



Analysis of Long-Term Dynamic Changes of Subglacial lakes in the Recovery Ice Stream, Antarctica

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Abstract. The dynamic activity of subglacial lakes plays a crucial role in modulating glacial dynamic processes and influencing the mass balance of the Antarctic ice sheet. The Recovery Ice Stream (RIS), projected to experience significant mass loss in East Antarctica during coming centuries, requires continued investigation of its subglacial hydrological activity. Prior to 2012, nine active subglacial lakes and their dynamics in the RIS were identified through combined analysis of ICESat satellite altimetry and IceBridge airborne altimetry data. However, recent subglacial hydrological dynamics require further investigation. In this study, we investigate recent activity of nine subglacial lakes in the inventory of the RIS region using newly available ICESat-2 altimetry data, updating their outlines based on observed activity during the ICESat-2 mission period. Furthermore, we identify 14 newly active subglacial lakes designated as RecN1-RecN14. By synthesizing multi-source altimetry data (ICESat, IceBridge, ICESat-2), we establish a 21-year (2003-2023) elevation change time series for subglacial lakes in the RIS region. Through crossover analysis, we precisely identify elevation changes within subglacial lakes and elucidate spatiotemporal patterns across distinct lake sectors, revealing significant disparities between lake centers and their peripheries with a maximum difference of 4 m (e.g., lake Rec6-1). Finally, quantitative analysis of volume changes within primary drainage networks, based on constructed subglacial hydrological networks, confirms effective hydraulic connectivity between subglacial lake clusters in the RIS region. This study elucidates the hydrological dynamics of subglacial lakes in the RIS region, providing scientific basis for a deeper understanding of the evolutionary processes of Antarctic subglacial hydrological systems.

1 Introduction

Active subglacial lakes in Antarctica play critical roles in modulating ice stream velocities and outlet glacier dynamics (Stearns et al., 2008; Siegfried et al., 2016), influencing subglacial hydrology (Siegert et al., 2016; Napoleoni et al., 2020), and serving as a crucial component in understanding the mass balance of the Antarctic ice sheet (Livingstone et al., 2022). According to the most recent comprehensive inventory of subglacial lakes, there are about 140 active subglacial lakes in Antarctica (Livingstone et al., 2022). The Recovery Ice Stream (RIS) is located in East Antarctica, and thus far, a significant number of active subglacial lakes have been discovered in this region (Smith et al., 2009; Fricker et al., 2014). It is predicted that RIS will become one of the areas with severe mass loss in East Antarctica in the coming centuries, bearing consequential implications for the mass



balance of the East Antarctic ice sheet and global sea level rise (Golledge et al., 2017). Therefore, long-term monitoring of the dynamic changes of subglacial lakes in the RIS is essential for understanding the subglacial hydrological processes in this region and predicting potential changes in the RIS in the future (Dow et al., 2018).

The filling-draining events of active subglacial lakes are typically associated with fluctuations in surface elevation, leading to increases and decreases in surface elevation. Therefore, satellite altimetry offers a distinct advantage by providing extensive coverage and long-term data on ice surface elevations (Fricker et al., 2016), opening new avenues for identifying active subglacial lakes and monitoring their activity (Fricker et al., 2007; Fricker and Scambos, 2009). Three primary methods are employed to detect surface elevation changes using satellite altimetry data. The first is the repeat-track analysis method, which involves resampling the repeated measurement tracks from different times to a reference track, allowing for the calculation of elevation changes at the same location relative to the initial measurement time (Smith et al., 2009). This approach is commonly applied to laser satellite altimetry data, such as ICESat and ICESat-2, due to their strictly repeatable ground tracks. The second is the crossover analysis method. This approach involves obtaining the elevation data at the crossovers where the ascending and descending tracks intersect, and then differencing the elevation data to obtain the changes at the same location over different time periods (Fricker et al., 2010; Leong, 2021). This crossover analysis method can be applied to both laser altimetry data, such as ICESat (Shi et al., 2009), and ICESat-2 (Leong, 2021), as well as radar altimetry data, such as Envisat (Fricker et al., 2010). The third is the differencing digital elevation model (DEM) method. This method involves establishing a reference DEM or incorporating an external DEM, and then comparing it with satellite altimetry data collected at different times to calculate the surface elevation changes over a specific time interval (Siegfried and Fricker, 2021; Fan et al., 2023). In recent years, the commonly used radar altimetry satellite CryoSat-2 employs SARIn mode to monitor active subglacial lakes. In this mode, the distribution of data points are relatively sparse, rendering both repeat-track analysis and crossover analysis less applicable. In response to this situation, the differencing DEM method is often adopted. This approach involves accumulating sufficient altimetry data over a specific period to generate a DEM, which are then compared to the reference DEM (Kim et al., 2016), thus obtaining surface elevation changes over a specific time interval and facilitating the monitoring of elevation changes in subglacial lakes.

In the RIS region, the first four subglacial lakes (referred to here as Lakes A–D) were identified using a combination of ice surface elevation changes from ICESat and satellite imagery (Bell et al., 2007). These lakes are located in extensive, flat, and featureless ice surface areas, delineated by upstream troughs and downstream ridges. In subsequent studies, Langley et al. (2011) and Diez et al. (2019) examined the subglacial environments of these lakes and found that only the southern part of Lake A had a typical subglacial lake area, while the other areas had drained and had wet beds. Downstream from Lakes A–D, Smith et al. (2009) identified 11 active subglacial lakes based on surface elevation changes from repeat-track analysis using ICESat data between 2004 and 2008. This study also offered initial evidence of hydrological connectivity within the RIS (Smith et al., 2009). By combining ICESat satellite altimetry data and IceBridge airborne altimetry data, using an improved repeat-track analysis that divides tracks into narrower strips for closer repetition to reduce cross-track slope errors compared to Smith et al. (2009), the active subglacial lakes in RIS were re-investigated, and the existence of nine subglacial lakes (Rec1-Rec9) between 2003 and 2012 was ultimately confirmed (Fricker et al., 2014).



Previous studies utilized satellite altimetry data to monitor subglacial lake activity in the RIS region until 2012. According to simulations based on the Glacier Drainage System model (GlaDS), the basal hydrological system of the RIS has maintained an active state and is expected to continue this activity in the long term (Dow et al., 2018). Following the retirement of ICESat, a significant gap in continuous monitoring has limited our understanding of recent changes. The CryoSat-2 radar satellite provides only partial coverage through its SARIn mode, limited to lakes Rec1 and Rec2. During this monitoring gap, the Operation IceBridge airborne mission offers a valuable alternative, providing not only comprehensive coverage for lakes Rec1 through Rec6 but also extensive repeat survey data for the RIS over multiple years (Fricker et al., 2014). These features make IceBridge a significantly better choice for studying this area compared to CryoSat-2. Furthermore, the successful launch of ICESat-2 provides high-resolution and high-accuracy altimetry data of the Earth's surface, offering valuable opportunities for detailed investigation of the recent dynamics of subglacial lakes in the RIS region.

In this paper, the recently active subglacial lakes in the RIS region are investigated by using new satellite altimetry data from ICESat-2. The outlines of subglacial lakes in the inventory are updated, and several new subglacial lakes are also identified. Additionally, by integrating altimetry data from ICESat, IceBridge, and ICESat-2, the time series of elevation changes in subglacial lakes within the RIS region from 2003 to 2023 is obtained. Additionally, through crossover analysis, the variations in elevation changes at different locations within the lakes are investigated. Finally, the hydrological connections among subglacial lakes in the RIS are identified based on the subglacial hydrological networks and volume changes of the subglacial lakes.

2 Study area and data

2.1 Study area

The Recovery Basin is situated in Queen Maud Land, East Antarctica, covering approximately 996,000 km², which represents about 8% of the East Antarctic ice sheet's area (Rignot et al., 2008). As shown in Fig. 1, RIS is the core ice stream of Recovery Basin, contributing 58% of the total flux to the Filchner Ice Shelf (Joughin and Bamber, 2005), extending into the interior of Recovery Basin with a distinctive funnel-shaped structure—narrower in the downstream area while widening in the upstream region (Jezek, 1999). RIS borders the Shackleton Range to the north, while to the south it develops two important tributaries, namely Ramp Ice Stream and the less active Blackwall Ice Stream (Eis, 2019). The RIS features a distinctive narrow bedrock trough that extends approximately 1000 km, reaching depths of 1,500-2,000 m below sea level (Fricker et al., 2014). The subglacial hydrological system of the RIS is primarily governed by this bedrock topography, where the bedrock gradient exceeds the ice surface gradient by more than an order of magnitude (Fricker et al., 2014). The bedrock trough is divided into upper and lower sections by a ridge located at -17° W (Fricker et al., 2014). Most reported active lakes in the RIS region are located within the bedrock trough. The surface ice flow velocity increases from the upper trough to the lower trough, with speeds reaching approximately 870 m/year in the rapid ice flow region of the RIS (Floricioiu et al., 2014).

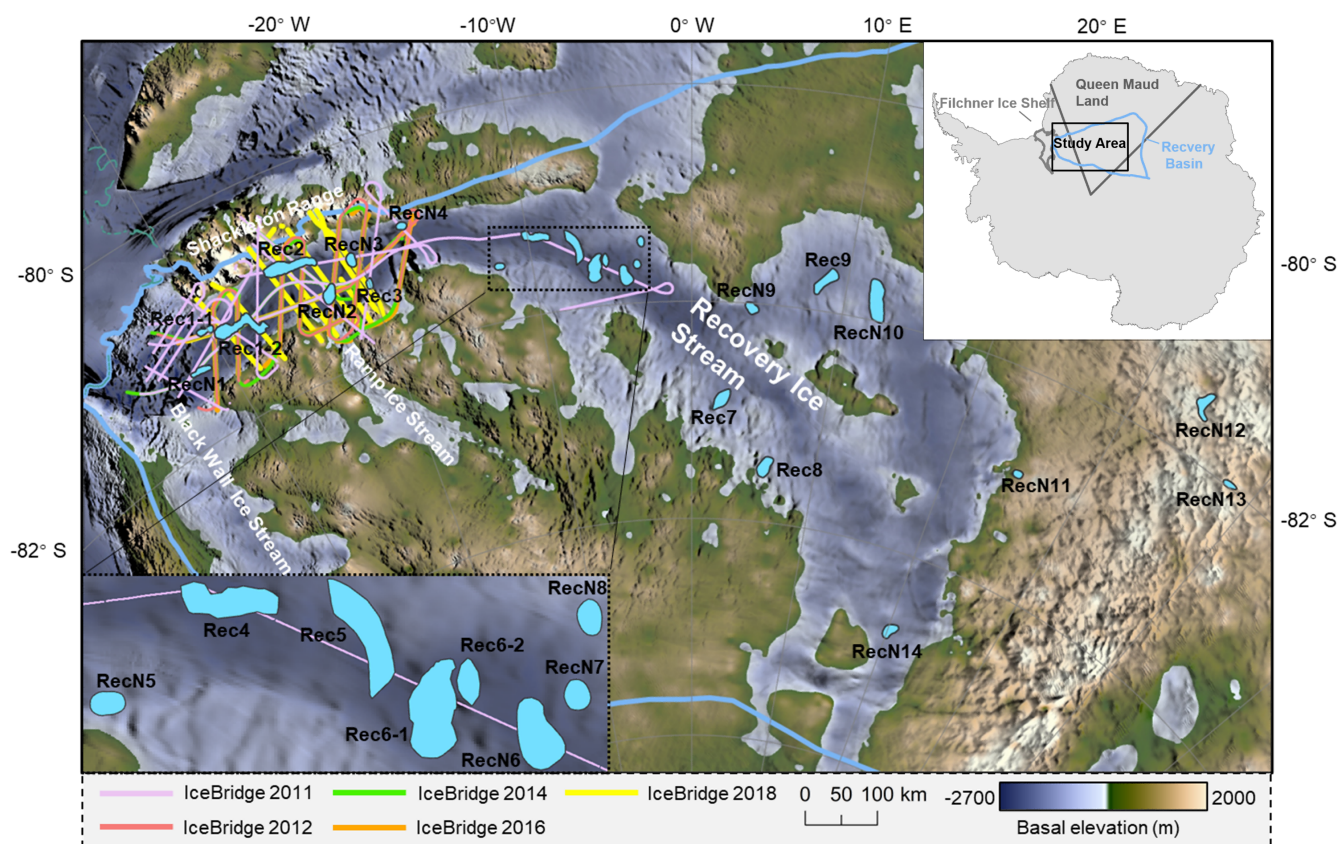


Figure 1. The inset map indicates the location of the study area. The main panel presents the bed elevation from BedMachine V3 (Morlighem, 2022), overlaid with the MODIS Mosaic of Antarctica (MOA) (Haran et al., 2014). The figure also highlights the flight lines from IceBridge campaigns in 2011, 2012, 2014, 2016, and 2018, as well as the locations of subglacial lakes.

2.2 Data

2.2.1 Altimetry data

In this study, three altimetry missions, including ICESat satellite altimetry data from 2003-2009, IceBridge airborne altimetry data from 2011-2018, and ICESat-2 satellite altimetry data from 2018-2023, are combined to obtain the long-term dynamics of the subglacial lakes in the RIS. The detailed information of these altimetry data are illustrated in Table 1

ICESat uses a single-beam laser altimeter equipped with a Geoscience Laser Altimetry System (GLAS) to sample the Earth's surface. The ground footprint of each laser pulse of ICESat is about 50-100 m in diameter, and the resolution along the satellite ground orbit is about 170 m (Abshire et al., 2005). Three identical lasers (Laser 1-Laser 3) were mounted on GLAS to ensure redundancy and extend the mission's operational lifetime. Laser 1 onboard ICESat malfunctioned 56 days after launch, resulting in very limited data collection. Additionally, the integration of its data with subsequent data require various error



Table 1. The acquisition time of the altimetry data used in this study.

Data	Dates
ICESat	Laser 2a: Oct. 13, 2003 - Nov. 19, 2003
	Laser 2b: Feb. 17, 2004 - Mar. 21, 2004
	Laser 2c: May. 18, 2004 - Jun. 21, 2004
	Laser 3a: Oct. 03, 2004 - Nov. 08, 2004
	Laser 3b: Feb. 17, 2005 - Mar. 24, 2005
	Laser 3c: May. 20, 2005 - Jun. 23, 2005
	Laser 3d: Oct. 21, 2005 - Nov. 24, 2005
	Laser 3e: Feb. 22, 2006 - Mar. 28, 2006
	Laser 3f: May. 24, 2006 - Jun. 26, 2006
	Laser 3g: Oct. 25, 2006 - Nov. 27, 2006
	Laser 3h: Mar. 12, 2007 - Apr. 14, 2007
	Laser 3i: Oct. 02, 2007 - Nov. 05, 2007
	Laser 3j: Feb. 17, 2008 - Mar. 21, 2008
	Laser 3k: Oct. 04, 2008 - Oct. 19, 2008
	Laser 2d: Nov. 25, 2008 - Dec. 17, 2008
	Laser 2e: Mar. 09, 2009 - Apr. 11, 2009
	Laser 2f: Sep. 30, 2009 - Oct. 11, 2009
IceBridge	2011 flights: Oct. 20, 2011 and Nov. 07, 2011
	2012 flight: Oct. 18, 2012
	2014 flights: Oct. 25, 2014 and Nov. 08, 2014
	2016 flight: Oct. 24, 2016
	2018 flights: Oct. 18, 2018 and Nov. 14, 2018
ICESat-2	Cycle 1: Oct. 13, 2018 - Dec. 28, 2018
	Cycle 2: Dec. 28, 2018 - Mar. 29, 2019
	Cycle 3: Mar. 29, 2019 - Jun. 28, 2019
	Cycle 4: Jul. 09, 2019 - Sep. 26, 2019
	Cycle 5: Sep. 26, 2019 - Dec. 26, 2019
	Cycle 6: Dec. 26, 2019 - Mar. 26, 2020
	Cycle 7: Mar. 26, 2020 - Jun. 25, 2020
	Cycle 8: Jun. 25, 2020 - Sep. 24, 2020
	Cycle 9: Sep. 24, 2020 - Dec. 23, 2020
	Cycle 10: Dec. 24, 2020 - Mar. 24, 2021
	Cycle 11: Mar. 24, 2021 - Jun. 23, 2021
	Cycle 12: Jun. 23, 2021 - Sep. 22, 2021
	Cycle 13: Sep. 22, 2021 - Dec. 22, 2021
	Cycle 14: Dec. 22, 2021 - Mar. 23, 2022
	Cycle 15: Mar. 23, 2022 - Jun. 21, 2022
	Cycle 16: Jun. 21, 2022 - Sep. 20, 2022
	Cycle 17: Sep. 20, 2022 - Dec. 20, 2022
	Cycle 18: Dec. 20, 2022 - Mar. 21, 2023
	Cycle 19: Mar. 21, 2023 - Jun. 20, 2023

100 corrections. Therefore, this study only utilizes data collected by Laser 2 and Laser 3. Laser 2 was shut down after the Laser 2c campaign, and was restarted following the failure of Laser 3, so the Laser 2d-Laser 2f campaign period occurred after Laser 3k



(Borsa et al., 2014, 2019). The GLAH12 polar ice sheet elevation product provided by the National Snow and Ice Data Center (NSIDC) is adopted in this study. This product has been processed with a series of corrections including saturation correction, receiver gain filtering, data processing flags, ellipsoid correction, task period deviation correction (Sun et al., 2017).

Operation IceBridge is a large-scale polar aerial survey mission designed to bridge the data gap between ICESat and ICESat-2 satellites, hence the name ‘ice bridge’ (Fricker et al., 2014). In the polar area, over 1,000 aircraft survey flights have been conducted from 2010 to 2018. However, only five years of ice bridge operation tasks in 2011, 2012, 2014, 2016, and 2018 collected data on active subglacial lakes in the RIS. This study incorporates the Airborne Topographic Mapper (ATM) data from the IceBridge operation. To maximize measurement accuracy, we only retained data collected along the nadir track, which provides more precise ice surface elevation measurements and minimizes the influence of terrain undulations and tilt angles on the measurement results. The locations of flight lines used in this study from the IceBridge mission are shown in Fig. 1.

ICESat-2 is equipped with an Advanced Topographic Laser Altimetry System (ATLAS), which achieves centimeter-level accuracy in surface elevation measurements. ICESat-2 Land-Ice Surface Heights product ATL06 and the Slope-Corrected Land Ice Height Time Series product ATL11 are employed to analyze elevation changes in subglacial lakes within the RIS region. The ATL06 data, oriented along the orbital path, utilize 40 m track segments to calculate average heights, with an along-track resolution of 20 m (Smith et al., 2019). The time span of the ICESat-2 ATL06 data used in this study extends from October 2018 to June 2023 (Cycle 1 to Cycle 19, as shown in Table 1). ATL11 provides a temporally organized land-ice surface height time series derived from the ATL06 product (Smith et al., 2023). Height variations in the ATL11 data are computed for successive observations (spaced 91 days apart) along individual ICESat-2 ground tracks in polar regions, with an along-track resolution of 60 m. Due to suboptimal overlap of repeated orbits during the initial two cycles, ATL11 began providing products from cycle 3 onward, starting after March 29, 2019. Additionally, ATL11 offers elevation data at crossovers with a temporal resolution reduced from the original 91-day cycle to one month or even a few days.

2.2.2 Ice thickness and bedrock elevation data

The ice thickness data provided by the latest Antarctic terrain dataset BedMachine V3 (Morlighem, 2022) is used. The ice thickness data with 500 m resolution are sourced from airborne ice-penetrating radar surveys (Morlighem, 2022). The surface elevation is derived from the surface DEM of Reference Elevation Model of Antarctica (REMA) (Howat et al., 2019). REMA represents the first continental-scale DEM with a resolution of less than 10 m. It is constructed using high-resolution commercial satellite imagery from GeoEye-1, WorldView-1, WorldView-2, and WorldView-3. The bedrock elevation is obtained by subtracting the ice thickness from the REMA surface DEM.



3 Methods

130 3.1 Detection of potential active subglacial lake areas

To detect potential active subglacial lake areas post-2019, ICESat-2 ATL11 data, which have a smaller data volume, are utilized to calculate elevation changes along repeat tracks for improved computational efficiency. The elevation change is defined as the absolute difference between the maximum and minimum elevations recorded for the data points. Typically, active subglacial lake areas in the RIS exhibit surface elevation changes greater than 0.5 m (Smith et al., 2009; Fricker et al., 2014). Therefore, a 0.5 m threshold is set for the magnitude of elevation change to filter potential active subglacial lake regions.

Significant apparent displacement tends to occur in areas where the surface slope exceeds 1 degree (Smith et al., 2009), as areas with large surface slopes have complex topography that impacts footprint positioning accuracy and may introduce errors in altimetry data. Consequently, a slope constraint calculated using the 100 m resolution REMA DEM product (Howat et al., 2019) is applied to areas with elevation changes exceeding 0.5 m. In addition, to eliminate elevation anomalies caused by factors other than subglacial lake activity, such as surface roughness that may affect the reliability of altimetry measurements (Smith et al., 2009; Shen et al., 2020), the Landsat Image Mosaic of Antarctica (LIMA) (Bindshadler et al., 2008) is used to visually inspect and exclude areas with large surface roughness. Finally, the filtered potential active subglacial lake regions, along with inventory lakes (Rec1–Rec9) reported by Fricker et al. (2014) in the RIS, are considered as potential active subglacial lake areas for further analysis.

145 3.2 Obtaining long-term elevation changes of subglacial lakes

The calculation of long-term elevation changes in subglacial lakes consists of three modules: generating a reference DEM for each potential active subglacial lake area to avoid the influence of topography, delineating the outlines of subglacial lakes based on ICESat-2 ATL06 data, and obtaining elevation changes of subglacial lakes from 2003 to 2023 using multi-mission altimetry data.

150 3.2.1 Generating reference DEMs

To ensure all lake areas are included, each detected potential active subglacial lake area is extended outward by 10 km. ICESat-2 ATL06 altimetry data are used to generate a reference DEM for each potential subglacial lake area. Outliers in the altimetry data are removed using an iterative three-sigma filter with a 95% convergence threshold (Siegfried and Fricker, 2018). Then, an adjustable tension continuous curvature spline interpolation method (Siegfried and Fricker, 2021) is applied to grid the block-averaged data points, resulting in a reference DEM for each potential lake area. In this study, the spatial resolution of the reference DEMs is set as 100 m, considering the density of ICESat-2 altimetry data in the RIS. These DEMs will serve as references for calculating elevation changes across all altimetry missions, enabling the quantitative analysis of elevation changes for each subglacial lake.



3.2.2 Delineating the outlines of subglacial lakes

160 Compared to ICESat and ATM altimetry data, ICESat-2 mission provides higher orbit sampling resolution and denser cross-track spacing (Smith et al., 2019). Therefore, ICESat-2 ATL06 altimetry data are used to delineate the outlines of lakes in this study. The reference DEMs are interpolated onto the ICESat-2 tracks, and surface elevation changes are calculated by subtracting the observed elevations from their corresponding values in the reference DEMs. To ensure extensive coverage of ICESat-2 for each active subglacial lake, following Siegfried and Fricker (2021), we use a three-month overlapping time
165 window centered on each month to calculate average elevation changes on a monthly scale. For each potential subglacial lake area, we comprehensively analyzed monthly elevation change maps from 2018 to 2023, identified regions with elevation changes exceeding 0.5 m, and extracted the common change areas across different periods as lake outlines by comparing multiple temporal elevation change maps.

3.2.3 Obtaining elevation changes of subglacial lakes from 2003 to 2023 using multi-mission altimetry data

170 To capture the long-term dynamic variations of active subglacial lakes in the RIS and gain a comprehensive understanding of subglacial hydrological patterns, altimetry data from ICESat (2003-2009), IceBridge (2011-2018), and ICESat-2 (2018-2023) are combined to calculate surface elevation changes for each active subglacial lake. As described earlier, surface elevation changes are derived by subtracting ICESat, IceBridge, or ICESat-2 altimetry data from their corresponding values in the reference DEM. To isolate elevation variations predominantly attributable to subglacial water activity from regional surface
175 elevation trends (such as glacier melting and accumulation), this study adopts the method proposed by Siegfried et al. (2014), which involves subtracting the average exterior lake measurements from the average interior lake measurements based on the delineated outlines of subglacial lakes. Moreover, we propose a weighting method that assigns weights to measurement points based on their distance from the lakes' outlines to calculate surface elevation changes in subglacial lakes accurately. Generally, for measurements within the lake, the farther a measurement point is from the lake's outline, the stronger the correlation
180 between ice surface elevation changes and subglacial lake activity. Conversely, for measurements outside the lake, the farther the point is from the outline, the weaker this correlation. The surface elevation changes are calculated by using Eq. (1).

$$\Delta h = \Delta h_{inlake} - \Delta h_{outlake} = \frac{\sum_{i=1}^{N_{in}} p_i h_i}{\sum_{i=1}^{N_{in}} p_i} - \frac{\sum_{j=1}^{N_{out}} p_j h_j}{\sum_{j=1}^{N_{out}} p_j} \quad (1)$$

Where Δh_{inlake} represents the elevation changes for lake interior points, $\Delta h_{outlake}$ represents the elevation changes for lake exterior points, N_{in} , N_{out} denote the quantities of lake interior and exterior points respectively, and p_i , p_j correspond to
185 the weights, which are assigned based on the minimum distance from the elevation measurement points to the lake outline, for lake interior and exterior points. h_i and h_j correspond to elevation measurement values for lake interior and exterior points.

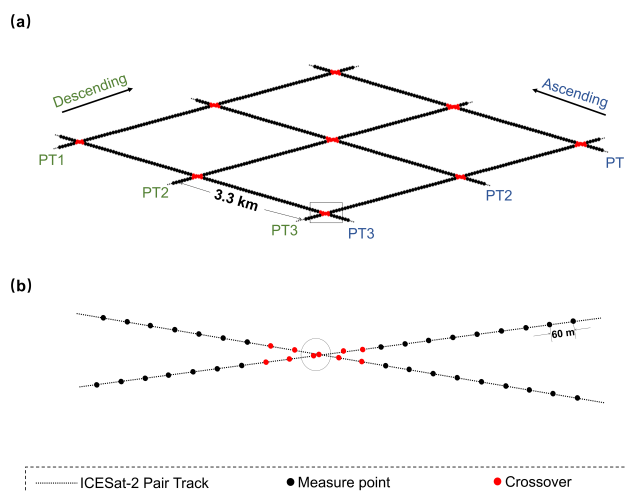


Figure 2. A schematic diagram of crossovers in ICESat-2 ATL11 data. (a) Distribution of crossovers at the intersections of ascending and descending reference ground tracks (RGTs), where each RGT consists of three pair tracks (PTs) spaced 3.3 km apart. The magnified view of crossovers within the box in (a) is shown in (b).

3.3 The detailed trend of elevation changes within lakes based on crossover analysis

The elevations at crossovers obtained from ascending and descending tracks, with the time interval approximately from one to several tens of days, are compared to reveal the detailed elevation change patterns in different regions of the lake.

190 In the altimetry data from ICESat-2, each measurement point is treated as the center of a circular search area with a radius of 65 m, within which neighboring measurement points are identified. If a measurement point from a crossing track is found within this range, it is recorded as a crossover stored in ATL11 data products. However, in our study area, multiple crossovers, forming X-shaped clusters as illustrated in Fig. 2(a), can be found in a pair of ascending and descending tracks. This is because large intersection angles between ascending and descending tracks at high latitudes allow a single crossing track to match multiple crossovers. To address this, we first identify the two measurement points closest to the theoretical intersection of the ascending and descending tracks within each crossover cluster, as shown by the two points inside the circle in Fig. 2(b). Next, we compare the number of valid data points associated with these measurements and select the point with the greater number of valid data points as the representative crossover. This point is then used to analyze elevation changes at the crossover. We organize the elevation measurement data at a crossover in chronological order. Then, the earliest elevation measurement value at time T_0 is subtracted from the elevation values at each moment T_i to calculate the elevation change at each moment relative to the initial time. Finally, the elevation changes for each crossover are arranged into time series.

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3.4 Subglacial hydrological analysis in the RIS

To explore the hydrological connections between subglacial lakes in the RIS region, the subglacial hydraulic potential ϕ is calculated using the Shreve hydraulic potential model (Shreve, 1972), as shown in Eq. (2).

$$\phi = B + \frac{\rho_i}{\rho_w} H \quad (2)$$

Where ρ_w and ρ_i represent the densities of water (1,000 kg/m³) and ice (917 kg/m³), respectively. B and H denote the bedrock elevation and ice thickness, respectively, which are obtained from BedMachine v3 in this study. First, based on the results of the hydraulic potential calculations, the hydraulic potential surface is generated in ArcGIS. Then, the D8 flow direction method (O'Callaghan and Mark, 1984) is employed to calculate the changes in hydraulic potential gradients in each direction within each grid cell, directing flow to the direction of the steepest hydraulic potential gradient, thereby determining the subglacial drainage networks. Finally, according to the Strahler (Strahler, 1957) method, all river systems are classified into hierarchical networks from first to sixth orders based on the calculated cumulative flow from largest to smallest, simulating the final configuration of the subglacial hydrological networks.

4 Results and discussions

4.1 Outlines of active subglacial lakes in the RIS region

Of the nine reported subglacial lakes, lakes Rec1, Rec2, Rec4, and Rec6 demonstrate noticeable drainage-filling cycles during the ICESat-2 mission. However, the drainage and filling areas of these four lakes during this time period show differences from those in the inventory. The updated outlines and the annual elevation changes of lakes Rec1, Rec2, Rec4, and Rec6 are shown in Fig. 3. During the ICESat-2 mission, it is observed that the elevation changes exhibited asynchronous variations within the area of lake Rec1 provided in the inventory (Fricker et al., 2014). A repeat-track analysis is performed to verify the asynchronous variations within the area of lake Rec1. The analysis is based on ICESat-2 ATL11 data, which are repeatedly collected over different cycles through three PTs (PT1, PT2, PT3) along each RGT. As shown in Fig. 4, we focus our analysis on three specific tracks (RGT 0063 PT3, RGT 0505 PT2, and RGT 0947 PT1), which intersect with two regions exhibiting asynchronous variations within lake Rec1. All track data are then differenced with the reference DEM synthesized in this paper, which yields elevation changes for each track in each cycle.

According to the elevation change ranges during the time periods of these three repeat tracks from Cycle 3 to Cycle 19 (Figs. 4 (b)-(d)), the elevation changes of the left part of lake Rec1 (approximately 3 m) are significantly greater than those of the right part of lake Rec1 (approximately 0.5 m). There are even periods when the elevation changes are reversed. For example, the left part of lake Rec1 is draining while the right part is filling during Cycle 3, and this situation is reversed in Cycle 17, as shown in Figs. 4 (b)-(d). Therefore, we recognize lake Rec1 as two separate lakes, named as Rec1-1 (left part of lake Rec1) and Rec1-2 (right part of lake Rec1) during the ICESat-2 mission, as shown in Fig. 3.

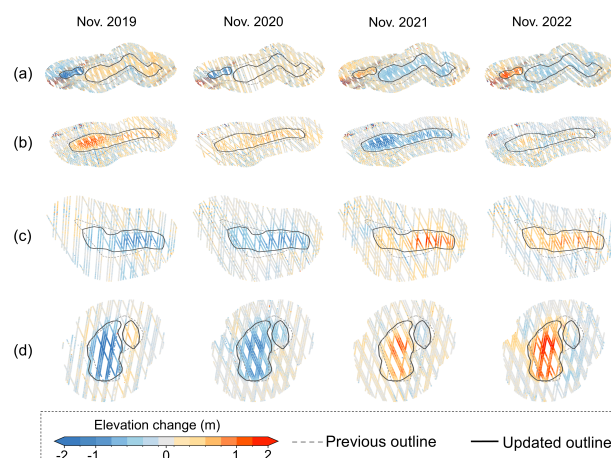


Figure 3. Updated outlines and the annual elevation changes of lakes (a) Rec1, (b) Rec2, (c) Rec4, and (d) Rec6.

As illustrated in Fig. 3, lake Rec2's outline contracted inward while preserving its central location, evolving into a more elongated form. The shape and position of lake Rec4 have also changed, developing a more elongated morphology, with a subtle displacement in the lake's center position. Lake Rec6 displayed two sections with contrasting elevation change patterns during the ICESat-2 mission, leading us to classify them as separate lakes: lake Rec6-1 (left section) and lake Rec6-2 (right section), as shown in Fig. 3.

The remaining five reported lakes (Rec3, Rec5, Rec7, Rec8, and Rec9) show low levels of activity during the ICESat-2 period, with slight elevation changes (less than 0.5 m), and therefore, they are not further analyzed in this study. In addition, 14 active subglacial lakes, named lakes RecN1 through RecN14 from downstream to upstream, are newly detected in this study. The spatial distribution of these newly detected subglacial lakes and updated subglacial lakes (Rec1-1, Rec1-2, Rec2, Rec4, Rec6-1, and Rec6-2) is illustrated in Fig. 1. The identification of these new lakes can be attributed to multiple factors, such as the increased orbit density and altimetry accuracy of ICESat-2 altimetry data, as well as hydrological changes in the subglacial lakes' activity.

4.2 Analysis of time series of elevation changes of subglacial lakes

According to Fricker et al. (2014), the bedrock trough in the RIS region is naturally divided into upstream and downstream sections by a ridge located at -17°W . Based on the geographical distribution of active lakes in the region, we classified all the lakes into three groups: The first group (lakes RecN1, RecN2, RecN3, RecN4, Rec1-1, Rec1-2, Rec2, and Rec3) is located in the downstream section of the bedrock trough; the second group (lakes RecN5, RecN6, RecN7, RecN8, Rec4, Rec5, Rec6-1, and Rec6-2) is concentrated in the upstream section of the bedrock trough; and the third group (lakes RecN9, RecN10, RecN11, RecN12, RecN13, RecN14, Rec7, Rec8, and Rec9) is primarily distributed in the upstream region outside the bedrock trough, exhibiting relatively dispersed spatial characteristics. To comprehensively investigate the spatiotemporal evolution of

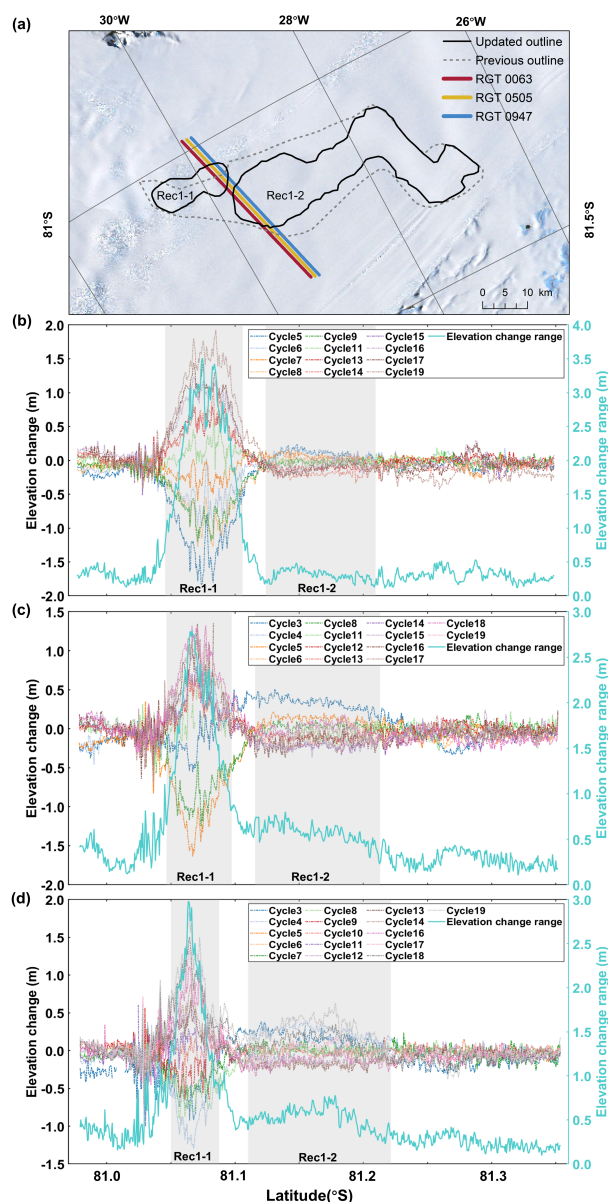


Figure 4. Repeat-track analysis results of lake Rec1. (a) The location of three repeat tracks crossing through lake Rec1. The range of elevation changes along the repeat tracks encompassing all cycles is shown in (b) RGT 0063, (c) RGT 0505, and (d) RGT 0947.

these lakes, we construct elevation change time series for each group by integrating multi-source altimetry data from ICESat, IceBridge, and ICESat-2. In this study, elevation changes are calculated by subtracting the elevation values at corresponding positions in the generated reference DEM. Following Siegfried and Fricker (2018), we normalize the elevation changes to ensure data comparability and facilitate analysis: all data are adjusted by subtracting the elevation change value at the initial

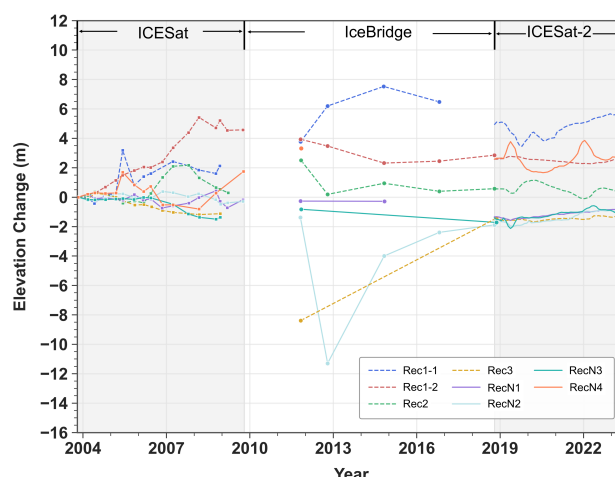


Figure 5. Time series of elevation changes of the lakes in the lower trough.

ICESat observation time, making each time series curve start from zero. These time series curves intuitively reflect the hydrological dynamic characteristics of the lakes: an upward trend indicates rising water levels during the filling phase, while a downward trend signifies decreasing water levels during the draining phase.

4.2.1 Lower trough

260 The temporal elevation changes of active lakes in the lower trough are shown in Fig. 5. During the ICESat mission, lakes Rec1-1 and Rec1-2 exhibit the most significant elevation changes: lake Rec1-2 shows a continuous filling trend from early 2003 to 2008, with a cumulative rise exceeding 5.5 m, while lake Rec1-1 experiences a notable filling event between May 2004 and May 2005, with an elevation increase of over 3 m. During the same period, lakes RecN4 and Rec2 also demonstrate significant dynamic features, with elevation changes exceeding 2 m. In contrast, lakes Rec3, RecN1, RecN2, and RecN3 show relatively
265 minor elevation changes, with fluctuations around 1 m.

During Operation IceBridge, lake RecN2 shows particularly significant variations, with elevation dropping sharply by over 10 m between October 2011 and October 2012, followed by a continuous rise of approximately 9 m before October 2018. During the same period, lake Rec3 also experiences significant elevation changes, with an increase of up to 7 m. Lake Rec1-1 exhibits a pattern of first accumulating water and then draining, with a maximum elevation change of approximately 4 m.
270 Lakes Rec1-2 and Rec2 initially experience a slight drainage before stabilizing. Lakes RecN1 and RecN3 remain relatively stable during this period. Lake RecN4 has only one observation recorded in October 2011, with an elevation approximately 1.5 m higher than that measured by ICESat in October 2009, and similar to the elevation measured by ICESat-2 in October 2018. Additionally, the observations from IceBridge in October 2018 show high consistency with ICESat-2 data from the same period, ensuring a seamless connection in elevation changes and further confirming the reliability of the observational data.



275 During the ICESat-2 observation period, lakes RecN4, Rec1-1, and Rec2 show significant elevation changes with distinct drainage and storage events. Lake RecN4 experiences two notable storage-drainage cycles. The first cycle begins in February 2019, with elevation rising by 1.1 m within three months, followed by a rapid decrease to its lowest point in July 2020, with a total decline of 2.1 m. The second cycle occurs between July 2020 and October 2022, initially experiencing an increase of approximately 2.4 m, reaching its peak in January 2022, followed by another decline of about 1.4 m by October 2022. Lake
280 Rec1-1 undergoes two drainage-storage cycles. Notably, between August 2020 and June 2023, a continuous elevation uplift is observed with a cumulative increase of 2.2 m. Lake Rec2 experiences two storage-drainage cycles. The first cycle commences in June 2019, with a gradual water accumulation of 0.9 m over a 10-month period. By April 2020, the lake transitions to a sustained drainage phase, culminating in a cumulative decrease of approximately 1.3 m by January 2022. The second cycle begins in January 2022, with elevation rising by 0.6 m over the subsequent eight months until September 2022. Finally, from
285 September 2022 through June 2023, Lake Rec2 persists in its draining trend, exhibiting an elevation decrease of 0.3 m. Lake Rec1-2 maintains relative stability during this period, showing an overall trend of initial decrease followed by increase. Lakes RecN1, RecN2, and RecN3 display similar change patterns: decreasing in elevation from October 2018 to June 2019, then transitioning to a fluctuating upward trend. The total elevation changes range from 0.5 to 1 m. Lake Rec3 exhibits relatively stable characteristics during this period, with minimal elevation changes.

290 4.2.2 Upper trough

The time series analysis of elevation changes for subglacial lakes in the upper trough is presented in Fig. 6. During the ICESat mission period, lakes Rec6-1 and Rec6-2 show the most significant changes. Lake Rec6-1 experiences intense drainage between early 2006 and early 2008, featuring a sustained elevation decrease exceeding 10 m. The elevation change pattern of lake Rec6-2 can be divided into two phases: between 2003 and 2006, it shows similar change trends to lake Rec6-1, while from
295 early 2008 to late 2009, it displays distinct dynamic characteristics, with four significant elevation change events recorded, each exceeding 4 m in magnitude. Lake Rec4 also exhibits significant hydrological activity, recording multiple major storage and drainage events with amplitudes exceeding 1 m. In contrast, lakes Rec5, RecN5, and RecN7 show relatively moderate change characteristics: lake Rec5's elevation displays a fluctuating slow rise with total amplitude less than 1 m; lake RecN5 overall undergoes a fluctuating drainage process with a cumulative elevation decrease of 0.8 m; while lake RecN7 records a
300 fluctuating rise of approximately 0.8 m. Lakes RecN6 and RecN8 exhibit similar elevation change characteristics throughout the observation period. Lake RecN6 first experiences a cumulative elevation decrease of about 1 m from late 2003 to late 2006; then undergoes a six-month rise-and-fall cycle with comparable amplitudes; subsequently enters a two-year storage period with an elevation increase of 0.7 m; and finally shows fluctuations of about 0.5 m. Lake RecN8 shows similar patterns to lake RecN6, with only relatively smaller magnitudes of change.

305 During the Operation IceBridge observation period, only lakes Rec4, Rec5, Rec6-1, and RecN6 are observed once in 2011. Compared to the elevations measured by ICESat in late 2009, lakes Rec4 and Rec5 experience a decrease of approximately 1 m, while both lakes Rec6-1 and RecN6 experience elevation increases, with rises of approximately 1 m and 0.5 m, respectively.

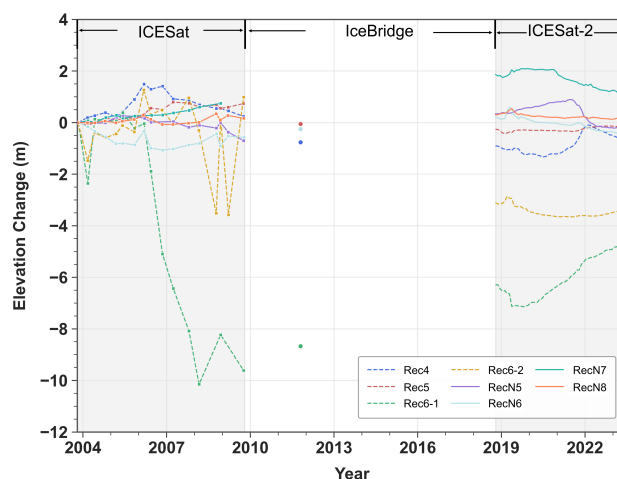


Figure 6. Time series of elevation changes of the lakes in the upper trough.

Compared to the elevation data observed by ICESat-2 in late 2018, the elevations of lakes Rec4, Rec5, and RecN6 show no significant changes (less than 0.5 m), while lake Rec6-1 exhibits a substantial increase of more than 2 m.

During the ICESat-2 observation period, lakes Rec6-2, RecN6, RecN7, and RecN8 initially show similar change patterns, successively reaching their peak elevations during May-June 2019. However, these lakes subsequently exhibit distinct change patterns: lakes RecN6 and RecN8 immediately enter continuous drainage modes, lake Rec6-2 stabilizes after approximately two years of drainage, while lake RecN7 maintains its peak elevation until January 2021 before beginning to decline, recording a cumulative decrease of over 1 m by the final observation in June 2023. Lake Rec6-1, as the most active lake in the region, displays a distinct change pattern compared to other lakes. Prior to May 2019, while other lakes are generally in filling phases, lake Rec6-1 exhibits continuous drainage characteristics. Subsequently, after May 2019, it transitions to a sustained filling mode accompanied by minor fluctuations. Lake Rec4 records a complete draining-filling-draining cycle: experiencing fluctuating drainage from late 2018 to May 2019 with an elevation decrease of approximately 0.5 m; then entering a sustained filling phase with gradual water level rise until reaching its peak in early 2022, accumulating an increase of about 1.5 m; finally entering a new drainage phase with an elevation decrease of approximately 0.6 m. Lake RecN5 shows a significant elevation increase of 0.6 m during the period from October 2018 to July 2021; subsequently experiences a drainage event between July 2021 and May 2022, with a sharp elevation decrease of 1.2 m; and finally enters a relatively stable period from May 2022 to June 2023, showing no significant changes. Lake Rec5 exhibits remarkable stability throughout the observation period, maintaining elevation changes within 0.3 m.

4.2.3 Upstream of bedrock trough

As shown in Fig. 7, the subglacial lakes in the upstream region of the bedrock trough exhibit different dynamic characteristics during various observation periods. During the ICESat mission period, lakes Rec7, Rec8, and RecN11 exhibit significant

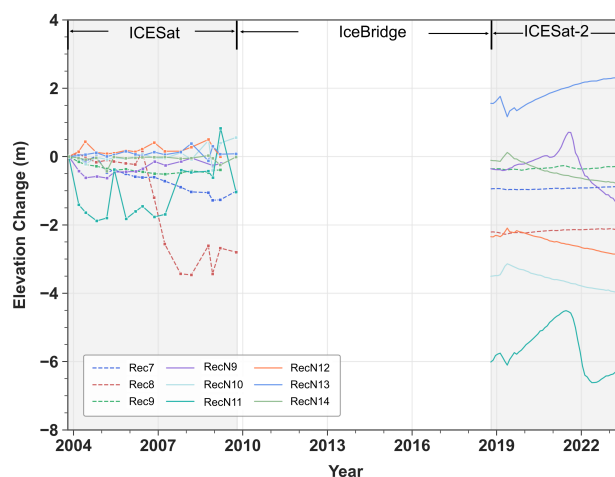


Figure 7. Time series of elevation changes of the upstream lakes.

elevation changes. Lake Rec7 shows a continuous declining trend with a cumulative decrease of 1.5 m; lake Rec8 experiences two distinct phases: initially showing minimal elevation changes, followed by a sharp decline of 3.6 m between March 2006 and February 2008; lake RecN11 demonstrates elevation changes exceeding 1.5 m during single filling or draining events. Lake RecN10 maintains relative stability during the early observation period, showing only one significant fluctuation from late 2008 to early 2009, characterized by a decrease followed by an increase, with both changes approaching 1 m in magnitude. Lakes Rec9, RecN9, RecN12, RecN13, and RecN14 maintain relatively stable conditions, with elevation changes limited to around 0.5 m.

Although the lakes in this area are not covered by IceBridge data, by comparing the latest ICESat data with the earliest ICESat-2 data, it is found that the elevations of lakes Rec7, Rec8, Rec9, RecN9 and RecN14 are similar. In contrast, the elevations of lakes RecN10, RecN11, and RecN12 decrease by approximately 4 m, 5 m, and 2.5 m, respectively, while the elevation of lake RecN13 increases by about 1.5 m.

During the subsequent ICESat-2 mission period, lake RecN9 experiences significant elevation changes, first rising by 1.1 m followed by a decrease of 2.1 m; lakes RecN10, RecN12, and RecN14 display highly consistent change patterns, all reaching peak elevations around May 2019 before continuously declining by approximately 0.8 m; lakes RecN13 and RecN11 initially show similar change trends, with lake RecN13 reaching its lowest point in May 2019 (dropping by 0.6 m) before gradually rising by 1.6 m, while lake RecN11 undergoes a significant transformation after July 2021, rapidly declining by 2.1 m followed by a slow recovery trend. Lakes Rec7, Rec8, and Rec9 show notably reduced activity during this period, maintaining relatively stable elevation changes.



4.3 The detailed trend of elevation changes within the lakes based on crossover analysis

To investigate the detailed elevation change trend within the subglacial lakes, we select four representative lakes based on their characteristic temporal variations. Lake Rec6-1, which demonstrates the most pronounced elevation change amplitude in long-term observations, is selected. Additionally, lake Rec6-2, which was part of the same lake as Rec6-1 in the past, is also investigated to facilitate a detailed comparison of the elevation change patterns between these two adjacent lakes. Lake Rec2 is geographically adjacent to the Shackleton Range, with its hydrological activity influenced by the topography of the Shackleton Range (Fricker et al., 2014). Considering its geographical significance, it is analyzed as a representative case. Lake RecN4 exhibits highly pronounced filling-draining cycle characteristics in its temporal elevation changes, with each complete filling-draining cycle lasting approximately 2 years and an elevation change range of about 2 m, as shown in Fig. 5. Therefore, it is also analyzed as a representative active subglacial lake. As shown in Fig. 8, in each subplot, every line represents the elevation change time series of a crossover, with color intensity related to the normalized magnitude of elevation change (darker colors indicate larger changes). Meanwhile, in the insets of each subplot, the spatial distribution of crossovers within each lake is displayed using exactly the same colors as their corresponding time series curves.

As shown in Fig. 8(a), the elevation of subglacial lake Rec6-1 exhibits a continuous increasing trend during the ICESat-2 observation period, indicating significant active characteristics. Although all crossovers display similar patterns of elevation change, their magnitudes show notable spatial variations: crossovers in the central lake area demonstrate the maximum elevation changes, while those distributed in the peripheral regions show smaller changes. By June 2023, this spatial differentiation reaches its most pronounced level, with maximum elevation changes exceeding 4 m in the central lake area, while the minimum elevation changes in the peripheral regions are only about 0.3 m.

Lake Rec6-2 shows different characteristics of elevation change during the ICESat-2 observation period. The elevation of crossovers in lake Rec6-2 initially decreases and then stabilizes as shown in Fig. 8(b). In particular, between May 2019 and May 2021, these two lakes show opposite activity patterns, with lake Rec6-1 in a phase of continuous water storage and lake Rec6-2 in a drainage process. This difference indicates that the original lake Rec6 evolves into two parts.

Lakes Rec2 and RecN4 exhibit distinct filling and draining characteristics. Based on the spatial distribution of crossovers and the temporal elevation change patterns shown in Figs. 8(c)(d), crossovers in the central areas of the lakes display significant elevation changes, whereas those in the peripheral areas exhibit minimal variation, remaining close to 0. As shown in Fig. 8(c), lake Rec2 is a large and elongated lake with extensive crossover observation data. During the ICESat-2 observation period, the lake undergoes two filling-draining cycles, with elevation changes at crossovers remaining within the range of 4 m. The first filling-draining event takes place from May 2019 to February 2021. During the filling phase, most crossovers reach their peak elevation in March 2020, when the elevation difference between crossovers in the central and peripheral regions exceeds 2 m. Subsequently, during the approximately two-year-long draining phase, the elevations at crossovers gradually decrease, reaching their lowest values in February 2022. The second filling-draining event spans from February 2022 to June 2023. By September 2022, the elevations at crossovers reach a second peak. This period also marks the stage with the most pronounced elevation differences, as the elevation difference between the central and peripheral crossovers exceeds 2.5 m. As shown in

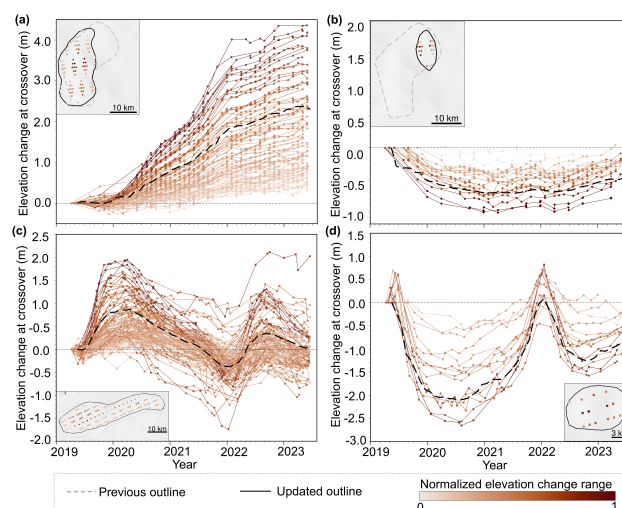


Figure 8. The detailed trend of elevation changes of lakes (a) Rec6-1, (b) Rec6-2, (c) Rec2, and (d) RecN4. The locations of crossovers in each lake are shown in the inset, with their colors indicating the corresponding normalized elevation change range.

380 Fig. 8(d), Lake RecN4 is a relatively small lake with fewer crossovers in its observation data. During the study period, the lake experiences two draining-filling cycles. The first draining-filling event has a longer duration, spanning from May 2019 to January 2022. During this period, the crossover elevations reach their first trough in August 2020, with the maximum elevation change of -2.8 m in the central region of the lake, while the elevation change in the peripheral region is relatively small at only -0.6 m, resulting in an elevation difference of over 2 m between the central and peripheral regions. The second draining-
385 filling event occurs between January 2022 and June 2023. The crossover elevations within the lake reach their second trough in September 2022, during which the elevation difference between the central and peripheral regions exceeds 1 m.

4.4 Hydraulic potential and hydrology of the RIS

The simulated hydrologic networks, as shown in Fig. 9(a), are obtained according to the subglacial hydrological analysis. It is found that most of the subglacial lakes are situated along the simulated subglacial hydrological networks, affirming that the
390 active subglacial lakes within the RIS form a hydrologically connected subglacial water system.

Based on the hydrological network analysis, we identify eleven active subglacial lakes located along the first-order and second-order stream networks (blue areas in Fig. 9(a)), which are selected for their representation of the primary subglacial hydrological networks within the subglacial hydrological system. From upstream to downstream, these subglacial lakes are sequentially arranged as lakes RecN10, Rec9, RecN9, RecN6, Rec6-2, Rec6-1, Rec4, RecN4, RecN2, Rec1-2, and RecN1. To
395 characterize the draining-filling dynamics of lakes between adjacent observation months, we conduct a quantitative analysis of volume changes for each lake. Assuming the subglacial lake outlines remain constant, we estimate the volume changes of each subglacial lake by multiplying the areas calculated based on their outlines with their elevation changes. By calculating the

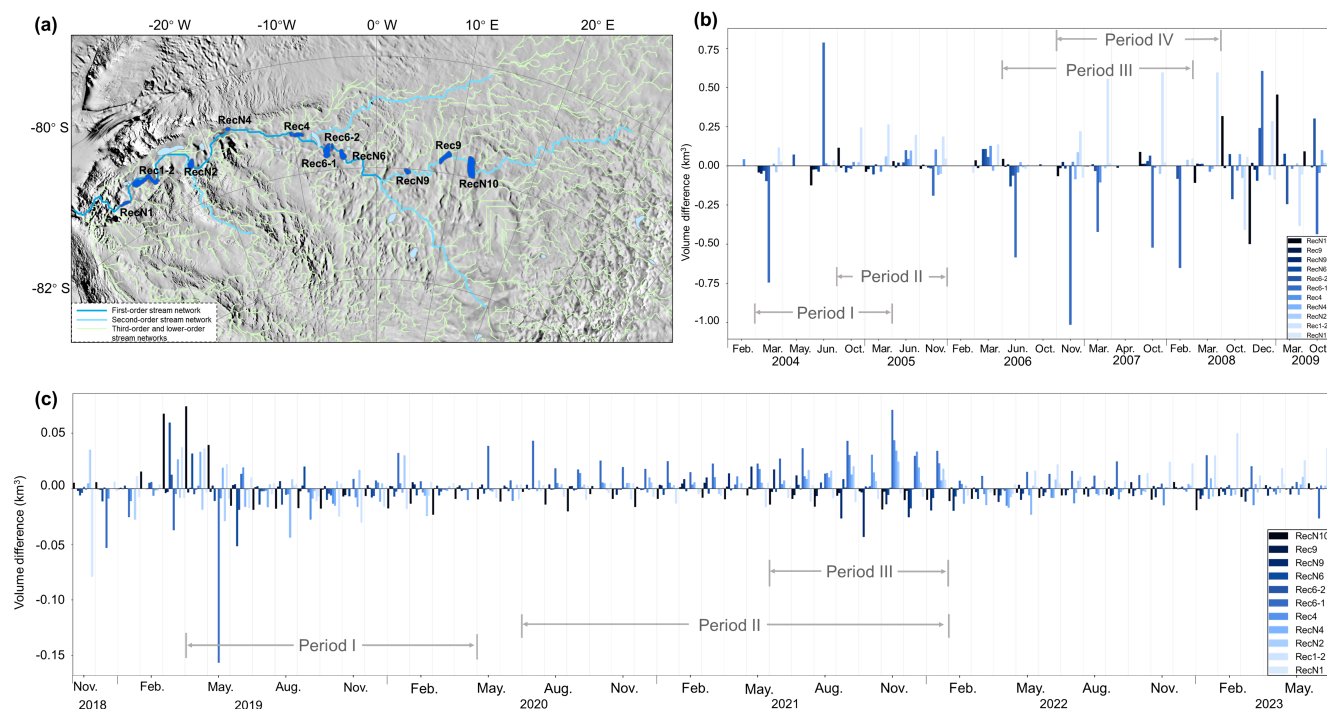


Figure 9. (a) The simulated distribution of hierarchical hydrological networks in the subglacial hydrological system. (b) and (c) present the histograms of elevation differences between adjacent observation months of eleven lakes along the first-order and second-order drainage hydrological networks during ICESat and ICESat-2 missions, respectively.

volume differences between adjacent observation months, we establish diagnostic criteria for lake draining and filling status: a positive volume difference indicates a filling process, while a negative volume difference indicates a draining process. Figs. 9(b) and 9(c) show histograms of volume differences for these eleven subglacial lakes during adjacent observation months throughout the ICESat and ICESat-2 missions, respectively. The lakes from upstream to downstream are marked using a color gradient transitioning from dark to light hues. Due to the significant sparsity of valid altimetry data obtained during the IceBridge mission, a detailed discussion is not conducted for this period.

During the ICESat mission period (from February 2004 to October 2009), the subglacial hydrological system of RIS shows a total discharge of 8.91 km^3 , a total storage of 8.75 km^3 , and a net water volume change of -0.16 km^3 , indicating that the RIS hydrological system releases a certain amount of water during this period. From March 2004 to March 2005 (Period I in Fig. 9(b)), the upstream system is predominantly characterized by discharge, with a cumulative water release of approximately 1.52 km^3 , while the downstream region between October 2004 and November 2005 (Period II in Fig. 9(b)) exhibits a storage-dominant state, accumulating approximately 1.62 km^3 . During this process, there exists a time lag of about three months between upstream discharge and downstream storage. From June 2006 to February 2008 (Period III in Fig. 9(b)), the midstream region of the RIS hydrological system is primarily discharge-oriented, with discharge reaching 4.05 km^3 during this



phase, significantly higher than the discharge in the previous period (Period I), more than twice the earlier volume. Between November 2006 and March 2008 (Period IV in Fig. 9(b)), the downstream continues to be storage-dominant, with storage volume approximately 2.50 km^3 , 1.5 times the previous period (Period II). At this time, the time difference between midstream
415 discharge and downstream storage is approximately 5 months, with the system's maximum discharge occurring in November 2006 and the maximum storage happening in October 2007, with an interval of nearly one year.

As shown in Fig. 9(c), during the ICESat-2 mission period (from November 2018 to May 2023), the RIS hydrological system shows a total storage of 2.80 km^3 , a total discharge of 2.53 km^3 , and a net water volume change of 0.27 km^3 , indicating that the RIS hydrological system accumulates a certain amount of water during this stage. Before May 2019, the upstream region
420 is primarily in a storage state; however, from May 2019, the upstream transitions to a discharge-dominant state. From May 2019 to April 2020 (Period I in Fig. 9(c)), the system's discharge significantly exceeds storage, with a total discharge of 0.96 km^3 and a total storage of only 0.37 km^3 . In the subsequent stage, from July 2020 to January 2022 (Period II in Fig. 9(c)), the hydrological dynamics undergo a reversal, with system storage (1.24 km^3) surpassing discharge (0.57 km^3). Between June 2021 and January 2022 (Period III in Fig. 9(c)), upstream discharge and downstream storage occur almost simultaneously.
425 Notably, the maximum upstream discharge occurs in October 2021, reaching 0.06 km^3 , while the maximum downstream storage happens in November 2021, reaching 0.18 km^3 , with a time interval of approximately one month. After February 2022, discharge is primarily concentrated in the upstream, but the water volume remains relatively small, averaging approximately 0.03 km^3 per month.

5 Conclusions

430 The recent activity of nine reported subglacial lakes in the RIS region is investigated based on ICESat-2 satellite altimetry data. It is found that five reported lakes show low levels of activity during the ICESat-2 period. Two reported lakes (lakes Rec1 and Rec6) have each evolved into two independent parts, exhibiting different drainage and accumulation characteristics. Two other lakes have shown slight changes in their activity range compared to previous observations. The updated outlines of these lakes are given in this study. Moreover, 14 new active lakes (named RecN1-N14) are discovered. The long-term elevation
435 changes of these lakes from 2003 to 2023 are established by integrating altimetry data from ICESat, Operation IceBridge's ATM measurements, and ICESat-2. Among the reported lakes, lakes Rec1-1, Rec1-2, Rec2, Rec4, Rec6-1, and Rec6-2 remain active (with elevation changes over 0.5 m) throughout the 20-year time series. Most newly discovered lakes gradually show active trends during the Operation IceBridge and ICESat-2 periods, particularly lakes RecN4, RecN9, and RecN11, which exhibit high levels of activity (over 2 m). Elevation change analysis at crossovers on four representative lakes reveals that the
440 lakes' central regions exhibit greater variation than the surrounding areas, with a maximum difference of up to 4 m. Finally, the drainage and accumulation of 11 lakes, distributed along major hydrological networks, are analyzed for their dynamic volume changes. It is suggested that there is an effective hydrological connection between the subglacial lakes in RIS. Future studies could introduce hydrological models to explore the response mechanisms of ice sheet internal hydrological systems and their



445 impact on glacier dynamics, providing more comprehensive scientific evidence for assessing Antarctic ice sheet stability and its influence on global sea level changes.

Code and data availability. The ICESat GLA12 data is freely accessible from the National Snow and Ice Data Center at <https://nsidc.org/data/gleh12/versions/34>. Similarly, the ICESat-2 ATL06 and ATL11 data can be obtained from <https://nsidc.org/data/atl06/versions/3> and <https://nsidc.org/data/atl11/versions/6>, respectively. The IceBridge ATM data is available at <https://nsidc.org/data/ilatm2/versions/2>, while the BedMachine V3 dataset can be accessed at <https://nsidc.org/data/nsidc-0756/versions/3>. The previous lake outlines of lakes Rec1-450 Rec9 in Recovery Ice Stream are from Helen Amanda Fricker, <http://dx.doi.org/10.3189/2014jog14j063>. Code for processing altimetry data into height anomalies and subglacial lake time series is developed by Matthew R. Siegfried, <https://doi.org/10.1029/2020GL091089>. Other code used in this study is available from the corresponding author upon reasonable request.

Author contributions. TF and TH conceptualised the research. TF, HD, YC and TH designed the study. HD and YC wrote and run of the code, analysed and interpreted of the results. TF and HD prepared the draft of this paper. All the co-authors contributed to paper editing.

455 *Competing interests.* The authors declare that they have no competing interests.

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