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Rising Lake Levels Across High Mountain Asia

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Abstract

High-altitude lakes across High Mountain Asia (HMA) are one of the critical freshwater reservoirs and sensitive indicators of climate change due to their remote locations and limited human disturbances. This study presents continuous water level estimates for 232 lakes across HMA from 2010 to 2024 using CryoSat-2 and ICESat-2 data. We analyzed temporal and spatial variations and inter-mission consistency in the lake water level across HMA. Our results reveal an overall increasing trend (median rate: +0.1 ± 0.01 m yr^{-1}), with 77% of lakes experiencing rising levels and 91% exhibiting statistically significant trends. We find a substantial regional heterogeneity with the Tibetan Plateau contributing dominantly to regional increase (0.07 ± 0.001 m yr^{-1}), while Himalayan lakes show persistent decline (0.04 ± 0.001 m yr^{-1}). Water level times series observed with the satellite altimetry missions CryoSat-2 and ICESat-2 intercomparison demonstrates strong consistency (80% sign agreement, $p = 0.013$). Lake catchment scale analysis identifies precipitation as the dominant deriver of lakes water level variability ($r = 0.42$, $p < 0.001$), whereas lakes in glaciated catchments exhibit weak climate correlations despite significant increases in temperature, indicating nonlinear cryosphere buffering. We find systematic relationships between lake characteristics (area, elevation) and increasing water levels, with larger lakes generally showing more rapid growth. The contrasting hydrological responses with continued rising water levels in cryosphere influenced lakes and accelerating declines in precipitation sensitive lakes in Himalaya highlight divergent lake hydrological regimes. These findings underscore the critical importance of regional differentiation in understanding lake water storage changes and informing climate adaptation strategies for population vulnerable to these changes in the regions.

Key words: High Mountain Asia, Lake level change, satellite altimetry, climate change

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1. Introduction

The remote location and limited human disturbances of high-altitude lakes across High Mountain Asia (HMA) serve as sensitive indicators of climate change. In these data scarce regions, lake water level fluctuations offer essential constraints on catchment water storage and the evolving regional hydrological cycle (Lei et al., 2014; Pekel et al., 2016; Woolway et al., 2020). The HMA, often termed as the "Third Pole" has undergone rapid warming particularly the Tibetan Plateau (0.50-0.67°C/decade) in recent decades (Kuang and Jiao, 2016; Niu et al., 2021; Wu et al., 2023), with rates exceeding the global average (Duan and Xiao, 2015) contributing to accelerating glacier mass loss (Hugonnet et al., 2021; Zemp et al., 2025) and reduced snow persistence (Muhammad, 2024), along with precipitation changes (Na et al., 2024; Ouyang et al., 2020). Lakes within the region integrate these interacting processes, understanding their long-term behavior is essential to quantify the hydrological response and associated risks. This, in turn, has affected seasonal water availability in mountainous regions and has contributed to expansion of nearby lakes (Miles et al., 2021; T Zhang et al., 2023).

The pronounced increase in water levels of endorheic and glacial lakes in HMA has been evident in recent studies (Song and Sheng, 2016; Zhang et al., 2017b; Zhang et al., 2023), and attributed to both increase in precipitation and cryosphere melt (Lei et al., 2014; G Zhang et al., 2017b). In the meantime, since 1990, glacial lakes in the region have increased rapidly in both number and size (Shugar et al., 2020), heightening the risk of glacial lake outburst flood hazards for ~1 million people living within the immediate vicinity (Taylor et al., 2023). These changes underscore a need for continuous monitoring of lake water level changes, both as critical freshwater resources and hazards (Immerzeel and Bierkens, 2012; Zheng et al., 2021). Snow and ice melt contributions to lake volume change on the Tibetan Plateau is estimated to be limited and primarily driven by precipitation (Brun et al., 2020). Extreme precipitation anomalies previously lead to abrupt lake level changes on Tibetan Plateau (Lei et al., 2019; Song and Sheng, 2016). In-situ monitoring of these high-altitude lakes is logistically challenging, which limits the number of in-situ observations (Lei et al., 2017). On the regional scale, water level estimates in high-altitude lakes across HMA have been derived from satellite altimetry (Treichler et al., 2019) and the water balance from hydrological models (Zhou et al., 2015), where the majority of these studies are confined to the Tibetan Plateau (Jiang et al., 2017; G Zhang et al., 2017b).

Long-term, regionally consistent time series of lake level datasets and comprehensive assessments of spatiotemporal variations across HMA remained scarce. Satellite altimetry provides an indispensable opportunity for dynamic monitoring of water level changes in lakes

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over large regions. We use satellite altimetry from CryoSat-2 (2010 to 2023) and ICESat-2 (2018 to 2024) to examine water levels changes of 232 lakes across HMA (Fig. 1). We analyse the temporal and spatial characteristics of water level changes, for lakes in both glaciated and non-glaciated catchments, including endorheic lakes. We assessed the regional difference in lake level trends with catchment-scale climate forcing from ERA5-Land across HMA. By integrating multi-mission altimetry with climate reanalysis data across diverse climate settings, we provide new insights into the evolving lake water level changes and spatial heterogeneity. We selected lakes with surface area larger than 20 km^2 to ensure reliable water level retrievals from both CryoSat-2 and ICESat-2. Smaller lakes, particularly glacial lakes, in high-relief terrain fall below the effective spatial resolution to adequately retrieve the signal; their narrow open water surfaces are highly susceptible to land contamination and off-nadir reflections that degrade the data quality (Jiang et al., 2017; Kleinherenbrink et al., 2015).

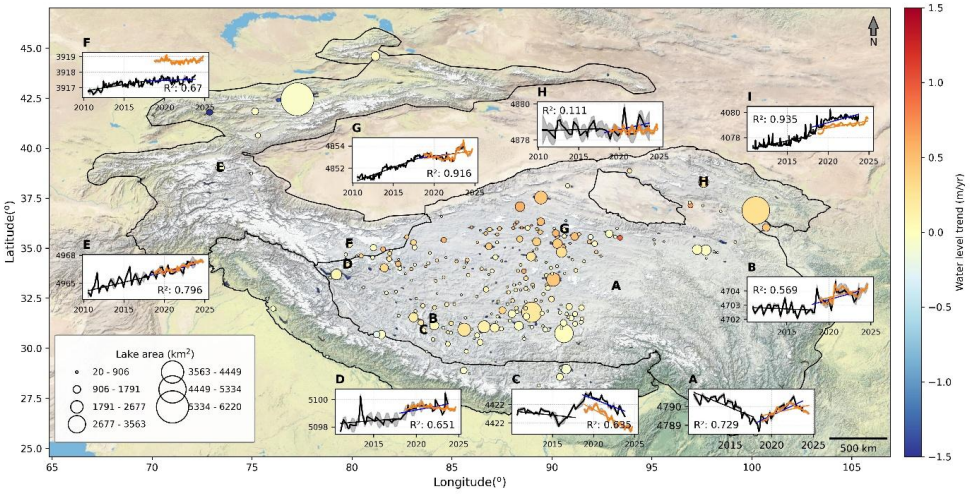

Figure 1 Spatial and temporal pattern of lake water level changes in High Mountain Asia. Each circle represents a lake, color shows the trend in lake water level from CryoSat-2 (2010 to 2023), corresponding to the colorbar, and the circle size is scaled by area of each lake. (A to J) Water level timeseries of selected lakes, black line for CryoSat-2 (2010-2023) and brown line represent lake level estimates from ICESat-2 (2018-2024). Y-axis of each subplot is water level in meters (EGS).

2. Materials and Methods

2.1. Lake Water Level based on CryoSat-2 (2010-2023)

We examine the variations in water levels of 232 lakes across HMA from 2010 to 2023 using satellite altimetry data from CryoSat-2. We analyse the characteristics of water level changes,

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including trends and inter-annual variability, for lakes in both glaciated and non-glaciated catchments. More specifically, we use the Level 1b product from the Baseline E Ice Processor (ESA, 2023, 2019a, b) ftp://science-pds.cryosat.esa.int/https://earth.esa.int/eogateway/catalog/cryosat-products. To retrieve range estimates, the waveforms are retracked with the Narrow Primary Peak Threshold retracker (Villadsen et al., 2015). The satellite altimetry-based water level with respect to a reference, here the geoid, is derived based on the expression:

$$H = h - (R + corr) - N$$

Here h is the altitude of the satellite with respect the reference ellipsoid (WGS84), R is the retracked range, or the distance from the satellite to the surface, *corr* includes corrections for the wet and dry troposphere, ionosphere, pole tide, solid earth tide, and loading tide, and N is the geoid elevation (EGM2008, (Pavlis et al., 2012))

Lake specific altimetry footprints are extracted using the SWOT Prior Lake Database (PLD) (Sheng et al., 2016), which includes a global lake boundaries. In addition, we use the Global Surface Water Occurrence raster product by (Pekel et al., 2016). This raster product with 30 m spatial resolution contains the probability, provided as a percentage, of water being present between 1984-2021. Here, we only retain observations if the occurrence value is 75 % or larger.

The water level time series is reconstructed via the method presented in Nielsen et al. (2015). In summary, the model includes a random walk as the process part to account for the temporal correlation, and the observations are assumed to follow a mixture between the Normal and Cauchy distributions to ensure robustness of the water level estimates. The Cauchy distribution is characterized by heavier tails compared to the Normal distribution. In contrast to assuming that the observations only follow a normal distribution, the mixture distribution reduces the influence of extreme observations on the estimated mean.

To evaluate how measurement uncertainty affects long-term change detection, the posterior water-level variance is carried forward to the trend analysis, where trend uncertainty is quantified using the bootstrap-based Sen's slope procedure described in Section 2.3. The resulting trend uncertainties therefore reflect both measurement noise and temporal sampling variability in the altimetry record. In Nielsen et al (2015) the standard deviation to each estimated mean water level in the timeseries is derived from the generalized delta method (Thorson and Kristensen, 2024) with the main contribution from the Hessian matrix related to the mean water levels and additionally how uncertainty in the fixed model parameters affects

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these estimates. In the estimation of the mean water levels, correlation among along-track water levels was not accounted for which implies that the standard deviation is underestimated.

2.2. Lake Water Level based on ICESat-2 (2018-2024)

To retrieve the water level time series using ICESat-2 we apply the inland water product ATL13 (Jasinski et al., 2023) version 6. For consistency across mission, ICESat-2 water levels are processed using the same extraction and filtering approach as described above for the CryoSat-2 data. The water level time series are reconstructed at monthly time steps using the methodology described in Nielsen et al., (2015) with the exception that the process part of the state-space model is an autoregressive model of order 1.

2.3. Lake Water Level Trend analysis

To quantify changes in the lake water levels, we analysed trends separately for the CryoSat-2 (2010-2023) and ICESat-2 (2018-2024) periods. For the trend analysis we excluded lakes where water levels are regulated. To isolate the signal from intra-annual seasonal fluctuation such as monsoon induced cycles in the central Himalaya, we applied Seasonal-Trend decomposition using LOESS (STL) to the monthly timeseries (Cleveland et al., 1990). STL separates the signal into three components, trend (T), seasonal (S), and residuals ®. The trend captures the low frequency variability, the seasonal components represent periodic cycles, and residuals account for high-frequency variability. For subsequent analysis, we used the de-seasonalized timeseries (T+R) to ensure that estimated trends represent sustained hydrological changes rather than seasonal cycles.

We assessed the statistical significance of monotonic trends in the de-seasonalized timeseries using the Mann-Kendall (MK) test ($p < 0.05$), while the magnitude of change was estimated with Sen's slope estimator. Uncertainty in the Sen's slope for each lake is derived from bootstrap resampling ($n = 100$), where the timeseries is resampled with replacement and Sen's slope recalculated. The standard deviation of the resulting slope distribution is taken as the standard error of the trend estimate.

We first estimated the trend for individual lakes and then aggregated into subregions based on geographic region (Tibetan Plateau, Himalaya, western High Mountain Asia and lakes in glaciated catchments). Regional trends are calculated as the uncertainty-weighted mean of the individual lake slopes, with the standard error of this weighted mean reported as the uncertainty of the regional trend. This allowed to better constrain the regional trend with lakes with low uncertainty in trend estimates. For comparison we also provided a median lake level change

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rate. To derive a continuous long-term trend from both altimetry missions, we corrected for systematic offsets between ICESat-2 and CryoSat-2 mainly related to different vertical references in the two missions. Our intercomparison analysis during the overlapping period (2018-2023) shows a systematic bias of +2.74 m between ICESat-2 and CryoSat-2 measurements. This offset is consistently observed across 77% of lakes (183 of 238) with statistical significance ($p < 0.05$). We therefore applied a -2.74 m correction to ICESat-2 timeseries for the mission intercomparison.

2.4. Climate data analysis

We analysed climate variability across High Mountain Asia using the ERA5-Land reanalysis data (Muñoz Sabater, 2021), We used near-surface air temperature (2 m), total precipitation, and total evaporation for the period of 2010 to 2024, focusing on temporal and spatial variability and trends on annual and seasonal scale. To isolate long-term changes, seasonal cycles were removed by subtracting the monthly climatology (1980–2023) from each series. We analysed trends in de-seasonalized anomalies using the MK test (Mann, 1945; Kendall, 1975). Trend magnitudes were estimated using ordinary least squares linear regression, expressed as rate of change per year. Significance in trends is evaluated at 95% confidence level ($p < 0.05$).

We used different methods to remove seasonality in lake water level and climate timeseries. The irregular sampling and string inter-annual cycles complicate the signal for lake water level derived from altimetry, the STL decomposition provides a flexible and robust method for separating trend, seasonality and noise. Climate data from ERA5-Land is regularly sampled and exhibit well-defined seasonal cycles in temperature, precipitation and evaporation therefore, subtracting monthly climatology can effectively remove seasonality, preserving the long-term trend.

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3. Results

3.1. Increasing lake water levels across High Mountain Asia

Our analysis of 232 lakes across HMA reveals a pattern of overall water level increase from 2010 to 2024 with 91% statistically significant trends ($p < 0.05$). The majority of the lakes analyzed (179, 77%) experience positive water level trend, while 54 lakes (23%) show declining water levels (Table S1). The median increase in water level is 0.10 m yr^{-1} across all lakes and 117 lakes (50.4%) experiencing strong increases exceeding 0.1 m yr^{-1}. The distribution of trend shows considerable variability (σ = 0.23 m yr^{-1}), ranging from rapid decline (-0.52 m yr^{-1}) to substantial growth (+1.08 m yr^{-1}). This heterogeneity is further evident by the interquartile range (0.006 to 0.29 m yr^{-1}), indicating that while most lakes in the region experienced heightened water levels, the rates varied substantially across HMA. Lake size exhibited a positive relationship with growth rates, as larger lakes generally showed higher mean trends (20-100 km^2: 0.12 m yr^{-1}; 1000-1000 km^2: 0.145 m yr^{-1}; larger than 1000 km^2: 0.176 m yr^{-1}). Lakes located in higher elevation show more positive trends compared to the lakes located in lower elevations with a positive correlation between elevation and water level increase rate (r = 0.35).

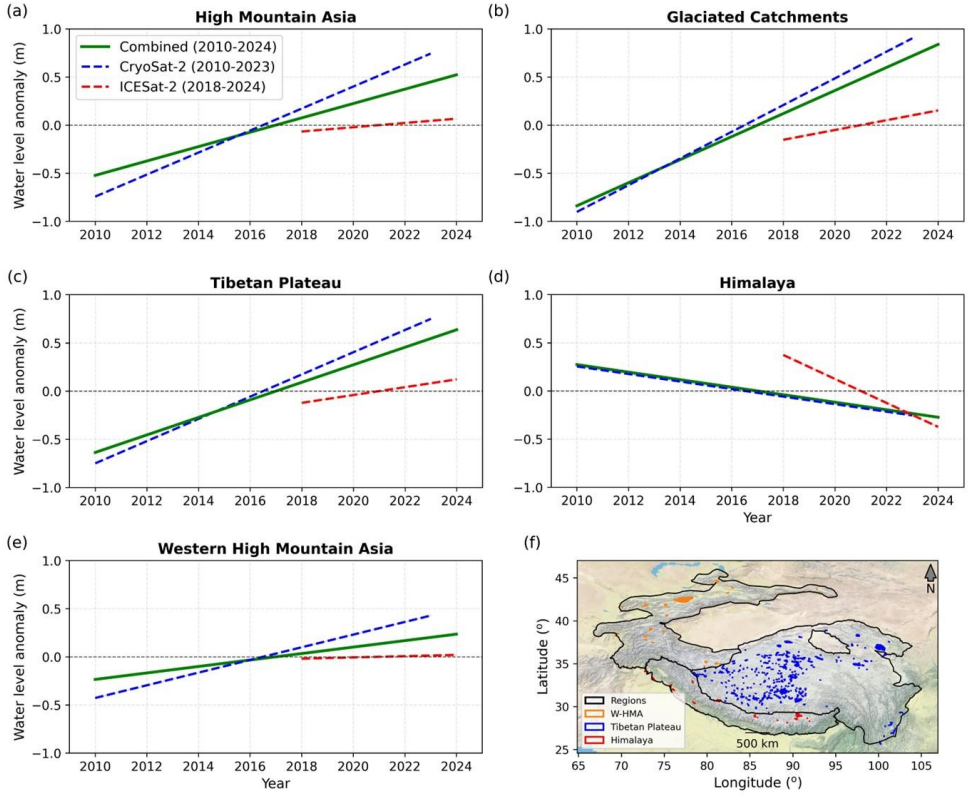

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Figure 2 (a) Regional water level trends across HMA derived from CryoSat-2 (blue, 2010–2023), ICESat-2 (red, 2018–2024), and the combined record after bias correction (green, 2010–2024), (b) lakes within glaciated catchments, (c) Tibetan Plateau, (d) Himalaya, and (e) Western HMA. Shading shows 1-σ uncertainty. (f) Distribution of lakes highlighted with different color, regions are highlighted with black line.

During the mission overlap period (2018 to 2023), intercomparison trend shows strong consistency between CryoSat-2 and ICESat-2 with near zero mean bias (-0.0001 ± 0.6177 m) and a precision of 0.37 m (Standard deviation of differences) (Fig. S1). Overall, 64% of lakes exhibit correlation ($r > 0.5$), with 45% particularly strong agreement ($r > 0.7$) (Fig. S1a). Trend estimates from both missions agree for the majority of lakes (80%), indicating consistency between the two sensors. During the CryoSat-2 period (2010 to 2023), lake level increased at a mean rate of 0.15 m yr^{-1} with 117 (49%) experiencing higher rate of increases greater than 0.1 m yr^{-1}. However, during the ICESat-2 period (2018 to 2024), the mean increase rate reduced to 0.052 m yr^{-1} with 98 lakes (41%) maintaining a water level increase rate higher than 0.1 m yr^{-1}. Analysis of trend persistence reveals that 47 lakes that were rising during the early CryoSat-2 period (2010 to 2017) shifted to declining trends in recent years during 2018 to 2024, while only 24 lakes transitioned from negative to positive trends.

3.2. Regional variations in lake water level

Lakes on the Tibetan Plateau show a consistent increasing trend across both altimetry periods (2010-2024), with the combined record indicating substantial growth (0.09 ± 0.001 m yr^{-1}) (Figure 2c). CryoSat-2 (2010 to 2023) based results show increasing lake levels at a rate of 0.18 m yr^{-1}, with 113 lakes (54%) showing consistent increasing trends (>0.1 m yr^{-1}), only 14 showed stable water levels (-0.01 to 0.01 m yr^{-1}) and the number of lakes with a strong decreasing trends (<-0.1 m yr^{-1}) is relatively low (7 lakes). The remaining 77 lakes experienced moderate change rates between -0.1 to 0.1 m yr^{-1}. ICESat-2 based results from 2018 to 2024 show lower rate of growth (0.004 m yr^{-1}), with only 93 lakes (44%) maintaining strong positive trends (>0.1 m yr^{-1}) and 25 show strong decreasing trends. 26 lakes showed relatively stable trends (-0.01 to 0.01 m yr^{-1}) during 2018 to 2024. We find a modest correlation between lake morphology and water level trends across the Tibetan Plateau. While correlation between the elevation and lake area with trend magnitude are positive but negligible, explaining less than 1% of the observed variance. However, we find a clear pattern in lake water level with lake size, larger lakes exhibited systematically higher growth rates, largest lakes (>1000 km^2) show higher rate of increasing water levels (0.23 ± 0.18 m yr^{-1}), lakes with an area between 100 to

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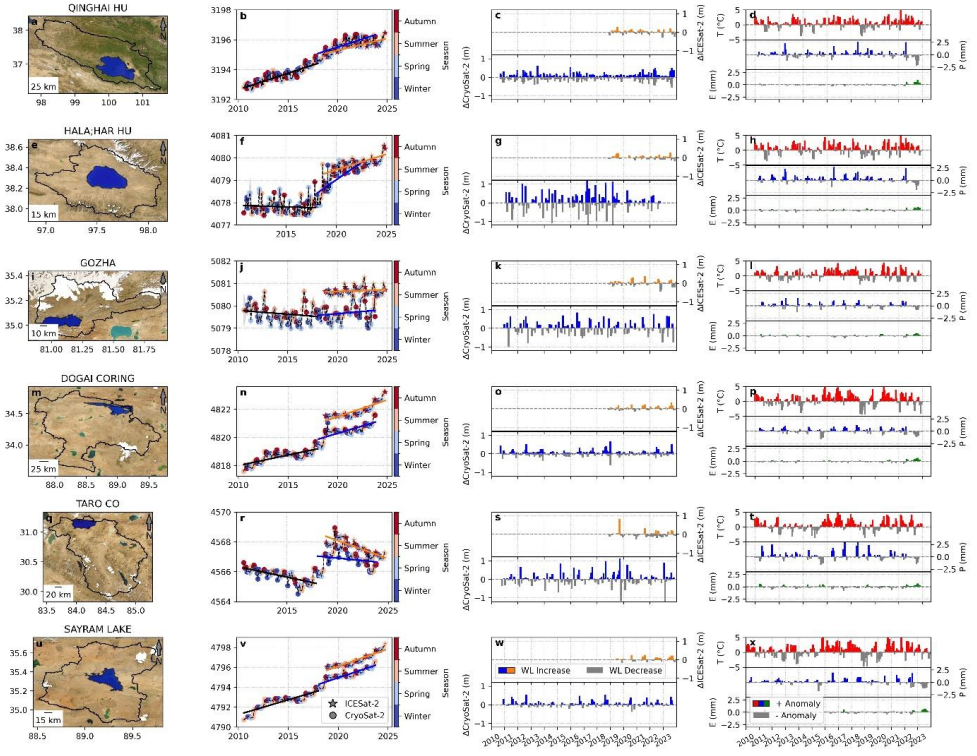
228 1000 km^2 shows growth rate of 0.19 ± 0.22 m yr^{-1} and the lakes with an area between 20 to 100
229 km^2 grew by 0.14 ± 19 m yr^{-1}.



230 **Figure 3** Water level change and climate variations from Tibetan Plateau. (a) The Qinghai Hu
231 Lake is shown in blue and catchment highlighted with black boundary. (b) Water level time
232 series (m) from CryoSat-2 (2010 – 2023) and ICESat-2 (2018 – 2024). The color corresponds
233 to the season of data acquisition, correspond to the color bar. The standard deviation of lake
234 levels is shown in grey. (c) Water level change during CryoSat-2 (blue) and ICESat-2 (yellow).
235 (d) The colored and grey bars represent anomalies in temperature (T°C), precipitation (P mm)
236 and Evaporation (E mm). Similarly, for Hala Har Hu Lake, Gozha Lake, Dogai Coring Lake,
237 Taro Co Lake, and Dogaicoring Qangco Lake in the Tibetan Plateau.

238 In contrast, analyzed lakes in Himalaya region shows persistent decline across both altimetry
239 datasets (Figure 2d). We find a median decreasing rate of -0.09 m yr^{-1} during CryoSat-2 (2010
240 to 2023) and ICESat-2 results show slightly larger declining water levels -0.62 m yr^{-1} 2018 to
241 2024. The number of lakes with strong decline (>0.1 m yr^{-1}) increased from the CryoSat-2 (2
242 lakes; 2018-2023) to ICESat-2 period (4 lakes; 2018-2024). Lake level time series for the lakes
243 in Himalayan region from both altimeter datasets are presented in Figure S4. Lakes with an
244 area between 20 to 100 km^2 are more rapidly decreasing (-0.08 ± 0.15 m yr^{-1}) compared to

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larger lakes (-0.03 ± 0.04 m yr^{-1}). We observed a positive correlation between elevation and trend magnitude (r = 0.38).

The lakes studied in western HMA, 7 out of 12 lakes experienced consistent growth in lake water level with a mean rate of 0.13 m yr^{-1} during 2010 to 2023 based on CryoSat-2. ICESat-2 results show the slowdown in water levels rise in recent years (2018 to 2024), with growth rate decreasing to near zero (Fig. 2e). However, three lakes transitioned from negative to positive trends between 2010 to 2017 and 2018 to 2024 (Fig. S5). Similarly, large lakes (100 to 1000 km^2) experienced a higher increase in water levels (0.17 ± 0.21 m yr^{-1}), while lakes with area range between 20 to 100 km^2 experienced a slight decline (-0.02 ± 0.10 m yr^{-1}). We find a positive correlation (r = 0.48) between elevation and trend magnitude suggesting lakes located in higher elevations are experiencing enhanced growth.

Lakes located in the glaciated catchments show an accelerating growth rates based on both altimetry results (2010 to 2023 and 2018 to 2024) with a rate of 0.028 to 0.096 m yr^{-1}, respectively (Fig. 2b). CryoSat-2 results show that these lakes exhibit highest mean growth rate (0.18 m yr^{-1}) during 2010 to 2023, with 18 out of 37 showing strong increase. ICESat-2 results show the slowdown of rapid increase in water level to 0.016 m yr^{-1} during 2018 to 2024. Lakes within glaciated catchments with an area between 100 to 1000 km^2 maintaining higher rate of increase in water levels (0.19 ± 0.27 m yr^{-1}) compared to lakes with an area between 20 to 100 km^2 (0.08 ± 0.13 m yr^{-1}). We find a slightly weak correlation with elevation (r = 0.02) compared to the regional analysis.

3.3. Regional Climate trends

On Tibetan Plateau, where most lakes are located, correlations with all three climate variables are weak and statistically not significant (r = 0.09). Based on seasonal climate data analysis we find that increase in temperature during autumn season is highest across HMA, particularly on the Tibetan Plateau where temperature increased with +0.15°C yr^{-1}, along with +0.06°C yr^{-1} during summer months. Precipitation trends show no statistically significant changes during 2010 to 2024. Lakes located in non-glaciated catchments on Tibetan Plateau exhibit a significant positive correlation with precipitation ($r = 0.32$, $p < 0.001$) and a weak negative correlation with evaporation ($r = -0.15$, $p = 0.04$), indicating changes in precipitation play dominant role in water level variability. Large endorheic lakes exhibit sustained water level rise. Qinghai, Hala Har and Sayram Lakes experienced substantial increase with a rate of 0.35 ± 0.01 ma yr^{-1}, 0.43 ± 0.02 ma yr^{-1}, and 0.59 ± 0.02 ma yr^{-1}, respectively during 2010 to 2024. These trends coincide with statistically significant long-term warming (0.01 ± 0.002°C yr^{-1} to 0.15 ± 0.002°C yr^{-1}) and slightly increasing precipitation up to 0.02 ± 0.01 mm yr^{-1} with no

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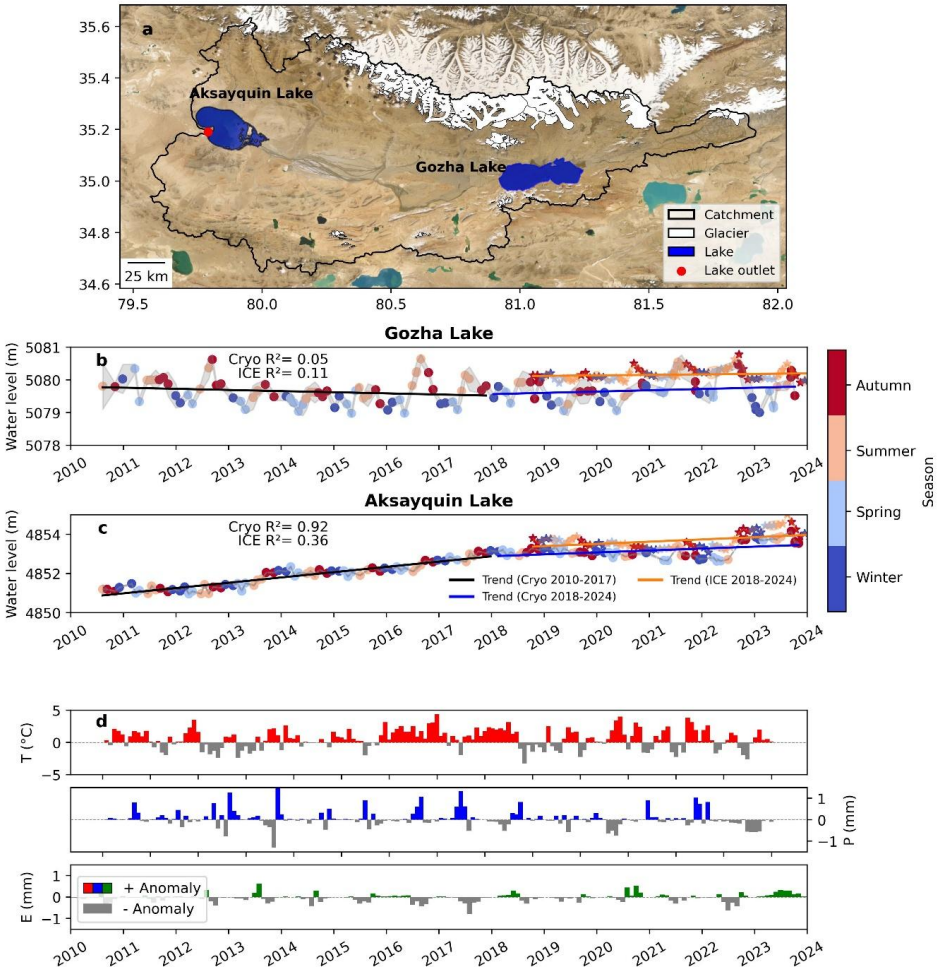
279 significant long-term evaporation changes (Fig. 2). Similarly, Ayakkum, Achik and Jingyu
280 Lakes in Eastern Kunlun Shan show rising water levels (0.54 ± 0.01 m yr^{-1}, 0.76 ± 0.02 m yr^{-1}
281 and 0.75 ± 0.02 m yr^{-1}, respectively). These three lakes are experiencing a coherent climate
282 signal of statistically significant increasing temperature (0.01 ± 0.002°C yr^{-1}) and precipitation
283 (0.001 ± 0.001mm yr^{-1}) combined with slight reduction in evaporation (-0.001 ± 0.00 mm yr^{-1}
284).



285 **Figure 4** (a) The locations of Aksayquin Lake and Gozha Lake situated in the Western Kunlun
286 Shan region. (b) Water level timeseries of Gozha Lake from CryoSat-2 (2010 to 2023) and
287 ICESat-2 (2018 to 2024), represented with circle and start, respectively. (c) Similarly, water
288 level timeseries of Aksayquin Lake from CryoSat-2 and ICESat-2. The color of dot and star in
289 each timeseries corresponds to the season of data acquisition, indicated by the color bar. The
290 black and blue lines represent trends from 2010 to 2017 and 2018 to 2023, respectively for the
291 CryoSat-2 period. The range of error in each time series is shown in gray. (d) Positive

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anomalies in temperature (T °C), precipitation (P mm) and evaporation (E mm) are shown red, blue and green color, respectively and negative anomalies are in gray.

Lake catchments in Himalayan experience an increase in temperature during summer (+0.06 ± 0.01°C yr^{-1}) and autumns (+0.08 ± 0.04°C yr^{-1}) which is statistically significant. Winter precipitation shows a significant decline (-0.07 ± 0.03 mm yr^{-1}), while other seasons exhibit weaker, non-significant trends. Lake water level and climate correlations are moderate but non-significant for both temperature (r = 0.48) and precipitation (r = 0.53), broadly consistent with the declining lake levels. Himalayan lakes, (though few observed, 11), show positive correlations with both temperature and precipitation (r = 0.48 and r = 0.53, respectively), though neither is statistically significant. Lake catchments across Western HMA show a statistically significant increase in temperature during summer months (-0.07 ± 0.04 mm yr^{-1}), with weaker but consistent positive trends in other seasons. Winter and autumn precipitation slightly reduced (-0.05- and -0.03-mm yr^{-1}), whereas other seasons do not exhibit strong trends. At the lake catchment scale, western HMA shows a clearer climate signal with precipitation significantly correlated with lake level trends (r = 0.72, p = 0.004), indicating that modest changes in moisture availability can strongly influence water level.

Across HMA lakes within glaciated catchments shows statistically significant increasing temperature trends (0.06 ± 0.02°C yr^{-1}) with no significant correlation with annual temperature, precipitation and evaporation trends (r < 0.17). Despite temperature being the dominant but statistically non-significant predictor among the three variables. This weak climate correlation with lake water level contrasts with the behavior of lower elevation, non-glaciated lakes, where precipitation exerts a stronger influence. The absence of robust correlations in glaciated catchments indicates that interannual water level variability in lakes is strongly influenced by snow and ice melt, including nonlinear melt runoff relationships and hydrological delays, rather than contemporaneous year-to-year climate anomalies. This pattern is clearly visible in lakes such as Aksayquin Lake (4844 m a.s.l.) and the upstream Gozha Lake (5080 m a.s.l.) in Western Kunlun Shan, experienced rising water level trends of 0.21 ± 0.01 m yr^{-1} and 0.01 ± 0.01 m yr^{-1}, respectively during CryoSat-2 period (2010 to 2023) (Fig. 4). Their catchment shows an increasing temperature (0.05 ± 0.02°C yr^{-1}) with declining precipitation (-0.01 ± 0.01 to -0.02 ± 0.01 mm yr^{-1}) and negligible long-term changes in evaporation. Despite these long-term lake level increase, annual correlation with climate variables remained weak (r < 0.15). Gozha lake shows significant negative winter precipitation correlation (r = -0.44, p < 0.05) and a weak positive autumn temperature correlation (r = 0.33, p < 0.05), suggesting snow accumulation delays meltwater runoff. Similarly, Burog Co and Niri Acuogai Lakes on Tibetan Plateau shows increasing water levels by 0.54 ± 0.04 m yr^{-1} and 0.26 ± 0.02 m yr^{-1}, respectively

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(Fig. S3). Both catchments exhibit sustained increasing temperatures, 0.07 ± 0.03℃ yr^{-1} at Burog Co and a higher rate of 0.17 ± 0.04 ℃ yr^{-1} at Niri Acuogai Lake, while precipitation trends remain negative, and evaporation trends minimal (Fig. S3). These differences are consistent with their (Gozha and Burog Co Lakes) hydrological positions adjacent to glacier and predominantly reflect immediate meltwater inputs, whereas Aksayquin and Niri Acuogai Lakes integrate both local melt and inflows routed from wider catchment upstream.

Table 1 Regional trends in lake water level (m yr^{-1}) across High Mountain Asia. Uncertainty weighted mean of individual lakes within three median absolute deviations. The combined trend represents the period 2010-2024. Lakes with water levels regulated by human activities are excluded for regional trend analysis.

Region	Altimetry mission	Period	Trend (m yr^{-1})	Number of lakes analyzed
High Mountain Asia	CryoSat-2	2010-2017	0.036 ± 0.001	194/232
	CryoSat-2	2018-2023	-0.055 ± 0.001	203/232
	ICESat-2	2018-2024	0.022 ± 0.002	209/232
	Combined	2010-2024	0.07 ± 0.001	202/232
Glaciated Catchments	CryoSat-2	2010-2017	0.028 ± 0.004	34/37
	CryoSat-2	2018-2023	0.096 ± 0.006	32/37
	ICESat-2	2018-2024	0.051 ± 0.007	36/37
	Combined	2010-2024	0.065 ± 0.002	33/37
Tibetan Plateau	CryoSat-2	2010-2017	0.041 ± 0.002	174/211
	CryoSat-2	2018-2023	0.120± 0.002	184/211
	ICESat-2	2018-2024	0.041 ± 0.002	185/211
	Combined	2010-2024	0.091 ± 0.001	181/211
Himalaya	CryoSat-2	2010-2017	-0.071 ± 0.009	9/9
	CryoSat-2	2018-2023	-0.095 ± 0.013	9/9
	ICESat-2	2018-2024	-0.125 ± 0.007	9/9
	Combined	2010-2024	-0.039 ± 0.003	9/9
Western HMA	CryoSat-2	2010-2017	0.101 ± 0.006	11/12
	CryoSat-2	2018-2023	0.010 ± 0.008	8/12
	ICESat-2	2018-2024	0.005 ± 0.006	7/12

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Combined	2010-2024	0.034 ± 0.002	8/12

4. Discussion

Our analysis of 232 lakes across HMA reveals a complex and heterogeneous pattern of lake water level change from 2010 to 2024, characterized by widespread but regionally divergent trends. The observed overall increase, with 77% of lakes rising at a median rate of 0.10 m yr^{-1}, (Table S1) aligns with the well documented lake expansion on the Tibetan Plateau since the early 2000s (Lei et al., 2022; Lei et al., 2014; Zhang et al., 2019). However, our extended record through 2024 and subregional analysis provides new insights into the evolving hydrological drivers and the fate of the notable 2016-2018 precipitation anomaly (Lei et al., 2019). The strong inter-mission consistency (80% sign agreement, $p = 0.013$) between CryoSat-2 and ICESat-2 during 2018-2023 overlap period underscores the robustness of these findings, despite a systematic +2.74 m bias stemming mainly from differences in use of quasi-geoid based on EGM2008 for CryoSat-2 and EGM2008 geoid model to ICESat-2. The statistical summary of water level changes for each lake is presented in Table S3 (Supplementary Data).

The Tibetan Plateau remains the primary contributor to regional lake water level increase during 2010 to 2024 (Table 1). This rising water level trends are particularly pronounced in the northern and Inner Tibetan Plateau, consistent with previous studies attributing expansion to spatially variable precipitation regimes (Jiang et al., 2023; Kuang and Jiao, 2016). Our catchment-scale analysis shows precipitation variability as the dominant driver of de-seasoned lake trends, with a significant positive correlation ($r = 0.42$, $p < 0.001$) except for lakes within glaciated systems such as endorheic basins in Tibetan Plateau (Jiang et al., 2020; Zhang et al., 2017a; Zhang et al., 2017b). When compared with individual lake water level time series derived from satellite altimetry and in situ measurements, our estimates show strong agreement with previous studies (Lei et al., 2022; Zhang et al., 2019; Zhang et al., 2017b). For the 57 lakes common to Zhang et al. (2019), we estimate a mean water level increase of 0.20 ± 0.04 m yr^{-1} during 2010 to 2018 (CryoSat-2), which is lower compared to 0.28 ± 0.03 m yr^{-1} for 2003 to 2018 based on ICESat and ICESat-2. This difference in the mean trend is primarily driven by Seling Co, Wulanwula Lake, and Meiriqie Co, which exhibit the largest discrepancies, with differences range between -0.29 ± 0.01 to -0.25 ± 0.02 m yr^{-1}. For lakes with declining water levels, our CryoSat-2 based estimates for 2010 to 2018 closely match those of Zhang et al. (2019) (Table S2), with the exception of Namuka Co, where our estimated rate of decrease is 0.15 ± 0.03 m yr^{-1} higher. The persistence of elevated levels in many lakes following the 2016-2018 wet anomaly (Lei et al., 2019) suggests that this episodic pulse had

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lasting impacts on regional lake hydrology, though its effect was mediated by catchment properties such as storage capacity and groundwater connectivity (Jiang et al., 2020; Lei et al., 2022; Lei et al., 2019). The recent modest deceleration in growth rates observed in the ICESat-2 record (2018-2024) aligns with the sharp precipitation decline in our ERA5-Land analysis post-2021, highlighting the ongoing sensitivity of these systems to interannual precipitation variability (Fig. S2). Lake expansion on Tibetan Plateau in recent decades have been attributed to precipitation, evaporation (Biskop et al., 2016; Yang et al., 2017), Snow and ice melt (Zhang et al., 2017b) ground Water (Lei et al., 2022). Climate data from meteorological station on Plateau shows increasing precipitation trend during 1978 to 2013, except for few stations on southeast Tibetan Plateau (Zhang et al., 2017a) consistent with lake water level changes (Fig. 2).

Lakes in glaciated catchments shows rising trends in water level. Despite significant regional warming (0.06 ± 0.02°C yr^{-1}), these lakes exhibit weak and statistically non-significant correlations with annual temperature, precipitation, and evaporation ($r < 0.17$). This apparent decoupling from contemporaneous climate anomalies, observed in rapidly rising lakes highlights the dominance of nonlinear cryosphere processes. The significant negative correlation between winter precipitation and Gozha Lake levels ($r = -0.44$, $p < 0.05$) suggests snow accumulation delays meltwater runoff, while weak positive autumn temperature correlations ($r = 0.33$, $p < 0.05$) indicate thermal controls on melt timing. This cryospheric buffering effect, where glacier and snow melt mediate the relationship between climate forcing and lake response, creates a complex hydrological regime that contrasts sharply with precipitation dominated catchments (Yao et al., 2022). High-frequency observations from glacier-fed Blue Moon Lake Valley in southeastern Tibetan Plateau shows glacier melt as a dominant driver of water level changes (5.2 m per unit melt increase, $p<10^{-176}$) exceeding the modest effect of rainfall (0.47 m, $p = 0.03$) with a meltwater transit time of about 4 hours from glacier to lake (Ai et al., 2024). Such temporal decoupling between melt and lake water level response exemplifies the cryosphere buffering in lakes near glaciers and weak direct correlation with instantaneous climate variables. Increasing lake water levels in endorheic basin during 2003-2009 on the Tibetan Plateau has been attributed to increasing precipitation (74%), accelerated glacier melt (13%), and permafrost degradation (12%) (Zhang et al., 2017b), while the processes responsible are yet to be investigated to close the lake water budget across HMA. Lake-catchment scale studies shows that cryosphere meltwater plays an important role in lake water budget Zhang et al. (2024) attributed 62.5% of the increase in Dogai Coring lake storage to glacier mass loss and 19.3% of the lake volume increase to permafrost degradation during 2014-2020. Ground ice melt contribution to the Selin Co lake volume expansion is estimated

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to be 12% during 2017-2020 (Wang et al., 2022). These permafrost contributions are consistent with boreholes observation on the Tibetan Plateau showing that the active layer thickened at an average rate of 19.5 cm/decade with an acceleration in recent years during 1981 to 2018 (Zhao et al., 2020). The accelerating growth rates in glaciated catchments from CryoSat-2 (0.028 m yr^{-1}) to ICESat-2 (0.096 m yr^{-1}) periods may reflect enhanced meltwater contributions under sustained warming, consistent with glacier mass loss across HMA (Hugonnet et al., 2021; Zemp et al., 2025).

In contrast to the Tibetan Plateau, Himalayan lakes show persistent decline, with a median rate of -0.09 m yr^{-1} (CryoSat-2) intensifying to -0.62 m yr^{-1} (ICESat-2). This pattern aligns with observed precipitation decreases and warming in the region (Salerno et al., 2025). Zhang et al. (2017a) estimated decreasing lake area in the Brahmaputra basin since 1998 attributed to decreased precipitation. The inverse size relationship in the Himalaya, where smaller lakes (20-100 km^2) decline more rapidly (-0.08 ± 0.15 m yr^{-1}) than larger counterparts (-0.03 ± 0.04 m yr^{-1}), suggests limited hydrological resilience in smaller catchments. Combined with shorter residence times and reduced capacity for cryosphere melt buffering, these systems appear highly vulnerable to precipitation deficits (Khanal et al., 2021; Treichler et al., 2019). Western HMA presents an intermediate case, where precipitation emerges as a significant correlate ($r = 0.72$, $p = 0.004$) despite overall mixed trends, indicating a transition zone between precipitation dominated and cryosphere influenced regimes.

The systematic relationship between lake area and growth rates across most regions, with the largest lakes (>1000 km^2) showing the most rapid increases, suggests that larger water bodies integrate runoff from more extensive catchments and exhibit greater resilience to interannual variability. This pattern was particularly evident on the Tibetan Plateau align with the finding of Zhang et al. (2019), though the statistical correlations were weak ($r = 0.09$), indicating that other catchment properties modulate this relationship such as precipitation. The difference between median individual lake trends (+0.10 m yr^{-1}) and uncertainty-weighted regional means (+0.07 ± 0.01 m yr^{-1}) likely reflects the higher measurement uncertainties in smaller lakes (Fig. S1), though it may also indicate slightly different change rates across the lake size spectrum. In altimetry, geoid errors, winter lake ice contamination, and retracking biases present potential limitations (Jiang et al., 2019; Meloni et al., 2020), though these predominantly affect annual signal interpretation rather than the long-term trends analyzed here. While ERA5-Land provides consistent spatiotemporal coverage, its performance in high elevations with complex topography remains uncertain due to coarse resolution and sparse ground observations (Orsolini et al., 2019; Tazi et al., 2024). Consequently, absolute magnitudes of precipitation

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and evaporation trends should be interpreted cautiously, though relative variability is generally reliable.

The heterogeneous lake responses documented in this study have important implications for water resources and hazards across HMA. Water level increase in endorheic lakes enhances surface water availability, while basins reliant on dominant glacier melt contributions face an uncertain trajectory as transient melt subsidies eventually with continued glacier retreat (Hassan et al., 2026; Hugonnet et al., 2021). The rapid growth of proglacial lakes (Chen et al., 2021), combined with an increasing population and infrastructure in downstream areas, heightens GLOF risks for vulnerable communities (Shugar et al., 2020; Taylor et al., 2023). Our observed increase in lakes with strong decline in the Himalaya underscores hydrological vulnerability of these lakes. By providing consistent, multi-mission lake-level trends from CryoSat-2 (2010 – 2023) and ICESat-2 (2018 – 2024), this study improves the temporal continuity and robustness of altimetry-based lake monitoring in HMA. These findings establish a valuable observational baseline for future assessments of regional hydrological change and climate-driven impacts on alpine water resources.

5. Conclusion

This study presents a comprehensive analysis of lake level changes across HMA from 2010 to 2024, leveraging timeseries derived based on CryoSat-2 and ICESat-2. Our results show regionally heterogeneous pattern, dominated by increasing trends on the Tibetan Plateau and declining water levels in Himalaya. The robust agreement between the CryoSat-2 and ICESat-2 observations during the overlapping period (2018-2023) confirms the reliability of these trends. The persistence of lake level increase on the Tibetan Plateau through 2024, demonstrates the extended hydrological impact of the 2016-2018 precipitation anomaly, though some lakes experienced declining lake levels in recent years. The divergent response of Himalayan lakes, with accelerating declines, particularly smaller lakes highlights the heightened vulnerability of precipitation changes and reduced cryosphere melt buffering capacity. The stronger increasing water level trends of lakes within glaciated catchments with overall weak and inconsistent correlations with contemporary climate variables highlight the dominant role of nonlinear glacio-hydrology processes and hydrological buffering in mediating response to climate change. The systematic relationship between lakes size, elevation and water level rates proved valuable insights for understanding differential vulnerability across the region. The consistent pattern of larger lakes exhibiting higher rate of increasing lake level suggest greater hydrological resilience to integrate runoff from extensive catchments, while the

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inverse size relationship in Himalaya points to the vulnerability of smaller lakes in declining precipitation regimes. The climate-change exposure represented by 250 million people dependent on HMA runoff presents (Immerzeel et al., 2020; Pritchard, 2019) a strong impetus to improve our understanding of the lake water level variability across HMA. The regionally heterogeneous response with accelerating water levels in heavily glacierized catchments and declining water levels in precipitation sensitive regions demand tailored adaptation strategies. The integration of multi-mission altimetry with climate reanalysis data provides an important approach for continuous monitoring of these changes and informs water resource management.

Data Availability

The CryoSat-2 data are available at: (ESA, 2023, 2019a, b). The HMA lake boundary file is available as a data Supplement to this publication. High Mountain Asia subregion boundaries are also available at: (Bolch et al., 2019). Lake water level timeseries from this study will be made available through GEUS Bulletin (https://geusbulletin.org/index.php/geusb).

Supplement

Supplementary information for this paper is available in the Supplement

Author contributions

JH, KN, and SAK conceptualized and designed the study and methodology, processed data, visualization, and drafted the manuscript with contributions from all co-authors. KN performed simulations for processing altimetry data. WC, RBK, MK, and SAK contributed to conceptualization, interpretation, discussion, review, and editing.

Competing interests

All other authors declare they have no competing interests.

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Preprint. Discussion started: 2 April 2026

References

Ai, S., Shah, S. A., Cai, Y., Ling, J., Chu, X., Wang, S., Yang, Y., Ouyang, R., An, J., and Rack, W.: Lake pulses driven by glacier melting and climate variability, Scientific Reports, 14, 31623, https://doi.org/10.1038/s41598-024-78660-4, 2024.

Biskop, S., Maussion, F., Krause, P., and Fink, M.: Differences in the water-balance components of four lakes in the southern-central Tibetan Plateau, Hydrol. Earth Syst. Sci., 20, 209-225, https://doi.org/10.5194/hess-20-209-2016, 2016.

Bolch, T., Shea, J. M., Liu, S., Azam, F. M., Gao, Y., Gruber, S., Immerzeel, W. W., Kulkarni, A., Li, H., Tahir, A. A., Zhang, G., and Zhang, Y.: Status and Change of the Cryosphere in the Extended Hindu Kush Himalaya Region. In: The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People, Wester, P., Mishra, A., Mukherji, A., and Shrestha, A. B. (Eds.), Springer International Publishing, Cham, 10.1007/978-3-319-92288-1_7, 2019.

Chen, F., Zhang, M., Guo, H., Allen, S., Kargel, J. S., Haritashya, U. K., and Watson, C. S.: Annual 30 m dataset for glacial lakes in High Mountain Asia from 2008 to 2017, Earth Syst. Sci. Data, 13, 741-766, https://doi.org/10.5194/essd-13-741-2021, 2021.

Cleveland, R. B., Cleveland, W. S., and Terpenning, I.: STL: A Seasonal-Trend Decomposition Procedure Based on Loess, Journal of Official Statistics, 6, 3, 1990.

Duan, A. and Xiao, Z.: Does the climate warming hiatus exist over the Tibetan Plateau?, Scientific Reports, 5, 13711, https://doi.org/10.1038/srep13711, 2015.

ESA: European Space Agency L1b LRM Precise Orbit, Baseline E, https://doi.org/10.5270/CR2-41ad749, 2023.

ESA: European Space Agency L1b SARin Precise Orbit Baseline E, https://doi.org/10.5270/CR2-6afef01, 2019a.

ESA: European Space AgencyL1b SAR Precise Orbit Baseline E, https://doi.org/10.5270/CR2-fbae3cd, 2019b.

Hassan, J., Colgan, W., Nielsen, K., Kayastha, R. B., Khadka, M., and Khan, S. A.: Accelerating High Mountain Asia Glacier Loss From ICESat and ICESat-2, IEEE Transactions on Geoscience and Remote Sensing, 64, 1-12, https://doi.org/10.1109/TGRS.2025.3648542, 2026.

Hugonnet, R., McNabb, R., Berthier, E., Menounos, B., Nuth, C., Girod, L., Farinotti, D., Huss, M., Dussaillant, I., Brun, F., and Kääb, A.: Accelerated global glacier mass loss in the early twenty-first century, Nature, 592, 726-731, https://doi.org/10.1038/s41586-021-03436-z, 2021.

Immerzeel, W. W., Lutz, A. F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., Hyde, S., Brumby, S., Davies, B. J., Elmore, A. C., Emmer, A., Feng, M., Fernández, A., Haritashya, U., Kargel, J. S., Koppes, M., Kraaijenbrink, P. D. A., Kulkarni, A. V., Mayewski, P. A., Nepal, S., Pacheco, P., Painter, T. H., Pellicciotti, F., Rajaram, H., Rupper, S., Sinisalo, A., Shrestha, A. B., Viviroli, D., Wada, Y., Xiao, C., Yao, T., and Baillie, J. E. M.: Importance and vulnerability of the world's water towers, Nature, 577, 364-369, 10.1038/s41586-019-1822-y, 2020.

Jasinski, M., Stoll, J., Hancock, D., Robbins, J., Nattala, J., Pavelsky, T., Morison, J., Jones, B., Ondrusek, M., Parrish, C., Carabajal, C., and Team, T. I.-S.: ATLAS/ICESat-2 L3A Along Track Inland Surface Water Data, Version 6. NASA National Snow and Ice Data Center Distributed Active Archive Center, https://doi.org/10.5067/ATLAS/ATL13.006, 2023.

Jiang, J., Zhou, T., Qian, Y., Li, C., Song, F., Li, H., Chen, X., Zhang, W., and Chen, Z.: Precipitation regime changes in High Mountain Asia driven by cleaner air, Nature, 623, 544-549, https://doi.org/10.1038/s41586-023-06619-y, 2023.

Jiang, L., Andersen, O. B., Nielsen, K., Zhang, G., and Bauer-Gottwein, P.: Influence of local geoid variation on water surface elevation estimates derived from multi-mission altimetry for Lake Namco, Remote Sensing of Environment, 221, 65-79, https://doi.org/10.1016/j.rse.2018.11.004, 2019.

https://doi.org/10.5194/egusphere-2026-808
Preprint. Discussion started: 2 April 2026

549 Jiang, L., Nielsen, K., Andersen, O. B., and Bauer-Gottwein, P.: A Bigger Picture of how the
550 Tibetan Lakes Have Changed Over the Past Decade Revealed by CryoSat-2 Altimetry, Journal
551 of Geophysical Research: Atmospheres, 125, e2020JD033161,
552 https://doi.org/10.1029/2020JD033161, 2020.
553 Jiang, L., Nielsen, K., Andersen, O. B., and Bauer-Gottwein, P.: Monitoring recent lake level
554 variations on the Tibetan Plateau using CryoSat-2 SARIn mode data, Journal of Hydrology,
555 544, 109-124, https://doi.org/10.1016/j.jhydrol.2016.11.024, 2017.
556 Khanal, S., Lutz, A. F., Kraaijenbrink, P. D. A., van den Hurk, B., Yao, T., and Immerzeel, W.
557 W.: Variable 21st Century Climate Change Response for Rivers in High Mountain Asia at
558 Seasonal to Decadal Time Scales, Water Resources Research, 57, e2020WR029266,
559 https://doi.org/10.1029/2020WR029266, 2021.
560 Kleinherenbrink, M., Lindenbergh, R. C., and Ditmar, P. G.: Monitoring of lake level changes
561 on the Tibetan Plateau and Tian Shan by retracking Cryosat SARIn waveforms, Journal of
562 Hydrology, 521, 119-131, https://doi.org/10.1016/j.jhydrol.2014.11.063, 2015.
563 Kuang, X. and Jiao, J. J.: Review on climate change on the Tibetan Plateau during the last half
564 century, Journal of Geophysical Research: Atmospheres, 121, 3979-4007,
565 https://doi.org/10.1002/2015JD024728, 2016.
566 Lei, Y., Yang, K., Immerzeel, W. W., Song, P., Bird, B. W., He, J., Zhao, H., and Li, Z.: Critical
567 Role of Groundwater Inflow in Sustaining Lake Water Balance on the Western Tibetan Plateau,
568 Geophysical Research Letters, 49, e2022GL099268, https://doi.org/10.1029/2022GL099268,
569 2022.
570 Lei, Y., Yang, K., Wang, B., Sheng, Y., Bird, B. W., Zhang, G., and Tian, L.: Response of
571 inland lake dynamics over the Tibetan Plateau to climate change, Climatic Change, 125, 281-
572 290, https://doi.org/10.1007/s10584-014-1175-3, 2014.
573 Lei, Y., Yao, T., Yang, K., Sheng, Y., Kleinherenbrink, M., Yi, S., Bird, B. W., Zhang, X.,
574 Zhu, L., and Zhang, G.: Lake seasonality across the Tibetan Plateau and their varying
575 relationship with regional mass changes and local hydrology, Geophysical Research Letters,
576 44, 892-900, https://doi.org/10.1002/2016GL072062, 2017.
577 Lei, Y., Zhu, Y., Wang, B., Yao, T., Yang, K., Zhang, X., Zhai, J., and Ma, N.: Extreme Lake
578 Level Changes on the Tibetan Plateau Associated With the 2015/2016 El Niño, Geophysical
579 Research Letters, 46, 5889-5898, https://doi.org/10.1029/2019GL081946, 2019.
580 Meloni, M., Bouffard, J., Parrinello, T., Dawson, G., Garnier, F., Helm, V., Di Bella, A.,
581 Hendricks, S., Ricker, R., Webb, E., Wright, B., Nielsen, K., Lee, S., Passaro, M., Scagliola,
582 M., Simonsen, S. B., Sandberg Sørensen, L., Brockley, D., Baker, S., Fleury, S., Bamber, J.,
583 Maestri, L., Skourup, H., Forsberg, R., and Mizzi, L.: CryoSat Ice Baseline-D validation and
584 evolutions, The Cryosphere, 14, 1889-1907, https://doi.org/10.5194/tc-14-1889-2020, 2020.
585 Muhammad, S.: HKH snow update 2024, International Centre for Integrated Mountain
586 Development (ICIMOD), Nepal, https://doi.org/10.53055/ICIMOD.1046, 2024.
587 Muñoz Sabater, J.: ERA5-Land hourly data from 1950 to present Copernicus Climate Change
588 Service (C3S) Climate Data Store (CDS), https://doi.org/10.24381/cds.e2161bac, 2021.
589 Na, Y., Lu, R., Fu, Q., and Leung, L. R.: Extreme Precipitation Over the Southern Slope of the
590 Tibetan Plateau and the Associated Atmospheric Circulation Anomalies, Journal of
591 Geophysical Research: Atmospheres, 129, e2024JD040872,
592 https://doi.org/10.1029/2024JD040872, 2024.
593 Nielsen, K., Stenseng, L., Andersen, O. B., Villadsen, H., and Knudsen, P.: Validation of
594 CryoSat-2 SAR mode based lake levels, Remote Sensing of Environment, 171, 162-170,
595 https://doi.org/10.1016/j.rse.2015.10.023, 2015.
596 Niu, X., Tang, J., Chen, D., Wang, S., and Ou, T.: Elevation-Dependent Warming Over the
597 Tibetan Plateau From an Ensemble of CORDEX-EA Regional Climate Simulations, Journal
598 of Geophysical Research: Atmospheres, 126, e2020JD033997,
599 https://doi.org/10.1029/2020JD033997, 2021.
600 Orsolini, Y., Wegmann, M., Dutra, E., Liu, B., Balsamo, G., Yang, K., de Rosnay, P., Zhu, C.,
601 Wang, W., Senan, R., and Arduini, G.: Evaluation of snow depth and snow cover over the

https://doi.org/10.5194/egusphere-2026-808
Preprint. Discussion started: 2 April 2026

Tibetan Plateau in global reanalyses using in situ and satellite remote sensing observations, The Cryosphere, 13, 2221-2239, https://doi.org/10.5194/tc-13-2221-2019, 2019.
Ouyang, L., Yang, K., Lu, H., Chen, Y., Lazhu, Zhou, X., and Wang, Y.: Ground-Based Observations Reveal Unique Valley Precipitation Patterns in the Central Himalaya, Journal of Geophysical Research: Atmospheres, 125, e2019JD031502, https://doi.org/10.1029/2019JD031502, 2020.
Pritchard, H. D.: Asia's shrinking glaciers protect large populations from drought stress, Nature, 569, 649-654, https://doi.org/10.1038/s41586-019-1240-1, 2019.
Salerno, F., Guyennon, N., Colombo, N., Melis, M. T., Dessì, F. G., Verza, G., Bista, K., Sheharyar, A., and Tartari, G.: What is climate change doing in the Himalaya? Thirty years of the Pyramid Meteorological Network (Nepal), Earth Syst. Sci. Data, 17, 4293-4304, https://doi.org/10.5194/essd-17-4293-2025, 2025.
Shugar, D. H., Burr, A., Haritashya, U. K., Kargel, J. S., Watson, C. S., Kennedy, M. C., Bevington, A. R., Betts, R. A., Harrison, S., and Strattman, K.: Rapid worldwide growth of glacial lakes since 1990, Nature Climate Change, 10, 939-945, 10.1038/s41558-020-0855-4, 2020.
Song, C. and Sheng, Y.: Contrasting evolution patterns between glacier-fed and non-glacier-fed lakes in the Tanggula Mountains and climate cause analysis, Climatic Change, 135, 493-507, https://doi.org/10.1007/s10584-015-1578-9, 2016.
Taylor, C., Robinson, T. R., Dunning, S., Rachel Carr, J., and Westoby, M.: Glacial lake outburst floods threaten millions globally, Nature Communications, 14, 487, 10.1038/s41467-023-36033-x, 2023.
Tazi, K., Orr, A., Hernandez-González, J., Hosking, S., and Turner, R. E.: Downscaling precipitation over High-mountain Asia using multi-fidelity Gaussian processes: improved estimates from ERA5, Hydrol. Earth Syst. Sci., 28, 4903-4925, https://doi.org/10.5194/hess-28-4903-2024, 2024.
Thorson, J. and Kristensen, K.: Spatio-Temporal Models for Ecologists. Chapman and Hall/CRC, https://doi.org/10.1201/9781003410294, 2024.
Treichler, D., Kääb, A., Salzmann, N., and Xu, C. Y.: Recent glacier and lake changes in High Mountain Asia and their relation to precipitation changes, The Cryosphere, 13, 2977-3005, https://doi.org/10.5194/tc-13-2977-2019, 2019.
Wang, L., Zhao, L., Zhou, H., Liu, S., Du, E., Zou, D., Liu, G., Xiao, Y., Hu, G., Wang, C., Sun, Z., Li, Z., Qiao, Y., Wu, T., Li, C., and Li, X.: Contribution of ground ice melting to the expansion of Selin Co (lake) on the Tibetan Plateau, The Cryosphere, 16, 2745-2767, https://doi.org/10.5194/tc-16-2745-2022, 2022.
Wu, F., You, Q., Cai, Z., Sun, G., Normatov, I., and Shrestha, S.: Significant elevation dependent warming over the Tibetan Plateau after removing longitude and latitude factors, Atmospheric Research, 284, 106603, https://doi.org/10.1016/j.atmosres.2022.106603, 2023.
Yang, K., Yao, F., Wang, J., Luo, J., Shen, Z., Wang, C., and Song, C.: Recent dynamics of alpine lakes on the endorheic Changtang Plateau from multi-mission satellite data, Journal of Hydrology, 552, 633-645, https://doi.org/10.1016/j.jhydrol.2017.07.024, 2017.
Yao, T., Bolch, T., Chen, D., Gao, J., Immerzeel, W., Piao, S., Su, F., Thompson, L., Wada, Y., Wang, L., Wang, T., Wu, G., Xu, B., Yang, W., Zhang, G., and Zhao, P.: The imbalance of the Asian water tower, Nature Reviews Earth & Environment, 3, 618-632, https://doi.org/10.1038/s43017-022-00299-4, 2022.
Zemp, M., Jakob, L., Dussaillant, I., Nussbaumer, S. U., Gourmelen, N., Dubber, S., A, G., Abdullahi, S., Andreassen, L. M., Berthier, E., Bhattacharya, A., Blazquez, A., Boehm Vock, L. F., Bolch, T., Box, J., Braun, M. H., Brun, F., Cicero, E., Colgan, W., Eckert, N., Farinotti, D., Florentine, C., Floricioiu, D., Gardner, A., Harig, C., Hassan, J., Hugonnet, R., Huss, M., Jóhannesson, T., Liang, C.-C. A., Ke, C.-Q., Khan, S. A., King, O., Kneib, M., Krieger, L., Maussion, F., Mattea, E., McNabb, R., Menounos, B., Miles, E., Moholdt, G., Nilsson, J., Pálsson, F., Pfeffer, J., Piermattei, L., Plummer, S., Richter, A., Sasgen, I., Schuster, L., Seehaus, T., Shen, X., Sommer, C., Sutterley, T., Treichler, D., Velicogna, I., Wouters, B.,

https://doi.org/10.5194/egusphere-2026-808
Preprint. Discussion started: 2 April 2026

655 Zekollari, H., Zheng, W., and The Gla, M. T.: Community estimate of global glacier mass
656 changes from 2000 to 2023, Nature, 639, 382-388, https://doi.org/10.1038/s41586-024-08545-
657 z, 2025.
658 Zhang, G., Chen, W., and Xie, H.: Tibetan Plateau's Lake Level and Volume Changes From
659 NASA's ICESat/ICESat-2 and Landsat Missions, Geophysical Research Letters, 46, 13107-
660 13118, https://doi.org/10.1029/2019GL085032, 2019.
661 Zhang, G., Yao, T., Piao, S., Bolch, T., Xie, H., Chen, D., Gao, Y., O'Reilly, C. M., Shum, C.
662 K., Yang, K., Yi, S., Lei, Y., Wang, W., He, Y., Shang, K., Yang, X., and Zhang, H.: Extensive
663 and drastically different alpine lake changes on Asia's high plateaus during the past four
664 decades, Geophysical Research Letters, 44, 252-260, https://doi.org/10.1002/2016GL072033,
665 2017a.
666 Zhang, G., Yao, T., Shum, C. K., Yi, S., Yang, K., Xie, H., Feng, W., Bolch, T., Wang, L.,
667 Behrangi, A., Zhang, H., Wang, W., Xiang, Y., and Yu, J.: Lake volume and groundwater
668 storage variations in Tibetan Plateau's endorheic basin, Geophysical Research Letters, 44,
669 5550-5560, https://doi.org/10.1002/2017GL073773, 2017b.
670 Zhang, T., Wang, W., An, B., and Wei, L.: Enhanced glacial lake activity threatens numerous
671 communities and infrastructure in the Third Pole, Nature Communications, 14, 8250,
672 https://doi.org/10.1038/s41467-023-44123-z, 2023.
673 Zhang, Z., Li, X., Zhou, C., Zhao, Y., Zhao, G., and Tang, Q.: Linking ground ice and glacier
674 melting to lake volume change in the Dogai Coring watershed on the Tibetan Plateau, Journal
675 of Hydrology, 629, 130581, https://doi.org/10.1016/j.jhydrol.2023.130581, 2024.
676 Zhao, L., Zou, D., Hu, G., Du, E., Pang, Q., Xiao, Y., Li, R., Sheng, Y., Wu, X., Sun, Z., Wang,
677 L., Wang, C., Ma, L., Zhou, H., and Liu, S.: Changing climate and the permafrost environment
678 on the Qinghai–Tibet (Xizang) plateau, Permafrost and Periglacial Processes, 31, 396-405,
679 https://doi.org/10.1002/ppp.2056, 2020.

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