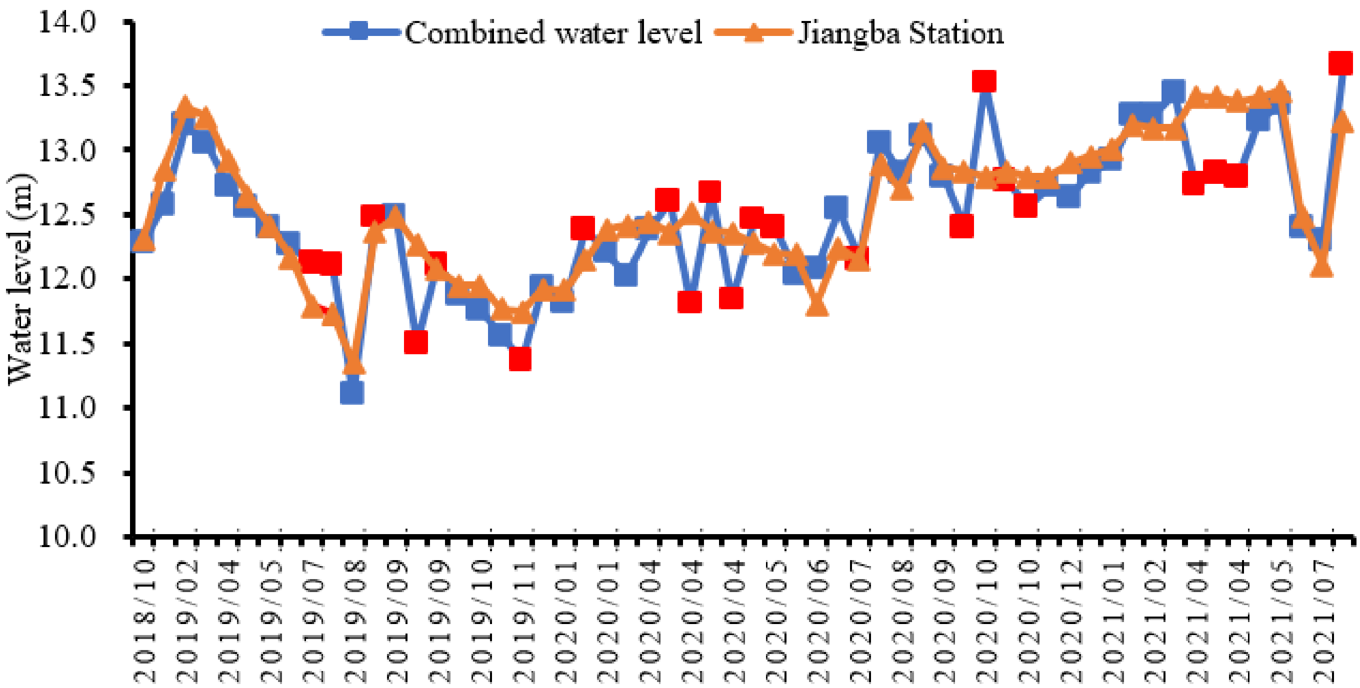

Figure 8

Water levels retrieved by combining ICESat-2 (the blue squares) and adjusted GEDI (the red squares) of Hongze Lake

Figure 9

Comparison of average water levels of each monthly and yearly variation of Hongze Lake: **a** Estimated water levels, **b** *In-situ* gauge water levels.