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# Obtaining Accurate Water Level Measurements in Lakes: Analysis of Changes in ICESat Altimetry Accuracy With Buffer Changes

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**ABSTRACT** Determining the accuracy of lake water levels calculated based on Ice, Cloud, and land Elevation Satellite (ICESat) data mainly relies on identifying lake water footprints (LWFs), which are obtained using an overlay analysis of lake water masks (LWMs) and ICESat tracks. However, most previous studies that have conducted a buffer analysis based on LWMs have set the buffer size subjectively without providing a detailed explanation for this or conducting a system analysis. In this study, the effects of using inside and outside buffers to obtain LWMs for seven lakes are analyzed. The Modified Normalized Difference Water Index (MNDWI) was applied to extract LWMs from Thematic Mapper (TM) images. The boxplot was used to remove footprints with abnormal elevations, and then the average of the remaining footprints was calculated as the ICESat water level. To compare with the *in situ* measured data, the root mean square error (RMSE) was used for accuracy evaluation. Results show the following: (1) for Yamzhog Yumco, which is a narrow lake, the altimetry accuracy is higher when using the outside buffer than for the inside buffer or with no buffer, and the highest accuracy is obtained with an outside buffer of approximately 100 m. (2) For other relatively wide lakes, such as Lake Michigan, Lake Erie, Lake Huron, Lake Ontario and Lake Superior, the inside buffer method does not always improve altimetry accuracy, and this result differs from those presented previously. (3) For different lakes, the range of change in altimetry accuracy is affected by the number of LWFs. This study is of value for use in studies that apply ICESat altimetry data to obtain changes in lake water levels, especially for relatively narrow lakes, and the results imply that the altimetry accuracy can be improved by using the outside buffer.

**INDEX TERMS** ICESat, lake, water level, altimetry accuracy, footprint, water mask.

## I. INTRODUCTION

Lakes are primary ways for water storage; as such, they make a large contribution to the water supply and adjustments [1]–[5]. Change in lake water levels represents the state of the water-heat balance [6], and lake water levels

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are a significant indicator of global warming and have been regarded as a viable and important proxy of climate change [7], [8]. The acquisition of water level data is a prerequisite for conducting relevant research on lake water levels. Traditionally, water level measurements are obtained *in situ*, but doing so is labor intensive and expensive. In addition, it is difficult to obtain water level information for lakes situated in remote areas [9], which results in low spatial data coverage.

**TABLE 1.** Different methods used to determine water masks in different lakes (in related studies).

Study	Satellite data used	Area of lake	Water mask used
Duan <i>et al.</i> (2013)	Landsat, ICESat/GLAS	290 km <sup>2</sup> (The Roseires Reservoir)	Extracted directly from images
Kropáček <i>et al.</i> (2012)	Landsat MSS/TM/ETM+, Envisat, GFO, ICESat	Approximately 2000 km <sup>2</sup> (Nam Co)	Extracted directly from images
Phan <i>et al.</i> (2012)	MODIS, ICESat/GLAS	154 lakes in Tibet with areas ranging from 0.973 km <sup>2</sup> to 4166.288 km <sup>2</sup>	Extracted directly from images
Wu <i>et al.</i> (2012)	Landsat TM, ICESat/GLAS	Greater than 768 km <sup>2</sup> (Dongting Lake, Hongze Lake, Taihu Lake, Poyang Lake, Gaoyou Lake, Chaohu Lake)	Used an inside buffer of 100 m based on results extracted from images to ensure that all footprints were fully on the lake.
Li <i>et al.</i> (2011)	Landsat TM/ETM+, ICESat/GLAS	Greater than 189.20 km <sup>2</sup> (24 lakes in Central Asia)	Used an inside buffer of 200 m based on results extracted from images to delete footprints that may be connected to lakeshore.
Wang <i>et al.</i> (2012)	Landsat ETM+, ICESat/GLAS	Greater than 216.6 km <sup>2</sup> (Peiku Co, Mapang yong Co, Qinghai Lake, Fuxian Lake)	Used an inside buffer of 400 m based on results extracted from images to prevent footprints falling outside the lake.
Huang <i>et al.</i> (2018b)	Landsat TM, Jason-2/3, Envisat	Brahmaputra River with different river widths ranging from 200 m to more than 1 km.	Used an outside buffer of 1.5 km for Jason-2/3 and 0.8 km for Envisat based on results extracted from images, and considered that the information contained in outside footprints was useful for studying inland water bodies.

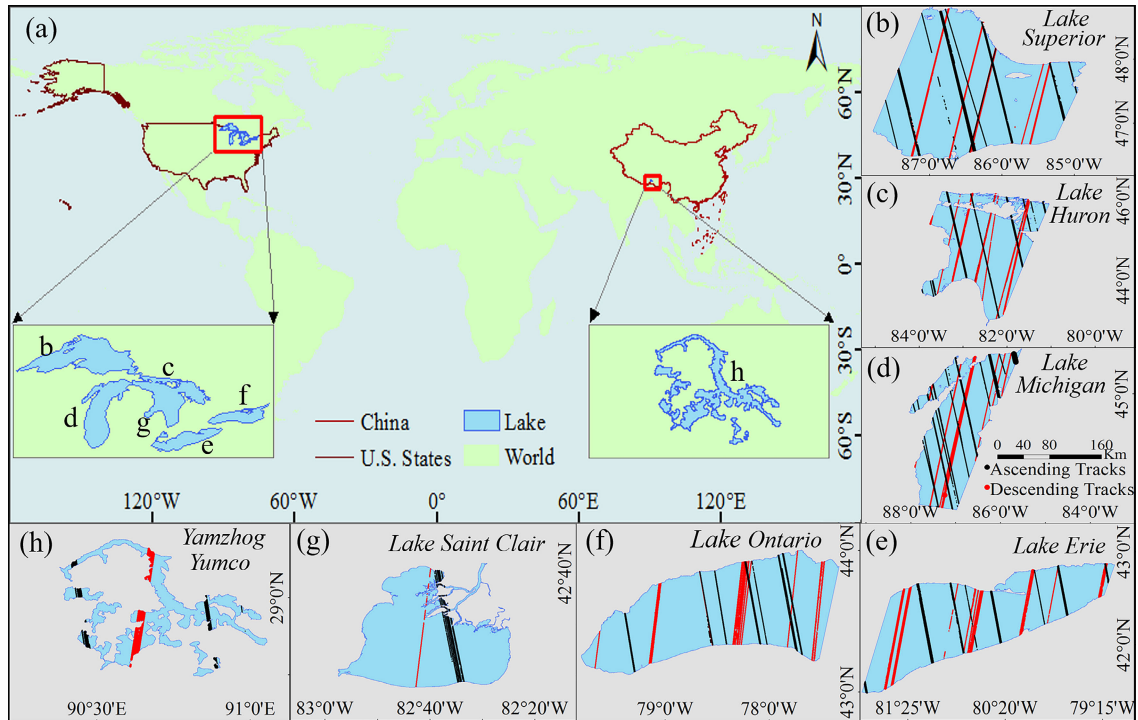
With the development of remote sensing, satellite altimetry data have been widely used in lake water level research [10]–[15]. Compared with *in situ* measurement data, satellite altimetry data provide high spatial coverage, are easy to acquire, and have a high time resolution; thus, they are extremely useful for lake water level research. Satellite altimetry technology is currently mainly divided into two types: laser altimetry and radar altimetry [16]. However, the large footprints with a diameter of several kilometers of radar altimetry limit its application in lake water level research, for example, footprint with diameter of 5 km for Jason-1, and 3.4 km for ENVISAT(RA-2) [17], [18]. This makes the data inapplicable for use in studying the water level of small water bodies [3]. Laser altimetry compensates for the limitations of radar altimetry. The footprint diameter of the ICESat (Ice, Cloud, and land Elevation Satellite) laser altimetry satellite launched in 2003 is only 70 m, which is obviously much smaller than that of radar altimetry. Therefore, the data are more suitable for water level research conducted on small water bodies [17]. Lake water level calculations based on ICESat altimetry data can be obtained by averaging lake water footprint (LWF) elevations, which are derived from an overlay analysis of the lake water mask (LWM) and altimetry tracks. Therefore, determining the LWM is one of the key factors that affects altimetry accuracy and its use in lake water level research.

Recently many researchers have identified LWFs based directly on water masks extracted from satellite images, such as those of Landsat [19]–[22] and Moderate Resolution Imaging Spectroradiometer (MODIS) [17], [23]–[25]. To improve the accuracy of identifying LWFs, some studies have conducted buffer analyses based on water masks extracted from satellite images. Of these analyses, some researchers have made buffers inside the LWM, whereas others have used

different buffer sizes, such as 100 m [26], 200 m [27], and 400 m [28]. Furthermore, buffers outside of the LWM have been used in some studies. For example, Huang *et al.* [29] suggested that water level information contained in LWFs outside of the water mask is useful when studying inland lakes, and they set a buffer zone outside the water mask for LWF identification with a radius equal to half the diameter of the altimetry mission used in their study. In summary, different studies have used different methods determine LWMs (Table 1).

The purpose of using an inside buffer is usually to remove any footprints connected to the lakeshore and ensure that the footprints identified are pure LWFs. However, it has not yet been confirmed whether this method can improve the altimetry accuracy. Huang *et al.* [29] showed that the limited number of footprints available in lakes that are small and narrow prohibits sufficient water level information from being obtained, and an outside buffer is needed to supplement the footprints. Although the use of both inside and outside buffer methods has been discussed in literature, the accuracies of these different methods have not yet been compared, nor whether they have an actual impact on altimetry accuracy. In addition, most research has set the buffer size according to subjective decisions, without providing any detailed explanation for doing so.

This study was conducted to evaluate the impact of the buffer zone setting on the accuracy of altimetry for lakes of different sizes. With respect to the amount of *in situ* measurement data available, seven lakes were selected as the study areas: Yamzhog Yumco in Nagazê County, Shannan, Tibet, China; the five Great Lakes (one of which lies in the USA and the other border both Canada and the USA) and Lake Saint Clair, which lies between the USA and Canada. The objectives of this study include determining:



**FIGURE 1.** Study areas: (a) locations of the seven lakes globally; (b) Lake Superior and associated ICESat tracks that intersect with it; (c) Lake Huron and associated ICESat tracks; (d) Lake Michigan and associated ICESat tracks; (e) Lake Erie and associated ICESat tracks; (f) Lake Ontario and associated ICESat tracks; (g) Lake Saint Clair and associated ICESat tracks; (h) Yamzhog Yumco and associated ICESat tracks. There are two directions of all ICESat tracks: ascending tracks and descending tracks, which are shown using black and red, respectively.

(1) whether it is necessary to conduct a buffer analysis based on LWMs extracted from images when identifying LWFs; (2) the effect of inside and outside buffers on altimetry accuracy; (3) the most relatively appropriate range of buffer sizes; (4) the factors driving the changes in altimetry accuracy in relation to the buffer.

## II. STUDY AREAS AND DATA PROCESSING

There are 2407 natural lakes in China with areas exceeding  $1 \text{ km}^2$  [30]; however, most are not monitored and therefore no long-term *in situ* records exist [31]–[33]. In this study, the *in situ* measured water level of Yamzhog Yumco was determined using information obtained from different projects. In addition, the National Oceanic and Atmospheric Administration (NOAA) provides free access to its *in situ* measured water levels; therefore, those of Lake Saint Clair and the five Great Lakes of North America (Lake Superior, Lake Huron, Lake Michigan, Lake Erie, Lake Ontario) were obtained and used in this study.

### A. STUDY AREA

Yamzhog Yumco ( $28.73^\circ\text{--}29.18^\circ \text{ N}$ ,  $90.30^\circ\text{--}91.10^\circ \text{ E}$ ) (Figure 1h), is the largest closed inland brackish lake on the northern foot of the Himalayas in southern Tibet [34], [35]. The following data were obtained for the lake: it lies at 4441 m above sea level, spans an area of  $638 \text{ km}^2$ , has a lake line of almost 1000 km, and a depth of over 20–40 m (the

greatest depth is approximately 60 m) [36], [37]. Yamzhog Yumco is a plateau-dammed lake with an irregular shape and a winding lakeshore [37], [38]. The lake experiences a typical Indian monsoon climate and, thus, seasonal variations in precipitation; most of the rain falls during summer [39].

Located on the Canada-USA border, the Great Lakes of North America are the largest freshwater watershed in the world and are known as the “Mediterranean of North America” [40]. The five Great Lakes are Lake Superior ( $47.7^\circ \text{ N}$ ,  $87.5^\circ \text{ W}$ ), Lake Huron ( $44.8^\circ \text{ N}$ ,  $82.4^\circ \text{ W}$ ), Lake Michigan ( $44^\circ \text{ N}$ ,  $87^\circ \text{ W}$ ), Lake Erie ( $42.2^\circ \text{ N}$ ,  $81.2^\circ \text{ W}$ ), and Lake Ontario ( $43.7^\circ \text{ N}$ ,  $77.9^\circ \text{ W}$ ), and they have respective areas of  $82,000 \text{ km}^2$ ,  $59,588 \text{ km}^2$ ,  $58,030 \text{ km}^2$ ,  $25,667 \text{ km}^2$ , and  $19,000 \text{ km}^2$ .

Lake Saint Clair ( $42.467^\circ \text{ N}$ ,  $82.667^\circ \text{ W}$ ) (Figure 1g) is located in the region of the Great Lakes and is also a part of the Great Lakes system. It spans an area measuring approximately  $1114 \text{ km}^2$  and connects with Lake Huron (to its north) and Lake Erie (to its south) (<https://www.epa.gov/greatlakes/physical-features-great-lakes>).

### B. DATASETS

#### 1) ICESat DATA

ICESat was launched by the National Aeronautics and Space Administration (NASA) in January 2003 and removed from service in February 2010 [3], [17], [14], [41]–[45].

In addition, ICESat-2 was successfully launched by NASA on September 2018 (<https://icesat-2.gsfc.nasa.gov/>). Due to the time span between ICESat and ICESat-2, only ICESat is chosen for altimetry data in this work. The Geoscience Laser Altimetry System (GLAS) onboard ICESat operated at a frequency of 40 Hz with two channels, 532 and 1064 nm [46], [47], and its precision was approximately 2 cm when measuring mean surface elevations of flat surfaces and footprints with a diameter of approximately 70 m, spaced at approximately 170 m intervals along a track [48], [49]. Level 2 GLAS14 data provides corrected surface elevations for land, rivers, and lakes ([http://nsidc.org/data/icesat/data\\_releases.html](http://nsidc.org/data/icesat/data_releases.html)) [16], [19]. In this paper, GLAS14 Release 34 data covering the study areas from 2003 to 2009 were selected as the satellite altimetry data. It's worth noting that the ICESat/GLAS14 altimetry data is referenced to Topex/Poseidon ellipsoid, which should be converted to the WGS84 ellipsoid [45]. The ICESat footprint elevation can be calculated by Eq. (1) [14], [50], [51],

$$ICESat\_elevation = ICESat\_elevation\_measured - ICESat\_geoid - 0.7m \quad (1)$$

where ICESat\_elevation\_measured and ICESat\_geoid can be directly obtained from the GLAS, and the 0.7 m term is the offset between the Topex/Poseidon ellipsoid and the WGS84 ellipsoid [52]. The resulting ICESat\_elevation is the orthometric height of the water surface relative to the WGS84/EGM2008 reference system.

### 2) THEMATIC MAPPER IMAGES

Considering the GLAS footprint with a diameter of 70 m, the Thematic Mapper (TM) with a spatial resolution of 30 m is, thus, used for identifying LWFs from ICESat. In this study, Landsat 5 TM images from 2003 to 2009 provided by the United States Geological Survey (USGS: <http://glovis.usgs.gov>) were chosen to extract LWMs.

The Great Lakes cover a large area, and the time resolution of TM images is 16-days; therefore TM images for different dates were required to splice the complete water area of each lake. However, this can cause boundary errors; therefore, for the Great Lakes, we chose images from the same date that covered the target lake to the greatest extent possible, as shown in Figure 1 and Table 2. For example, the images of path 23, row 26, path 23, row 27, and path 23, row 28, which were captured on the same date, were used in image mosaicking for Lake Superior. The same method was applied to Lake Huron, Lake Michigan, Lake Erie, and Lake Ontario.

### 3) IN SITU MEASURED DATA

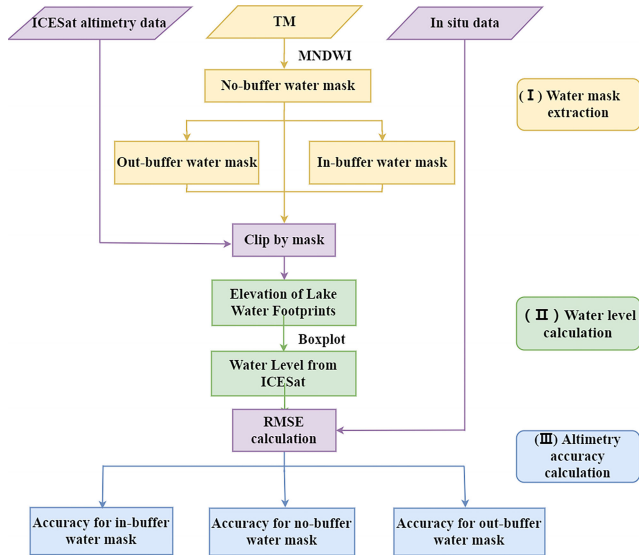
To calculate the altimetry accuracy of ICESat in providing lake water level measurements, *in situ* measured data were used to conduct a correlation analysis and evaluate the accuracy of the satellite altimetry data. In this study, the *in situ* data used to verify the altimetry accuracy of

**TABLE 2. Path and row of corresponding lake images or path and row combinations from the same date that provided greatest possible lake coverage.**

Lake	Path	Row
Yamzhog Yumco	138	40
	23	26
Lake Superior	23	27
	23	28
	20	28
Lake Huron	20	29
	20	30
	23	28
Lake Michigan	23	29
	23	30
	18	30
Lake Erie	18	31
	17	29
Lake Ontario	17	30
Lake Saint Clair	20	30

Yamzhog Yumco were obtained from daily water level observation data recorded at Baidi Station from 2003 to 2009, which is located in the northwestern region of Yamzhog Yumco (29.124° N, 90.439° E), and is the only continuous water level observation station at Yamzhog Yumco [34], [53], [54]. The *in situ* data from Baidi Station were based on 1985 Chinese National Datum, and it was firstly necessary to transform them into WGS84/EGM2008 to enable a comparison with ICESat data. Two transformations were required: the first converted the 1985 Chinese National Datum height to the WGS84/EGM1996 height using an offset of 35.7 cm [51], [55], and the second converted the WGS84/EGM1996 height to the WGS84/EGM2008 height using VDatum, which is a datum conversion software provided by NOAA (<https://vdatum.noaa.gov/welcome.html>).

The *in situ* data to verify the altimetry accuracy of other six lakes were available on the website of NOAA, and we obtained daily water level observations during 2003-2009 (<https://tidesandcurrents.noaa.gov/stations.html?type=Water+Levels>). Although NOAA provides data for more than one hydrological stations of the six lakes, we selected only one station for each lake to verify ICESat water levels obtained using different buffer analysis. The selected station should be near to the selected part of the lake and have relatively higher accuracy compared to other stations in the same lake. It is of note that the *in situ* data from observation stations provided by NOAA were based on the International Great Lakes Datum of 1985 (IGLD85); therefore, we converted the *in situ* data provided by NOAA to WGS84/EGM2008 using VDatum. From these *in situ* measured data, the water level associated with consistent observation data and the altimetry date was selected to verify altimetry accuracy.



**FIGURE 2.** Overall framework of altimetry accuracy calculations with water masks derived from different inside and outside buffers.

**III. METHODOLOGY**

The methodology applied in this work is shown in Figure 2. The water mask was first extracted (Section III.A); then, the water level was calculated (Section III.B), and the accuracy of the water level retrieved from ICESat was calculated (Section III.C).

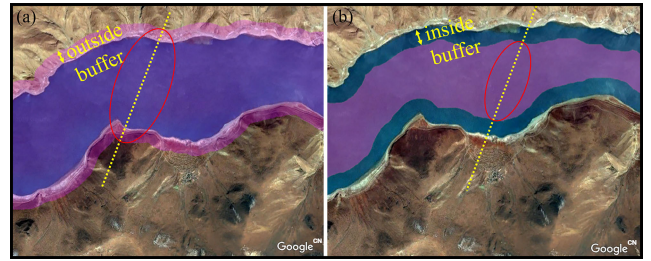
**A. LAKE WATER MASK (LWM) EXTRACTION AND BUFFER ANALYSIS**

Based on the TM images covering the study areas, the Modified Normalized Difference Water Index (MNDWI) was used in conjunction with the Google Earth Engine to extract water mask from images [45], [56]. Density slicing was further applied to determine the threshold [45], [57], [58]. The threshold ranges of all lakes were determined as 0.05 to 0.11. The MNDWI was calculated by Eq. (2),

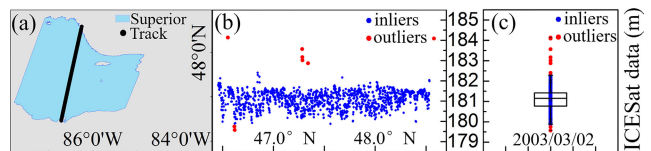
$$MNDWI = (B2 - B5)/(B2 + B5) \tag{2}$$

where B2 and B5 refer to the second band of the TM (green band) and the fifth band of the TM (middle-infrared band), respectively.

As shown in Figure 2, the water masks extracted directly from images using the TM are referred to as “no-buffer water masks”. Based on the no-buffer water mask, different outside and inside buffers were extracted and denoted as “out-buffer water mask” (Figure 3a) and “in-buffer water mask” (Figure 3b), respectively. As for the setting of buffer size, different studies have chosen different buffer sizes in their researches, such as 100 m [26], 200 m [27], etc. Considering the size of the ICESat footprint, the buffer size was set according to half the diameter of the altimetry footprint [29]. And the inside and outside buffer size was set from 35 m to 210 m at intervals of 35 m in this work, to explore whether altimetry accuracy varied with buffer size.



**FIGURE 3.** Schematic diagram of buffer analysis based on a water mask extracted directly from images: (a) outside buffer based on no-buffer water mask, (b) inside buffer based on no-buffer water mask, and yellow points in red circle represent identified lake water footprints.



**FIGURE 4.** Schematic diagram of boxplot filtering method: (a) Lake Superior and its ICESat track in 02 March, 2003, (b) the scatter of the altimetry data from the track, and the red points are the outliers, and the blue points are the inliers; (c) the boxplot of the altimetry data from the track, and the red points are the outliers identified by the boxplot filtering method, and the blue points are the inliers which are the normal data contained in the boxplot.

**B. LAKE WATER LEVEL CALCULATION**

ICESat altimetry data calculated in Section II.B were clipped by the different LWMs derived in Section III.A to extract the LWFs. ICESat measurements can be influenced by clouds, signal saturation, and lakeside topography [16], [17], which results in elevation outliers; therefore, the boxplot filtering method was used to remove any footprints that suggested an abnormal elevation [16]. The boxplot visualization tool generates a box by calculating the median, lower and upper quartiles, and the upper and lower bounds of the dataset; therefore, most of normal data are contained. Any data outside the upper and lower boundaries are considered outliers of the dataset. Compared with visual inspection and removing outliers based on the standard deviation [14], the boxplot filtering can avoid human intervention in the process of removing outliers. As Zhang *et al.* [14] pointed out in their research, an abnormally high standard deviation should be defined first when using standard deviation to remove outliers. Wu *et al.* [26] set the abnormally high standard deviation as 0.2 to control the standard deviation of each altimetry track within 0.2, and Li *et al.* [27] set the value to 0.1. Taking the altimetry track of Lake Superior on 02 March 2003 (Figure 4a) as an example, the abnormally high standard deviation is set to 0.5, 0.2, and 0.1, respectively. The results in Table 3 have clearly shown that the different abnormally high standard deviation result in different ICESat water level, which further proves that human factors interfere with the outlier removing method based on standard deviation, while boxplot filtering will not. As it’s shown in Figure 4, after the ICESat track in 02 March 2003 is clipped by the water mask

**TABLE 3.** ICESat water level on 02 March 2003 obtained by different abnormally high standard Deviation under the 35 m outside buffer in lake superior.

The value of abnormally high standard deviation	0.5	0.2	0.1
<i>In situ</i> water level (m)	182.411	182.411	182.411
ICESat water level (m)	181.420	182.012	182.216

of Lake Superior (Figure 4a), outliers still exist (Figure 4b), and the further applied boxplot can detect these outliers of the current track effectively (Figure 4c). The mean value of the ICESat elevation for each measurement date was then calculated as the water level from ICESat. Compared with the median value of the ICESat elevation used in the study by Huang *et al.* [29], the mean elevation has been proved that it can remove small geoid error [14], [51], [59], the more detailed comparison will be given in Section IV.D.

**C. ACCURACY OF WATER LEVEL RETRIEVED FROM ICESat**

The water level calculated from ICESat in Section III.B was compared with *in situ* measurement data collected on the same date, and the accuracy of the water level from ICESat was evaluated using the widely used root mean square error (RMSE) [60]–[63]. When the RMSE is lower, the deviation between altimetry data and *in situ* data is smaller; therefore, the accuracy of ICESat is higher. The Pearson correlation coefficient was also used to determine the consistency between the trend of *in situ* data and that of ICESat water level calculated based on the no-buffer water mask [16], [51], [62].

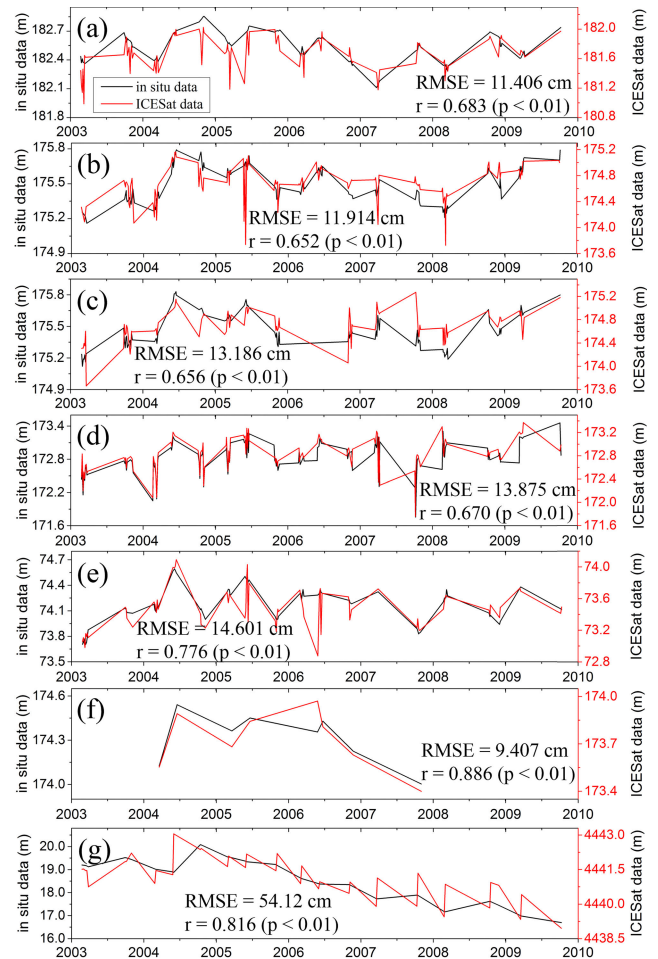
**IV. RESULTS AND DISCUSSION**

**A. WATER LEVEL TIME SERIES OBTAINED FROM IN SITU MEASUREMENTS AND ICESat DATA WITH NO-BUFFER**

Based on the water mask extracted directly from images, LWFs were identified and used to calculate the altimetry water level. The water level time series for the seven lakes are shown in Figure 5, and they contain *in situ* data and altimetry water level data. In general, the Pearson correlation coefficient between the water level from ICESat and *in situ* water level of the lakes was higher than 0.6, which indicates an overall consistent trend. However, as there were outliers in the water level obtained from ICESat, the altimetry accuracy needed improvement. A subsequent inside and outside buffer analysis was conducted to determine any changes in altimetry accuracy with buffer size, and the results are presented in Section IV.B.

**B. CHANGE IN SATELLITE ALTIMETRY ACCURACY WITH BUFFER SIZE**

The water masks obtained from different inside and outside buffers were intersected with the ICESat tracks to identify LWFs, and the average elevations of these footprints were calculated using the same method as that presented in Section III.B. The altimetry accuracy of water levels derived from ICESat for different inside and outside buffers was



**FIGURE 5.** Time series of water level from *in situ* measurements and ICESat data with no-buffer: (a) Lake Superior, (b) Lake Huron, (c) Lake Michigan, (d) Lake Erie, (e) Lake Ontario, (f) Lake Saint Clair, (g) Yamzhog Yumco.

**TABLE 4.** The RMSE (cm) of Yamzhog Yumco in different inside and outside buffers.

Buffer	RMSE (cm)						
	*0 m	35 m	70 m	105 m	140 m	175 m	210 m
In-buffer	54.12	54.07	55.14	55.62	55.75	56.36	56.76
Out-buffer	54.12	54.10	53.39	52.95	52.70	53.13	53.49

\*A buffer size of 0 m represents an RMSE calculated based on a no-buffer water mask; bold numbers represent RMSEs lower than those under the no-buffer water mask for Yamzhog Yumco.

determined for the seven lakes and compared with *in situ* measurements. The changes in the altimetry water level accuracy for Yamzhog Yumco and the other six lakes with a change in buffer size are shown in Table 4 and 5, respectively.

The changes in the numbers of LWFs extracted with respect to the buffer size were consistent for the seven lakes (Figure 6). A greater number of footprints were obtained using the water mask based on outside buffer analysis than that based on inside buffer analysis. In addition, fewer footprints were obtained with an increase in the inside buffer size,

**TABLE 5. RMSEs (cm) of other six lakes using different-sized inside and outside buffers.**

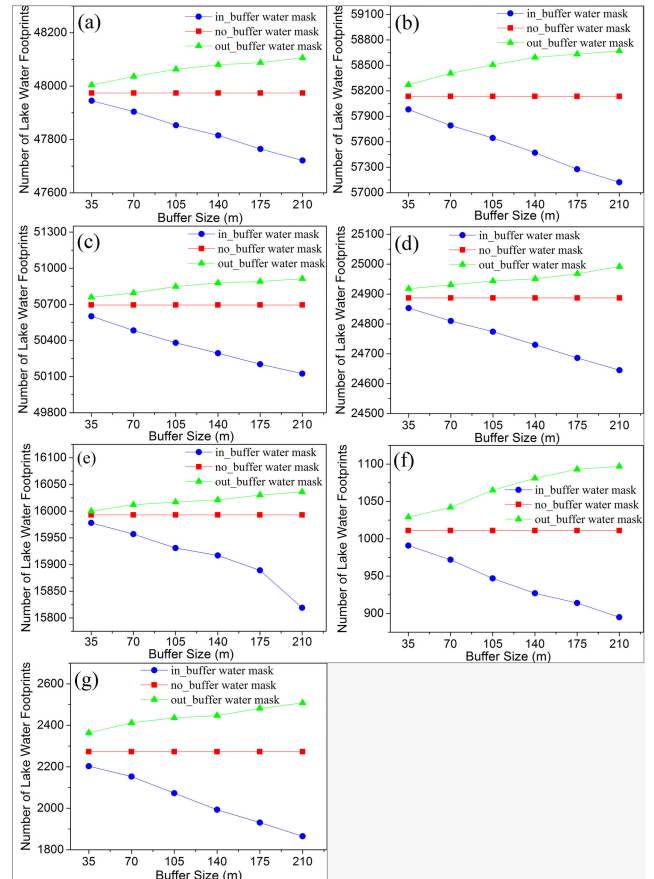
Lake	Buffer	RMSE (cm)						
		*0 m	35 m	70 m	105 m	140 m	175 m	210 m
Lake Superior	In-buffer	11.41	11.42	11.42	<b>11.40</b>	11.41	<b>11.40</b>	11.40
	Out-buffer	11.41	11.41	11.41	<b>11.40</b>	11.41	11.41	11.42
Lake Huron	In-buffer	11.91	11.95	11.93	11.91	<b>11.90</b>	11.92	11.93
	Out-buffer	11.91	11.97	11.95	11.97	11.97	11.97	11.98
Lake Michigan	In-buffer	13.19	13.19	13.13	13.19	13.22	13.22	13.23
	Out-buffer	13.19	13.19	13.13	13.11	<b>13.09</b>	13.11	13.12
Lake Erie	In-buffer	13.79	13.79	13.79	13.80	13.80	13.80	13.80
	Out-buffer	13.79	13.79	13.80	13.80	13.87	13.87	13.87
Lake Ontario	In-buffer	14.60	14.59	14.58	14.58	14.60	14.58	14.61
	Out-buffer	14.60	14.60	14.58	14.58	14.59	14.60	14.60
Lake Saint Clair	In-buffer	9.05	8.76	8.71	8.43	8.53	8.50	8.39
	Out-buffer	9.05	9.01	8.99	8.93	8.90	8.91	8.76

\*A buffer size of 0 m represents an RMSE calculated based on a no-buffer water mask; bold numbers represent RMSEs lower than those under the no-buffer water mask for each lake.

whereas the number of footprints increased with an increase in the outside buffer size, which makes good sense. The specific changes in altimetry accuracy are presented in the following section. Compared with the six lakes in the Great Lakes region, Yamzhog Yumco is smaller, has a relatively narrow lake extent, and a broken water body; thus, it is discussed separately.

1) CHANGES IN ICESat WATER LEVEL ACCURACY WITH CHANGE IN BUFFER SIZE IN YAMZHOG YUMCO

For a narrow lake, such as Yamzhog Yumco, use of the outside buffer can increase the water level accuracy of ICESat. The RMSE of the inside and outside buffers for Yamzhog Yumco changed with an increase in the buffer size from 35 m to 210 m (Table 4). When the buffer size was set as 35 m for Yamzhog Yumco, the water level accuracies with the in-buffer water mask, no-buffer water mask and out-buffer water mask were fairly consistent. However, as the buffer size increased, the differences became apparent. It's clear that the out-buffer water mask provided a higher accuracy than that of the in-buffer water mask and no-buffer water mask. When the outside buffer was increased from 35 m to 140 m, the accuracy increased (as shown by the decreasing RMSE), which indicates that the outside buffer increased the number of LWFs that then participated in the water level calculation [29] and subsequently increased the accuracy. However, when the outside buffer size increased after 140 m, the accuracy decreased, even though the number of LWFs increased. This indicates that the excessive outside buffer caused a large number of mixed footprints connected with the lakeshore, which resulted in a decreased accuracy. For Yamzhog Yumco, the ICESat water level accuracy was the highest (RMSE = 52.70 cm) when the outside buffer size



**FIGURE 6. Changes in number of LWFs for different inside and outside buffer sizes: (a) Lake Superior, (b) Lake Huron, (c) Lake Michigan, (d) Lake Erie, (e) Lake Ontario, (f) Lake Saint Clair, (g) Yamzhog Yumco.**

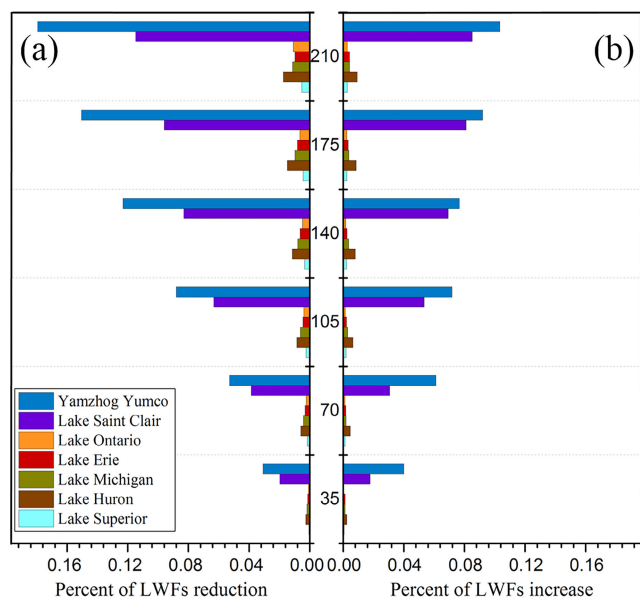
was set as 140 m and was 1.42 cm higher than that based on no-buffer water mask (RMSE = 54.12 cm).

2) CHANGES IN ICESat WATER LEVEL ACCURACY WITH BUFFER SIZE FOR OTHER SIX LAKES

The results of this study are different to those of previous studies (Table 1) in that the inside buffer did not always improve altimetry accuracy (Table 5). As the data shown in Table 5, the inside buffer of 105 m did not improve the altimetry accuracy of Lake Huron, Lake Michigan, and Lake Erie. Similarly, the inside buffer of 210 m did not improve the accuracy of Lake Huron, Lake Michigan, Lake Erie, and Lake Ontario, which proves that the inside buffer setting in researches of Wu *et al.* [26] and Li *et al.* [27] did not necessarily have a positive effect on the improvement of altimetry accuracy. Concretely, altimetry accuracy was not improved for Lake Superior when the inside buffer was below 105 m. However, for Lake Huron, an inside buffer with a size ranging from 105 m to 140 m slightly increased altimetry accuracy, whereas a size above 105 m failed to improve altimetry accuracy for Lake Michigan and failed to improve accuracy for Lake Erie. For Lake Ontario, the inside buffer of 210 m reduced altimetry accuracy. However, the inside

buffer slightly improved altimetry accuracy for Lake Saint Clair, and the maximum improvement was approximately 0.6 cm (Table 5).

The altimetry accuracy of the outside buffer also changed with a change in the buffer size, but it was difficult to make any consistent conclusions. For Lake Huron and Lake Erie, the outside buffer caused lower altimetry accuracy; however, for Lake Michigan, Lake Ontario, and Lake Saint Clair, the outside buffer slightly improved altimetry accuracy. However, for Lake Superior, altimetry accuracy of outside buffer decreased with an increase in the buffer size over 105 m (Table 5).



**FIGURE 7. Percentage number variations in lake water footprints (LWFs) for seven lakes with different inside and outside buffer sizes: (a) Percentage LWF reduction for seven lakes with inside buffers; (b) Percentage LWF increase for seven lakes with outside buffers.**

### 3) VARIATION IN SATELLITE ALTIMETRY ACCURACY WITH PERCENTAGE LWF CHANGES

It is evident from Figure 7 that relatively large variations in LWFs occurred for Yamzhog Yumco and Lake Saint Clair with both inside and outside buffers, which represents the sensitivity of their LWFs to the buffer size. However, there were no significant changes in the number of LWFs for the other five lakes, and their sensitivity is therefore considered to be low. As evident from Figure 6, there were approximately 2300 and 1000 LWFs for Yamzhog Yumco and Lake Saint Clair, respectively, while those for the other five lakes ranged from 4800 to 58,000. This indicates that the percentage footprint change is related to the number of LWFs obtained. With respect to the changes of RMSEs, it is not difficult to determine that the range of RMSE variation for Yamzhog Yumco and Lake Saint Clair is larger than for the other five lakes (1.42 cm for Yamzhog Yumco (Table 4) and 0.66 cm for Lake Saint Clair, whereas the range of RMSE variation for the other five lakes was below 0.1cm) (Table 5). This result

suggests that with a larger number of LWFs, there is a smaller proportional change in the numbers of LWFs with buffers, and the variation in altimetry accuracy is reduced.

### C. WATER MASK EXTRACTION ACCURACY

There are potential associated problems when extracting the water mask. Xu [56] presented an improved method of water mask extraction known as the modified NDWI (MNDWI), and his experiments showed the overall accuracy of extracted water body information reached 99.85% with a kappa coefficient of 0.9927, which verified the ability of the MNDWI to effectively reduce, and even eliminate, built-up land noise. In our research, footprints containing mixed pixels appeared at the edges of water bodies; thus, we considered that the use of the MNDWI method could effectively reduce the influence of mixed pixels. Sagin *et al.* [64] compared the water area extracted using the MNDWI method between Landsat images and SPOT images on the same date, and found that the error rate was only 1%. Thus, it is considered that the MNDWI method is reliable for extracting the water area. Based on the results of the above two studies, the method of extracting the water body using Landsat TM images and MNDWI appears to be feasible, and as its water body edge error is very small, we considered that it would not have an impact on the buffer analysis in this work.

### D. SELECTING MEAN OR MEDIAN LWF VALUE

In this study, we calculated the mean LWF value of each track, using the boxplot to remove outlier footprints, and the mean value was used as the altimetry water level for the corresponding date. This method was shown to be feasible in other studies [16], [17]. We then compared the accuracy of the median LWF value for each track and the mean LWF value for each track after removing outlier footprints. Considering that the existence of outlier footprints were mainly related to using the outside buffer, we used Lake Erie as an example to compare the satellite altimetry accuracy using the two methods under different outside buffer sizes. The results in Table 6 show that the median LWF value for a track with different outside buffers was almost the same, which also proves that the median LWF value is not sensitive to outlier footprints. Meanwhile, as we can see from Table 6, the RMSE of the median LWF value is higher than that of the mean LWF value, which means that the accuracy of the median LWF value for the track was lower than that of the mean LWF value after the outlier footprints were removed. For example, the RMSE of the median value is 13.787 cm under the outside buffer of 35 m, which is evidently lower than the RMSE of the mean LWF value after boxplot (18.700 cm). Therefore, the exclusion effect of the median LWF value on outlier footprints is not as good as that of the mean value after applying the boxplot. Zhang *et al.* [14], [51] also clearly determined that the mean value can remove small geoid errors; therefore, we calculated the mean value for each track after removing outliers via the boxplot.



**TABLE 6. RMSE (cm) of outside buffer with different sizes in Lake Erie.**

	Mean value after boxplot	Median of track
35 m	13.787	18.700
70 m	13.803	18.700
105 m	13.804	18.700
140 m	13.865	18.701
175 m	13.871	18.701
210 m	13.867	18.701

## V. CONCLUSIONS

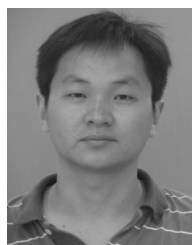
This study used satellite images to firstly extract LWFs by intersecting ICESat altimetry tracks and LWM without buffer analysis, and then compared lake water levels calculated from ICESat with corresponding *in situ* measured data. The main conclusions can be made as follows: Yamzhog Yumco has a narrow shape, and altimetry accuracy under the outside buffer was higher than those under the inside buffer and without the buffer. Altimetry accuracy was the highest when the width of the outside buffer was set as approximately 100 m. This also validates the reliability of the method of Huang *et al.* [29], which uses an outside buffer with narrow and long rivers. For the other relatively wide lakes, we found that altimetry accuracy was not improved when using the inside buffer method in any of the cases (Lake Michigan, Lake Erie, Lake Huron, Lake Ontario, and Lake Superior), which differs from those of previous studies. We also observed that for different lakes, the change in the range of altimetry accuracy was affected by the number of LWFs: the more LWFs, the smaller change in the proportion of LWFs obtained when buffer analysis was conducted and the smaller variation range in altimetry accuracy for the lake. In contrast, with a smaller number of LWFs, there was a larger change in the proportion of LWFs obtained when buffer analysis was conducted and a greater variation range in the altimetry accuracy for the lake.

When extracting altimetry satellite footprints, we found that the shape of a lake had an important influence on the number of LWFs obtained, which then affected the altimetry accuracy of the lake and its range of variation. This point has often been neglected in previous studies and is relevant, in particular, for relatively narrow lakes—the use of the outside buffer has a significant improvement on altimetry accuracy, as it increases the number of LWFs by enlarging the buffer zone outwards.

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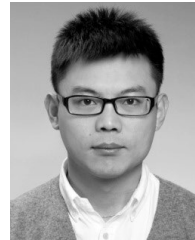
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