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Key Points:

- Two patterns of lake level seasonality between the northwestern TP and the other regions are identified
- Lake level variations in the central, northern, and northeastern TP are consistent with regional total mass changes
- Lake level variations in the northwestern TP deviate from regional total mass changes

Supporting Information:

- Supporting Information S1

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Lake seasonality across the Tibetan Plateau and their varying relationship with regional mass changes and local hydrology

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Abstract The recent growth and deepening of inland lakes in the Tibetan Plateau (TP) may be a salient indicator of the consequences of climate change. The seasonal dynamics of these lakes is poorly understood despite this being potentially crucial for disentangling contributions from glacier melt and precipitation, which are all sensitive to climate, to lake water budget. Using in situ observations, satellite altimetry and gravimetry data, we identified two patterns of lake level seasonality. In the central, northern, and northeastern TP, lake levels are characterized by considerable increases during warm seasons and decreases during cold seasons, which is consistent with regional mass changes related to monsoon precipitation and evaporation. In the northwestern TP, however, lake levels exhibit dramatic increases during both warm and cold seasons, which deviate from regional mass changes. This appears to be more connected with high spring snowfall and large summer glacier melt. The variable lake level response to different drivers indicates heterogeneous sensitivity to climate change between the northwestern TP and other regions.

1. Introduction

Due to its large spatial coverage and high elevation, the Tibetan Plateau (TP) and its surroundings play a significant role in the Earth's climate system through its unique interactions among the atmosphere, cryosphere, hydrosphere, lithosphere, and biosphere [Yao *et al.*, 2015]. The hydrological processes shaped by glaciers, permafrost, snowfall, and precipitation provide permanent flow for Asia's major rivers, thus significantly influencing social and economic development of the surrounding countries [Immerzeel *et al.*, 2010]. For a comprehensive understanding of the Third Pole Environment, international, interdisciplinary, and integrated studies are needed. For this purpose, the Third Pole Environment Program is now being implemented and is drawing increased attention among the international academic community [Ma *et al.*, 2011; Yao *et al.*, 2012].

While it is projected that climate warming will increase the discharge of the major large rivers in South and East Asia as a result of increased rainfall and glacier melt in their watersheds [Su *et al.*, 2016], the paucity of instrumental data from sparsely populated TP has limited investigations of hydroclimate response to recent climate change. The abundance of large, high-altitude closed-lake systems in the TP, however, provides a means to assess regional hydroclimate response to recent climate change. Initial work along these lines indicates that on a decadal time scale, lakes in the interior TP expanded and deepened significantly since the late 1990s [e.g., Bian *et al.*, 2010; Li *et al.*, 2011; Zhang *et al.*, 2013, 2014; Song *et al.*, 2013] in response to a variety of factors, including increased precipitation [Lei *et al.*, 2013, 2014; Song *et al.*, 2014a; Biskop *et al.*, 2016], accelerated glacier melting [Zhu *et al.*, 2010], and permafrost degradation [Li *et al.*, 2014].

To date, only few studies have investigated seasonal lake level variations across the vast interior TP. The Ice, Cloud, and land Elevation Satellite (ICESat) data have been used to explore lake seasonality because of its high precision and large spatial coverage. Phan *et al.* [2012], for example, suggested that there are four distinct spatial patterns of seasonal lake level changes that can be recognized in the southern,

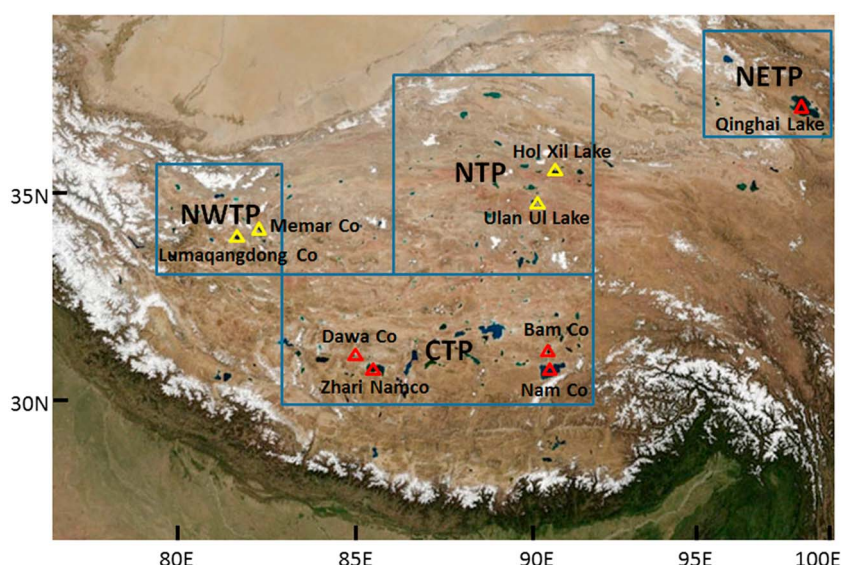


Figure 1. The location of the selected lakes in the NWTP, NTP, CTP, and NETP. The yellow triangles represent lakes with Cryosat-2 altimetry data, and red triangles represent lakes with in situ lake level observation. The four rectangles represent the location where GRACE gravimetry data are extracted.

central, northern, and western TP. Lake level differences between the “early dry” (mid-September to mid-December) and “late dry” (late February to mid-April) periods indicate that lake level variations are much larger in the southern TP than in the northern and western TP. Song *et al.* [2014b] identified eight regions with distinct patterns of lake level changes using cluster analysis of seasonal and abrupt lake level changes. While these results demonstrate that ICESat altimetry data are undoubtedly important for understanding general features of seasonal lake level changes, more frequent observations are needed to depict the seasonality of lake hydrology and its spatial pattern.

To what extent glacier melt can influence lake water budget and how to disentangle contributions of glacier melt and precipitation to lake water budget are still open questions because of the lack of in situ observation in this high-elevation region. In this study, we investigate the process, amplitude, and spatial pattern of seasonal lake level changes in the interior TP using in situ observations in combination with Cryosat-2 satellite altimetry data between 2010 and 2014 and evaluate the contribution of glacier melt and precipitation to seasonal lake level changes by combining two sets of precipitation dataset and Gravity Recovery and Climate Experiment (GRACE) data.

2. Study Area

Nine closed lakes larger than 100 km² across the TP were selected to investigate the spatial patterns of lake level seasonality (Figure 1). These lakes are distributed in the northwestern (NWTP, $n=2$), northern (NTP, $n=2$), central (CTP, $n=4$), and northeastern (NETP, $n=1$) TP. More detailed information about these lakes can be found in the supporting information (Table S1) [Lanzhou Institute of Geology, CAS, 1979; Guan *et al.*, 1984; Wang *et al.*, 2009, 2010; Lei *et al.*, 2012; Wei *et al.*, 2014]. Climate in the TP is mainly influenced by the westerlies in winter and the Asian monsoon in summer and thus is characterized by a relatively warm and wet summer and a cold and dry winter [Maussion *et al.*, 2014]. However, the influence of the Asian summer monsoon and the westerlies in the TP is heterogeneous during the summer monsoon season, with a clearer fingerprint of the westerlies in the northern TP and more of the Indian summer monsoon in the southern TP [Yao *et al.*, 2013]. The mean annual temperature varies between -2 and 0°C in the CTP and decreases to -6 to -4°C in the NWTP and NTP [Maussion *et al.*, 2014]. Annual precipitation decreases from southeast to northwest, with an average value of ~ 400 mm in the CTP and NETP, ~ 300 mm in the NTP, and less than 200 mm in the NWTP [Xu *et al.*, 2008; Maussion *et al.*, 2014].

3. Data and Method

3.1. In Situ Observations

In situ lake level observations were conducted in the CTP using HOBO water level loggers (U20-001-01), which were installed in the study lake's littoral zone. Because the water levels were recorded as changes in pressure (less than 0.5 cm water level equivalent), air pressure data from nearby meteorological/observing station were subtracted from the level loggers to isolate pressure changes related to water column variations. Three lakes in the CTP (Zhari Namco, Bam Co, and Dawa Co) were monitored (Table S1) with loggers at an interval of 1 h, and daily data were used in this study by averaging the hourly water level data. Additionally, daily water levels of Nam Co were manually observed at Nam Co station (30°46'22.8"N, 90°57'43.2"E, 4,730 m above sea level). Observations were not carried out at Nam Co during the winter because of the influence of lake ice. Since the observed lake levels at Nam Co were discontinuous and could not be compared year to year, satellite altimetry data (LEGOS) were used to compare the interannual lake level changes [Crétaux *et al.*, 2011]. In addition, monthly water level data from Qinghai Lake, which were monitored by Bureau of Hydrology and Water Resources of Qinghai Province, were also used to represent lake level variations in the NETP.

3.2. Satellite Data

In the NTP and NWTP, where in situ lake level data are not available, Cryosat-2 altimetry data [Kleinherenbrink *et al.*, 2015] were used because of its robustness over small lakes and frequent passes over the larger ones. Four lakes which were mostly passed and detected by this satellite were selected (Table S1). In the NTP, there were 8–10 altimetry data per year for the two selected lakes, Hol Xil Lake and Ulan Ul Lake. In the NWTP, there were 6–8 altimetry data per year for the two selected lakes, Lumajiangdong Co and Meima Co. Since we mainly focused on the process of lake level fluctuations, we did not consider the absolute elevation of each lake but only used the relative lake level changes (Figure 2).

GRACE Release 05 data presented by UT-CSR (CSR05) and processed by Yi and Sun [2014] were used to compare with lake level changes in all regions. The GRACE data have a spatial resolution of 300 km at monthly time steps. Although validation data were limited from the TP, the GLDAS model was applied to correct the effect of soil water storage [Rodell *et al.*, 2004]. Considering its low spatial resolution, mass changes in four regions that corresponded to the selected lakes were extracted (Figure 1). The domains of the four regions were NWTP (79–83°E, 33–36°N), NTP (86–92°E, 33–38°N), CTP (83–92°E, 30–33°N), and NETP (97–101°E, 36–39°N).

3.3. Precipitation Data

A gridded precipitation data set from Institute of Tibetan Plateau Research, Chinese Academy of Sciences (ITPCAS), which was developed by merging the Tropical Rainfall Measuring Mission 3B42 precipitation products, precipitation observations from Chinese meteorological stations, and GLDAS precipitation data [Chen *et al.*, 2011], was compared with seasonal lake level changes to investigate the influence of precipitation. Another precipitation data set, the High Asian Reanalysis (HAR), which was generated by the downscaling of global analysis data using the Weather Research and Forecasting model [Maussion *et al.*, 2014], was also used to confirm the precipitation seasonality in this study. To avoid the influence of topography, monthly precipitation in an area of 1° × 1° covering the selected lakes was extracted and averaged.

4. Results and Discussion

4.1. Seasonal Lake Level Fluctuations

Figures 2 and 3 (middle lines) show the relative lake level changes in a hydrological year (October to September) and the full time series of lake level changes between 2010 and 2014, respectively. During the study period, lake levels in the NWTP, NTP, and NETP increased considerably, while lake levels in the CTP were relatively stable. Therefore, the lake level seasonality in this study mainly represents processes related to lake expansion in the northern parts of the TP while that in the CTP represents an equilibrium state. The causes for the spatial difference of lake level changes have been discussed in Crétaux *et al.* [2016]. Here we mainly focus on the seasonal dynamics.

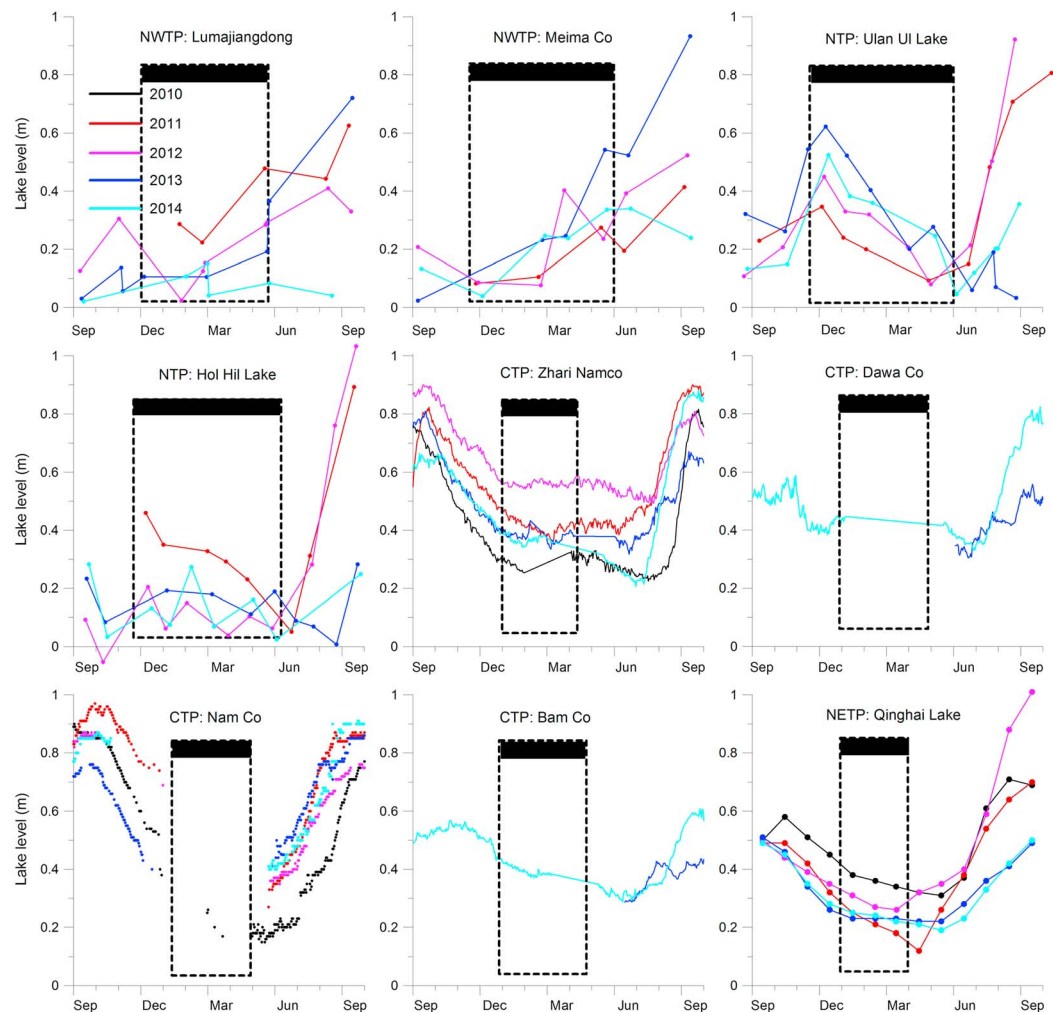


Figure 2. Relative lake level changes in a hydrological year (October to September) between 2010 and 2014. The black squares represent ice-covered period for each lake.

Lakes in the CTP and NETP exhibited obvious seasonal fluctuations, namely, significant lake level increases during the summer monsoon season that were followed by decreases during the nonmonsoon season. These lake level increases began in June or July (depending on onset of monsoon precipitation) with the highest levels reached in middle to late September. After that, the lake levels decreased considerably until late December to early January when the lake surface froze (Table S2). During the frozen period, the lake levels were stable since lake ice precluded lake evaporation. After the breakup of lake ice in April, lake levels decreased until the onset of the summer monsoon, but at lower rates than the preceding dry season. For the two large and deep lakes (Zhari Nam Co and Nam Co) investigated by this study, lake levels increased by 0.3–0.6 m during the monsoon season, with reduction of similar magnitude by 0.3–0.5 m during the nonmonsoon season. For the two small lakes (Dawa Co and Bam Co), although there was a similar pattern of lake seasonality, the amplitude of seasonal lake level fluctuations was considerably smaller than the two large lakes (Figure S1).

In the NTP, rapid seasonal increases in lake level also mainly occurred during the summer monsoon season with peak increases reaching as high as +1 m in wet years (e.g., 2011 and 2012). Slight lake level increases (or stable) could also be found in dry years (e.g., 2013). During the cold season, lake levels decreased slightly (less than 20 cm) or remained nearly stable before the lake surface froze (in middle to late November). During the ice cover period between the middle of November and early June, lake surface elevations derived from Cryosat-2 satellite sharply increased initially and then decreased gradually until lake ice broke up in June

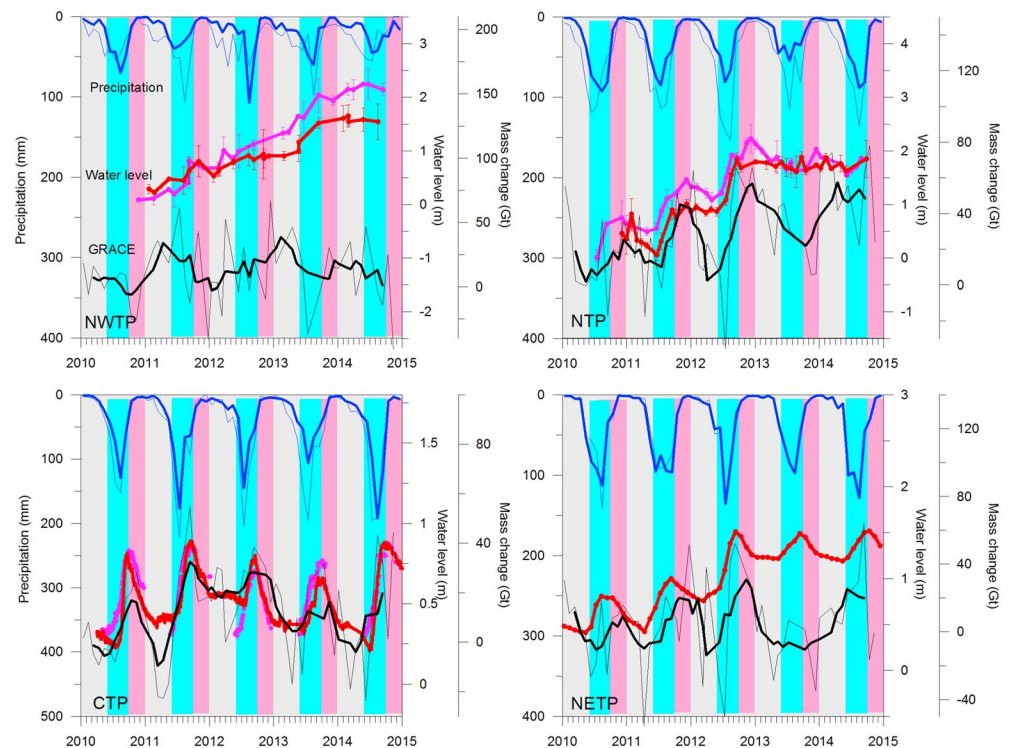


Figure 3. Comparison of monthly precipitation, lake level changes, and GRACE mass changes in the NWTP, NTP, CTP, and NETP. The top lines are monthly precipitation from ITPCAS (thick blue) and HAR (thin blue) data set. The middle lines are seasonal lake level changes, including Lumajiangdong Co (red) and Meima Co (magenta) in the NWTP, Hol Xil Lake (red) and Ulan Ul Lake (magenta) in the NTP, Zhari Namco (red) and Nam Co (magenta) in the CTP, and Qinghai Lake in the NETP. The bottom lines are GRACE data (thin black) and its five-point running average (thick black). The blue columns represent summer monsoon period (June to September), and the pink represent early winter period (October to December).

(Figure 2), with a slight decrease (or nearly stable) for the period as whole. Therefore, we suggest that the changes in lake surface elevation during the cold season derived from Cryosat-2 may not reflect the real water balance change because (1) the phase transition between liquid and solid could change the water volume; (2) the appearance of lake ice could made the lake surface irregular, interfering with lake elevation estimates; and (3) snowfall accumulation on the lake ice could cause overestimations of the lake surface elevation in early winter. These nonhydroclimate controls on lake surface elevation during the cold season were also observed at other lakes in the NTP (Figure S3), which indicates that this warrants attention when using cold-season lake elevation data in this area.

In the NWTP, lake levels derived from Cryosat-2 altimetry data exhibited seasonal variations that contrasted with regions discussed above. During the study period, lake levels increased on average by 0.4 m yr^{-1} with maximum increases as large as $0.8\text{--}1.0 \text{ m}$ (e.g., 2013). Most notably, lake levels increased in a nearly linear trend during the study period with no obvious seasonal fluctuation (Figure 2). Indeed, lake level increases were observed during both the warm and cold seasons. For the two selected lakes, Meima Co and Lumajiangdong Co, the average value of the lake level increases in the cold season was close to, or even larger than that in the warm season. Considering the impact of lake ice on lake surface elevation, we carefully compared the lake level before and after the frozen time (Figure 2) and found that the lake levels indeed rose considerably during the cold season, which was different from the northern TP. It should be noted that the absence of an obvious seasonal cycle in the NWTP may be partly explained by its small amplitude, which is less than can be detected by the satellite altimetry.

4.2. Lake Level Rise and Precipitation Seasonality

A comparison between lake level changes and monthly precipitation is shown in Figure 3. The most prominent feature is the good correspondence between lake level increases and the summer monsoon

precipitation for lakes in all regions but the NWTP. Lake level increases were typically associated with the onset of monsoon precipitation in June or July, with the highest levels reached at the end of monsoon season in middle to late September. The amplitude of warm-season lake level increases showed a good relationship with precipitation amount. For example, the significant lake level increases in 2011 and 2012 in the NTP and NETP corresponded with relatively high precipitation, while there was almost no lake level increase in summer 2013 when precipitation was relatively low. In the CTP, larger amplitude of lake level increases also occurred during wet years (e.g., 2011 and 2014), while smaller lake level increases occurred in dry years (e.g., 2013). This suggests that summer precipitation contributed significantly to the positive water budget in the warm season and that reduced monsoonal precipitation resulted in the lowering of lake levels in the cold season.

In the arid NWTP, seasonal lake level changes also tracked the precipitation cycle, but with differences in the timing of lake level variations that reflected the regional precipitation seasonality. Both the ITPCAS and HAR precipitation data (Figure 3) showed that substantial precipitation occurred in both summer and spring, the latter contributing as much as 30–40% of total annual precipitation. This was different from the other regions in the interior TP, where more than 80% of total precipitation occurred in summer monsoon period. Lake level increases during the cold season could be mainly controlled by spring snowmelt since there was almost no glacier runoff during this season. The different precipitation seasonality in the northwestern TP is also consistent with the high spring snow cover here. Spatially, the northwestern part of the TP including Karakoram and western Kunlun Mountains is one of the two highest snow cover areas in the TP [Chu *et al.*, 2014]. Temporally, spring (March to May) is the most snow-covered season in this region. The lake level increase in the cold season could account for nearly half of the total increase in a hydrological year, indicating that the snow melt in spring may play an important role in lake water budget.

4.3. Comparison With Other Lakes

To test the representativeness of the selected lakes, we compared the seasonal lake level changes in this study with nine other lakes which had relatively less Cryosat-2 data (Figure S2). In the NTP, five other lakes were checked. Similar patterns with the two primary study lakes were found, i.e., significant lake level increases in the summer monsoon period followed by a weak lake level drop (or even stable) in the cold season. The considerable lake level increases in early winter and the subsequent decreases were also observed (Figure S3) but may still not reflect the real water budget. In the CTP, three other lakes were checked. Similar seasonal lake level cycles to the two primary study lakes were also found (Figure S4), namely, considerable lake level increases during the summer monsoon period and subsequent lake level drop during the cold season. In the NWTP, only one lake (Bamgdog Co) was checked and a similar lake level seasonality with the primary study lakes was found (Figure S5). The consistency with more lakes indicates that the spatial patterns of lake level seasonality we identified in this study reflected regional-scale hydroclimate processes.

We also find some difference in lake level seasonality between lakes. For instance, Aqqik Kul Lake in the NTP exhibited a continual lake level increase for the whole year, which is more like lakes in the NWTP (Figure S3). Siling Co in the CTP showed a less pronounced seasonal cycle that was difficult to distinguish from its considerable lake level increase (Figure S4). This difference may be attributed to the local characteristics, e.g., location, lake salinity, water depth, lake area, and with/without glacier supply. These nonclimate factors can influence lake level changes by affecting the seasonal patterns of lake evaporation and runoff [Lazhu *et al.*, 2016].

4.4. Lake Level Seasonality and Mass Changes Derived From GRACE

The contributions of glacier mass balance and precipitation to lake water budget were identified by comparing the continual lake level changes with GRACE gravimetry data (Figure 3). GRACE signals covering endorheic basins in the TP reflect mass changes related to glaciers [Jacob *et al.*, 2012; Yi and Sun, 2014], lake volume [Zhang *et al.*, 2013; Song *et al.*, 2013], soil water storage, tectonic process, and glacier isostatic adjustment (GIA). Tectonic process and GIA were not considered in this study because we mainly focused on the seasonal fluctuations. Although soil water storage was corrected, it is still challenging to quantitatively explain the total mass changes derived from GRACE data because changes in soil water storage (e.g., permafrost and groundwater) are still poorly constrained for interior regions of the TP [Yi and Sun, 2014]. Here we

made a simplification and attributed the total mass changes derived from GRACE data to the combined changes in lake volume and glacier mass balance.

In the CTP, where there is a high density of lakes, but glacier density is relatively low, the GRACE data exhibited very similar fluctuations with seasonal lake level changes, namely, considerable increases during the monsoon season were followed by gradual decreases during the dry season (Figure 3). The high consistency suggests that the total mass changes may be mainly attributed to changes in lake volume. Although glacier mass changes and the associated lake volume changes could not be isolated in the GRACE signals, this consistency also indicates that the total mass changes were not likely to be significantly contributed by the low density of glaciers in the region. Instead, the good correspondence between total mass changes and precipitation seasonality strongly supports interpreting the GRACE data in terms of lake mass changes related to the balance between monsoon precipitation and evaporation.

In the NTP, where there are fewer lakes and more glaciers compared with the CTP, the GRACE data exhibited a similar increasing trend with lake levels on an interannual scale (Figure 3), which indicates that the increase in total mass changes could be mainly attributed to the significant lake growth rather than glacier melting because the latter could not lead to the increase in total mass. On a seasonal scale, the GRACE data showed a marked seasonal cycle as lake level in wet years (e.g., 2011 and 2012), indicating that the impact of glacier mass balance on the total mass changes in this area was relatively weak because the increase in lake volume was much greater than glacier mass balance (e.g., 2011 and 2012). However, the condition was different in dry years, when there was almost no lake level rise in summer (e.g., 2013). In this case, the decrease in total mass indicates that the total rainfall was less than evaporation (including land and lake surface). Since the lake level was nearly stable, the decrease in the GRACE data was mainly attributed to glacier mass loss. One can find that the lake would be in negative water balance without the supply of glacier mass loss in dry years.

In the NWTP, where there is much higher glacier coverage and fewer lakes relative to the CTP and NTP, the total mass did not exhibit a significant increase as those observed for lake levels on an interannual scale but remained relatively stable (Figure 3). This suggests that glacier mass balance may counterbalance lake volume changes; i.e., glacier mass loss offsets increases in lake storage to keep the total mass in a balanced state. Therefore, it is suggested that glacier mass loss was potentially an important contributor to lake level rise here. On a seasonal scale, the GRACE data exhibited considerable decrease in the warm season in contrast with the lake level increases, indicating that evaporation in the catchment was greater than precipitation. Meanwhile, the lake level increases in the warm season indicate that glacier mass loss was even larger than the increases in lake volume and thus potentially played an important role in the positive water budget as well as the gravity reduction. During the cold season, there was a considerable total mass gain, which indicates that snowfall was the main supply when there was almost no glacier melt and lake evaporation.

Rough quantitative estimates of changes in total lake storage based on the observed lake level changes, catchment area, and the total area of each region were considerably smaller (but still comparable) relative to GRACE mass changes (Figure S6). This is understandable because changes in soil water storage including permafrost and groundwater were also included in GRACE mass changes. Although it is still difficult to quantify changes in total water storage on catchment scale, the comparison between lake level changes and GRACE data demonstrates that the former was a good indicator of terrestrial water storage changes with the exception of the NWTP where glaciers and snowfall were more important. Our study further indicates that the positive lake water budget since the late 1990s was mainly a result of increases in the monsoon precipitation in the CTP, NTP, and NETP [Lei *et al.*, 2013, 2014]. Additionally, the different seasonality of lake hydrology shows that causes for the positive lake water budget in the NWTP may be more complex, including intensified snowfall in spring, glacier melt, and monsoon precipitation in the summer.

5. Conclusions

Here we showed the process of seasonal lake level changes in the TP, and two patterns of lake level seasonality were identified. For most lakes in the CTP, NETP, and NTP, water level increases mainly occurred during warm seasons in response to summer monsoon precipitation, whereas lake level decreases occurred during cold seasons in response to less precipitation and reduced runoff. Contrastingly, lake levels in the NWTP

increased considerably in both warm and cold seasons. The good consistency between lake level changes and GRACE gravimetry data in the CTP, NTP, and NETP indicates that lake water budget was mainly controlled by monsoon precipitation, while the inconsistency between them in the NWTP indicates that it was more likely to be influenced by snowfall in spring and glacier melt in summer. Our results additionally show that glacier melt in the NTP may be also important to lake water budget in dry years because it can offset part of evaporative water loss. This study not only reveals the linkage between lake water budget and cryosphere hydrology but also has important implications for the causes of the rapid lake growth in the interior TP since the late 1990s.

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