Response to Reviewer #1 for Manuscript "Contribution of ground ice melting to the expansion of Selin Co (lake) on the Tibetan Plateau"

In this study, Wang et al. estimated deformation rate of permafrost in the Selin Co basin by Sentinel-1 SAR data. The subsidence volume was assumed as ground ice melting. The contribution (ratio) of ground ice melting to lake water volume gain was estimated. This study first quantified the contribution of ground ice change to the expansion of Serlin Co. This study is novel and suitable to publish in Cryosphere after further improvement/clarification.

The authors are very grateful for the valuable comments and suggestions from the reviewer.

Detailed responses and revisions based on the comments are listed below.

Major comments:

1) In this study, the contribution of ground ice melting to water volume increase of Selin Co was estimated by subsidence space derived from Sentinel-1 SAR data. The ice density of 0.91 g/cm3 was used to estimated the water released from ground ice into lake. This process is not easy to understand. The authors can add more interoperation of this hypothesis that the subsidence volume equals to ground ice melting supply is reasonable.

Thank you very much for the comment. We have added more interoperation of this hypothesis in the "Introduction" and "Method" sections.

In the "Introduction" section, we first stated that "Significant permafrost degradation has been observed on the TP under the impacts of the warming climate. The monitoring of ten boreholes on the TP revealed that from 1981 to 2018, the active layer thickened at an average rate of 19.5 cm per decade; moreover, this thickening trend has been accelerating in recent years (Zhao et al., 2020). In the meantime, different permafrost regions across the TP experienced thaw settlements (Daout et al., 2017; Chen et al., 2022). The ice content within the uppermost layer of permafrost is typically higher than the saturated water content after this permafrost layer thaws; hence, the thawing of this layer might result in terrain settlement (Streletskiy et al., 2016; Shiklomanov et al., 2013; Günther et al., 2015; Lantuit and Pollard, 2008; Kokelj and Jorgenson, 2013). The terrain settlement was attributed to the melting of ground ice from the ice-rich permafrost layer just below the permafrost table and the further release of this water into the hydrological cycle (Zhao et al., 2019)", then stated "It is well known that the permafrost layer just below the permafrost table always contains ground ice higher than 50% in volume (Cheng, 1983; Mackay, 1983; French and Harbor, 2013; Zhao and Sheng, 2019). Therefore, we assumed that the amount of surface settlement would release the same amount of ground ice caused by compressing the thawing ice-rich permafrost layer.".

In the Method section "3.4 Conversion from ground deformation to ground ice meltwater contribution", we stated that "A considerable amount of ground ice is always buried in permafrost regions, especially just below the permafrost table (Cheng, 1983; Mackay, 1983; French and Harbor, 2013). Thawing of the uppermost permafrost layer is always accompanied by the compaction of sediment and subsidence of the ground surface due to the melting of super-saturated ground ice (French, 2017). Hence, the higher the ice content in permafrost, the larger the surface subsidence occurred as it was thawed. In this study, we assume that the long-term cumulated settlement is equal to the thickness of ground ice melted, and then released to the hydrological cycle.".

2) This study only presents three-year study from 2017 to 2020. How the lake volume and space of subsidence were estimated and uncertainties? ICESat-2 stared from 2018, how about the data in 2017? The authors could include a comparison (lake level/volume changes) in discussion with a supplementary table with previous studies?

Thank you very much for the comment and suggestion.

1) To be clear, **we have added the statements in the revised manuscript as "To calculate the changes in the** lake water storage of Selin Co, Eq. (1) was applied taking the areas of 2408.1 km^2 in 2018 and 2441.2 km^2 in 2020 and taking the water surface elevation change of ~0.4 m between these two years; then, the change in lake volume from 2018 to 2020 was estimated, and finally, the annual volume change rate was obtained by dividing the results of these two years. The annual rate of change in the lake volume of Selin Co during 2018–2020 was ~485×10^6 m^3/a." Both the subsidence and lake volume change are expressed in the way of rates. Although there is a slight inconsistency between their periods, they could represent the characteristics of this certain period.

2) Taking the reviewer's suggestion, **we have reviewed the changes in the lake area, water level, and water volume in previous studies and compared them with our results.** The changes in lake area, lake level, and volume are shown in Fig. 10 in the revised manuscript.

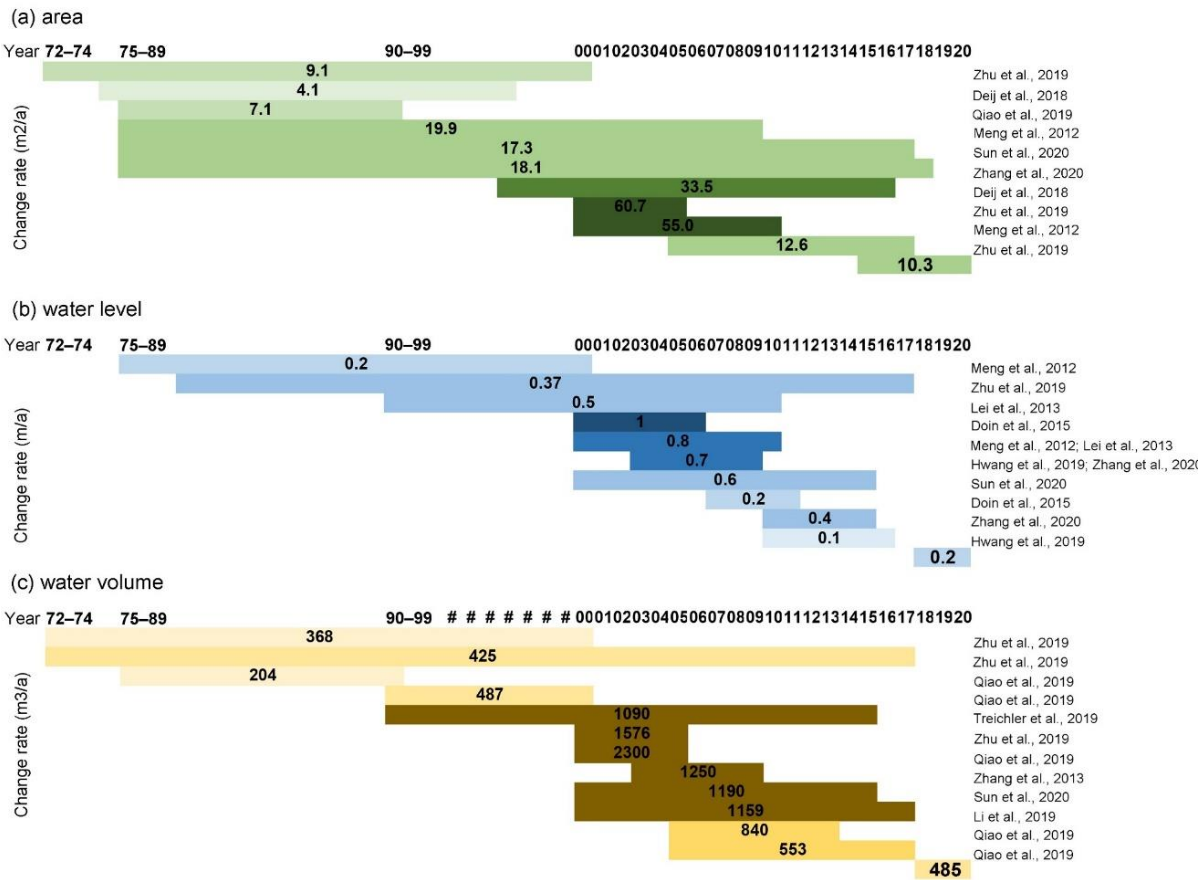

Figure 10 Comparisons of the changes in the lake area (subfigure a) water surface elevation (b) and lake volume (c) of Selin Co with historical values.

We have stated in the discussion section “4.4.1 Uncertainties and accuracies of lake volume change rate” that “Our analysis shows that during the period of 2018–2020, the water level increased at a rate of ~0.2 m/a, the lake area increased at a rate of 10.3 km^2/a, and the lake water storage increased at a rate of 485×10^6 m^3/a. These values are compared with those recorded in previous studies in Fig. 10. lake area change information are from (Zhu et al., 2019b; Qiao et al., 2019; Meng et al., 2012; Sun et al., 2020; Zhang et al., 2020; Deij et al., 2018); water level change information are from (Meng et al., 2012; Lei et al., 2013; Doin et al., 2015; Zhang et al., 2013; Sun et al., 2020; Hwang et al., 2019; Zhang et al., 2020; Zhu et al., 2019a); and water volume information are from (Zhu et al., 2019b; Qiao et al., 2019; Treichler et al., 2019; Sun et al., 2020; Zhang et al., 2013; Li et al., 2019). As illustrated in Fig. 10, the expansion of Selin Co was slow before 2000, with lake area and volume increases of 9.1 km^2/a and 368×10^6 m^3/a, respectively. Then, in the period of 2000–2005, the lake expanded extremely fast, with the water level increasing at an approximate rate of 1.0 m/a and the lake area and volume increasing at rates of 60.7 km^2/a and 1576×10^6 m^3/a, respectively. After 2005, however, these rates of increase slowed down, with those of the lake area and lake water storage slowing to only 12.6 km^2/a and 553×10^6 m^3/a

during 2005–2017, respectively, and the rate of increase in the water surface elevation slowing to 0.2 m/a during 2007–2011 (Doin et al., 2015). Overall, the values retrieved in this study are all within the ranges of the historical values and are closest to the values after the 2010s.”

3) Regarding the uncertainties of spatial deformation, we used two indicators that qualitatively evaluated the quality of unwrapped phases and inverted raw phase time series: the phase closure of interferogram triplets and temporal coherence. Their meanings are described in section 3.3.1 SBAS-InSAR processing ii) Deformation time series estimation as follows.

Two indicators evaluated the quality of unwrapped phases and inverted raw phase time series: the phase closure of interferogram triplets and temporal coherence. The phase unwrapping algorithms add integer number of 2π phase jumps to recover the unwrapped phase. Interferometric phase noise and discontinuities among different coherent regions may lead to the wrong 2π jumps added to the phase field known as unwrapping error. Unwrapping errors can bias the estimated time series. For an interferogram triplet ($\Delta\phi^{ij}$, $\Delta\phi^{jk}$ and $\Delta\phi^{ik}$), unwrapping errors introduce a nonzero integer component ${C_{int}}^{ijk}$ in the closure phase C^{ijk}. Therefore, the number of interferogram triplets with nonzero integer ambiguity T_{int} can be used to detect unwrapping errors:

$$C^{ijk} = \Delta\varphi^{ij} + \Delta\varphi^{jk} - \Delta\varphi^{ik} \tag{2}$$

$$C_{int}^{ijk} = \frac{C^{ijk} - \text{wrap}\,(C^{ijk})}{2\pi} \tag{3}$$

$$T_{int} = \sum_{i=1}^{T} \left(C_{int}^{ijk}! = 0\right) \tag{4}$$

where $\Delta\varphi^{ij}$, $\Delta\varphi^{jk}$ and $\Delta\varphi^{ik}$ are the three unwrapped interferometric phases generated from the SAR acquisitions at t_i, t_j and t_k, respectively; wrap is an operator that wraps each input number into $[-\pi, \pi)$; and T is the number of interferogram triplets. A triplet without unwrapping errors has $C_{int}^{ijk} \equiv 0$.

The second index, temporal coherence, represents the consistency of the time series with the network of interferograms (Pepe and Lanari, 2006):

$$\gamma_{temp} = \frac{1}{M}\left|H^T \exp\,[j(\Delta\phi - A\hat{\phi})]\right| \tag{5}$$

where (for N SAR images and M interferograms) $\Delta\phi$ is the unwrapped interferometric phase; A is the $M \times (N-1)$ design matrix indicating the acquisition pairs used for interferograms generation (consisting of -1, 0 and 1 for each row with -1 for the reference acquisition, 1 for the secondary acquisition and 0 for all other acquisitions (Berardino et al., 2002)); $\hat{\phi}$ denotes the estimated time series; H is an M×1 all-ones column vector; and j is the imaginary unit.

Temporal coherence varies from 0 to 1: pixels with values closer to 1 are considered reliable, whereas pixels with values closer to zero are considered unreliable.

The uncertainties and accuracy of deformation time series estimation are stated in section 4.4.2 Uncertainties and accuracies of deformation, as follows.

Fig. 11 shows the spatial distribution of the number of interferogram triplets with nonzero integer ambiguity T_{int} (Eq(4) in the manuscript), with the histogram illustrating the distribution of T_{int} values within the Selin Co watershed after excluding glaciers and water bodies. The areas having T_{int} smaller than three take part 95% of the watershed, while 72.3% of the watershed has T_{int} value of zero (no wrapping error on all the interferograms). The value of T_{int} evaluated the quality of original interferometric unwrapped phases, the unwrapping errors could be further reduced by bridging reliable regions before network revision (Zhang et al., 2019b).

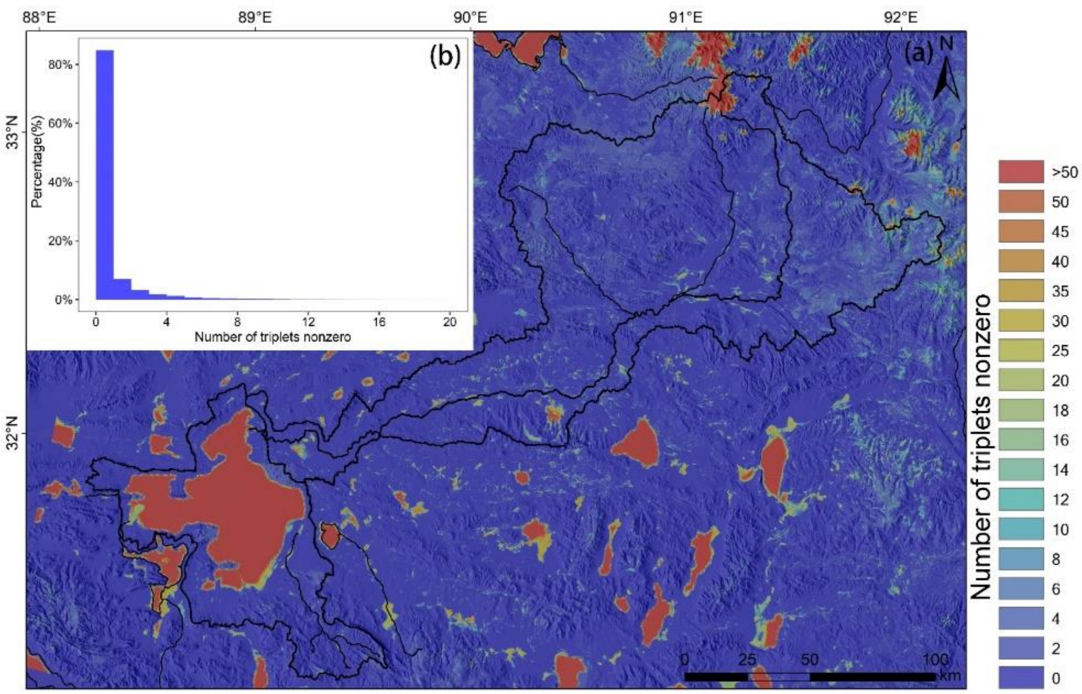

Figure 11 (a) Map of the number of interferogram triplets with nonzero integer ambiguity T_{int} (Eq(4)), (b) histogram illustrating the distribution of T_{int} values within the Selin Co watershed excluding glaciers and water bodies.

Fig. 12 shows the spatial distribution of temporal coherence (Eq.(5) in the manuscript), which is used to evaluate the quality of raw phase time series. 99.0% of the watershed has temporal coherence higher than 0.8, 98.1% has temporal coherence higher than 0.85, 96.0% has temporal coherence higher than 0.9 and 89.1% has temporal coherence higher than 0.95.

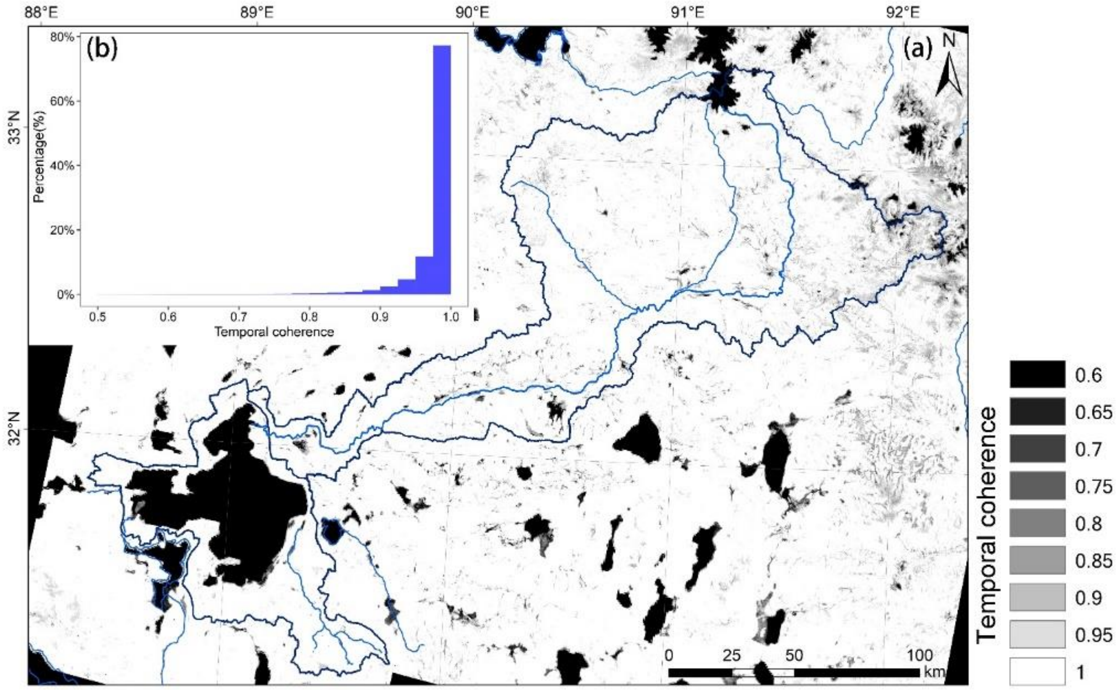

Figure 12 (a) Map of temporal coherence (Eq(5)), (b) histogram illustrating the distribution of temporal coherence values within the Selin Co watershed excluding glaciers and water bodies.

3) The uncertainties (plus minus) of all estimates could be included.

Thank you. In the previous manuscript, the ground ice meltwater volume was calculated considering two extreme situations regarding the uplift signal. But due to a lack of field investigation, it is hard to attribute the uplift signal absolutely to permafrost aggradation or the rise of the groundwater table or sedimentation. Thus, we only presented the uplift signal and discussed this phenomenon in the discussion section. The volume value caused by the uplift signal is small compared to that calculated by subsidence. Thus, the revised manuscript no longer provides the estimated volume considering two extreme situations.

4) Figure 4: The seasonal cycle of lake level looks strange. Please check your data and compare with other studies.

Thank you for the comment. The lake level data has been checked and examined. In the previous manuscript, the mask used to extract the ICESat-2 measurements located in the lake is the lake extent of 2020. To avoid some unstable values in the lake shores of the year 2018 and 2019, in the revised manuscript, we used the water mask of the corresponding year. The tracks of ICESat-2 in each year were presented in Fig. 4(a)-(c) as follows.

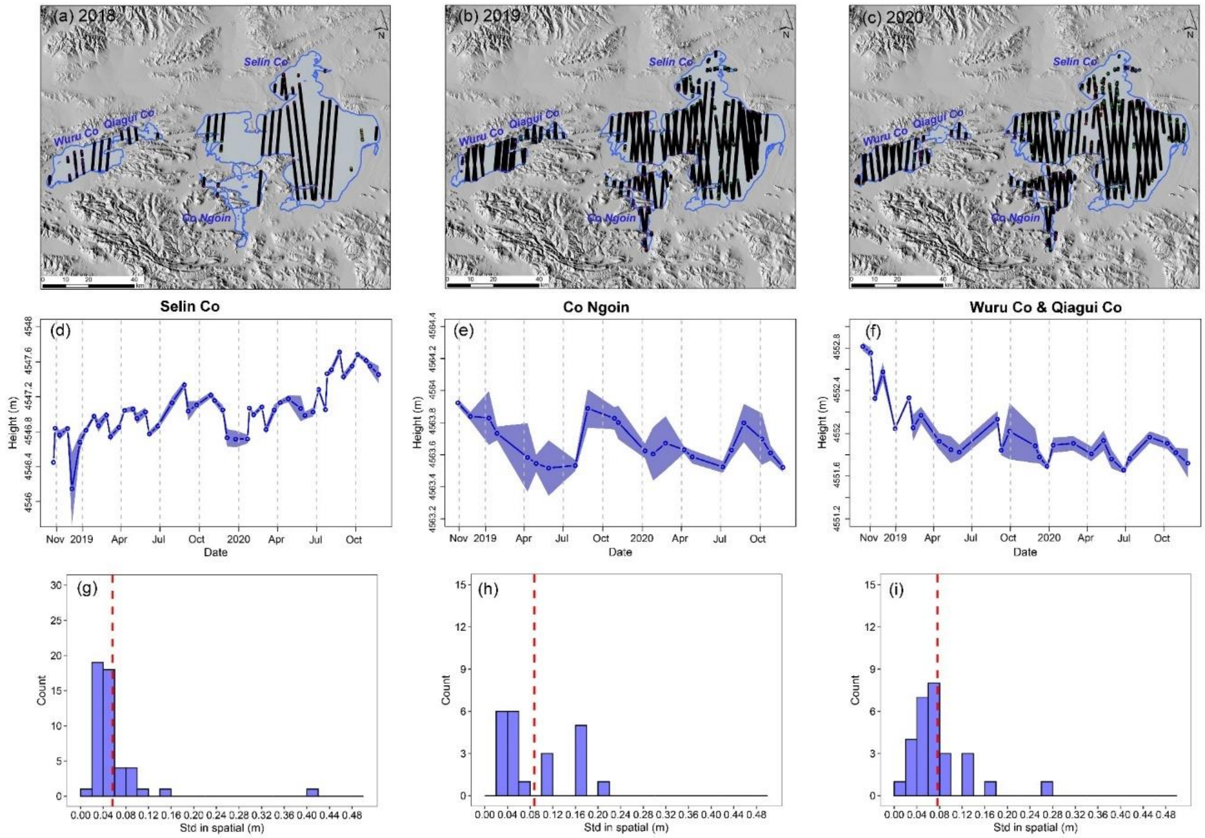

Figure 4 Water surface elevations of the three lakes. Subfigures (a)-(c) show tracks of the elevation measurements for each year. Sufigures (d)-(f) show the ICESat-2 derived elevations. The solid lines indicate the average values of all elevation measurements within the lake on a given date. The light-colored areas show the mean ± one standard deviation. Subfigures (g)-(i) further show histograms of the standard deviations of the water surface elevation of the lake from all acquisition dates. The Red dashed line indicates the mean value.

The Co Ngoin shows a clear periodic seasonal cycle in which the lake level was low during April-July and high during September-November. Wuru Co & Qiqgui Co also illustrate that the water level is higher in September-October than in the other months. The possible explanation might be the strong evaporation during April-August reduced water level. Although the water level of Selin Co fluctuates a lot, it also manifests some trend that the water level increases from July to October. It also reveals the pattern stated in other studies that the Selin Co's water level reaches a stable maximum during October and November.

5) Table 6: How the surface water elevation for each year was decided? The mean or level in a month was used/selected? The column of velocity is no value and can be removed.

Thank you for the comment. To be clear, we have stated in the revised manuscript that the surface water elevation listed in Table 6 was the averaged value of all elevation measurements of the lake within each year. In the revised manuscript, the mean ± one standard deviation of all elevation measurements of the lake within the year were listed in Table 6. The tracks of ICESat-2 elevation measurements are shown

6) The English writing of this manuscript need improve. It is better to polish by a native English speaker. For example, Line 375, too many "them had amplitudes" was used.

Thank you for the suggestion. The language has been polished.

Specific comments:

- Serling Co lake to Serlin Co throughout, not include lake as Co means lake in Tibetan.

Thank you. We have modified it throughout the manuscript.

- "increases in precipitation and glacial melting are not enough to explain the increased water volume of lake expansion" How to understand this? The previous studies have closed the lake water balance.

To be clear, we have stated in the Abstract that "Selin Co, located within permafrost regions surrounded by glaciers, has exhibited the greatest increase in water storage among all the lakes on the Tibetan Plateau over the last 50 years. Most of the increased lake water volume has been attributed to increased precipitation and the accelerated melting of glacier ice, but these processes are still not sufficient to achieve the water balance with the expansion of Selin Co. Ground ice meltwater released by thawing permafrost due to continuous climate warming over the past several decades was regarded as another source of lake expansion."

Although the contribution of each item (precipitation, glacier meltwater, permafrost meltwater, evaporation) could be estimated from the model perspective (Zhang et al., 2017), there is still ambiguities of water balance from the monitoring perspective and the water balance is at stake.

According to the work of "Limited contribution of glacier mass loss to the recent increase in Tibetan Plateau lake volume, Brun, F., Treichler, D., Shean, D., & Immerzeel, W. W. (2020). Frontiers in Earth Science, 8, 495. DOI: 10.3389/feart.2020.582060" recommended by the reviewer, in Selin Co basin the water excess considering the changes in the lake and glacier water storage is 34.8 ± 3.4 mm/yr, and Δ (Precipitation-evapotranspiration) is 15 mm/yr.

In recent years, the contribution from the glacier has become much clear. Then the uncertainties mainly come from quantifying the contribution of increasing precipitation and thawing permafrost. The quantification of increasing precipitation contribution is still challenging. The accurate monitoring of precipitation/snow in TP is challenging work without reliable measurement.

- Line 20: the long-term, I do not suggest to use this as the short study period.

Thank you very much for the comment. The word has been replaced with “cumulated settlement” in the revised manuscript.

- Line 35: Tibetan Plateau to Tibetan Plateau (TP), and use TP thereafter.

Thank you. They have been corrected through the manuscript.

- Line 35: 1000 lakes, 40,000 km2, please use new values.

Thank you.

Based on the newest reference of “Zhang, G., Ran, Y., Wan, W., Luo, W., Chen, W., Xu, F., & Li, X. (2021). 100 years of lake evolution over the Qinghai–Tibet Plateau. Earth System Science Data, 13(8), 3951-3966.” that “The Qinghai–Tibet Plateau has ∼ 1200 lakes larger than 1 km^2 with a total area of ∼ 46 000 km^2… The QTP includes 87 % of the lakes of the TP and 92 % of their area”.

Accordingly, we have modified the statement as “More than 1200 lakes on the Tibetan Plateau (TP) span an area exceeding 1 km^2, and the total lake area is greater than 46000 km^2 (Zhang et al., 2021b)”

- Line 40: lake area and volume increase to 2017, please use the value from new published paper updated to 2019

Thank you for the suggestion. The values have been updated, and the sentence has been modified as “In particular, Selin Co (also known as Siling Co, Serlin Co, and Serling Co) exhibited the greatest increases in both lake area and water storage: its lake area expanded by ~40% from ~1700 km^2 in 1972 to ~2400 km^2 in 2020, and its water storage increased by 80% from 309.4×10^8 m^3 in 1972 to 558.4×10^8 m^3 in 2017 (Zhu et al., 2019b; Zhang et al., 2021b).”

- surpassed Nam Co lake in 2014, it is about 2011, please check new published paper, and include the citation.

Thank you for the comment. We checked the lake area of these two lakes during 2005–2013 in the lake data sets and the relevant literature (Zhang et al., 2021; Bian et al., 2010)”, and found that 2001-2005 might be the period of surpassing Nam Co. In the manuscript, the sentence has been modified as “Its lake area surpassed that of Nam Co in the early 2000s (Zhang et al., 2021b; Bian et al., 2010); consequently, Selin Co is now the second largest saltwater lake in China. Such rapid changes in Selin Co have significantly affected the regional environment and have thus attracted substantial interest within the scientific community.

- Line 45: For the statistics of glacier number and area, please use the data from the second China glacier inventory.

Thank you for the comment and suggestion.

The numbers have been calculated and updated according to the second China glacier inventory in the revised manuscript. It has been revised as "The entire Selin Co watershed covers a drainage area of 4.4×10^4 km^2, 18 times the lake surface. The entire watershed hosts 299 glaciers with a total area of 369.7 km^2 and ice reserves of 27.9 km^3 based on the second Chinese glacier inventory (Guo et al., 2015; Liu et al., 2012b)"

- the ground ice volume in the watershed reaches 132.3 km3 (Zhao and Sheng, 2019). How about the value compared with Farinotti et al. (2019) (doi: 10.1038/s41561-019-0300-3)?

Thank you very much for the literature.

Based on the dataset published in the work "Farinotti, D., Huss, M., Fürst, J. J., Landmann, J., Machguth, H., Maussion, F., & Pandit, A. (2019). A consensus estimate for the ice thickness distribution of all glaciers on Earth. Nature Geoscience, 12(3), 168-173.", the Selin Co basin has 377 glaciers with a total area of 289.1 km^2 and ice volume of 21.8 km^3. Based on the second Chinese glacier inventory (Guo et al., 2015; Liu et al., 2012), the glacier ice volume is 27.9 km^3. The two numbers both indicate that the ground ice volume is about five times the glacier ice volume.

In the revised manuscript, we have included the number of glacier ice volume from Farinotti et al. (2019) and the ratio number with ground ice. It is stated as follows "The entire Selin Co watershed covers a drainage area of 4.4×10^4 km^2, 18 times the lake surface. The entire watershed hosts 299 glaciers with a total area of 369.7 km^2 and ice reserves of 27.9 km^3 based on the second Chinese glacier inventory (Guo et al., 2015; Liu et al., 2012b); additionally, according to the new estimation by (Farinotti et al., 2019), the glacier volume reaches 21.8 km^3 in the watershed…the ground ice volume in the watershed reaches 132.3 km^3 (Zhao and Sheng, 2019), approximately five times the glacier ice volume in the Selin Co watershed."

- glacial meltwater contributed ~ 10% of the total water input to Serling Co lake since the 1970s (Lei et al., 2013; Tong et al., 2016). The two other studies (doi: 10.3389/feart.2020.582060; doi: 10.1016/j.scitotenv.2021.145463) for the estimates could be included for comparison together.

Thank you very much for providing these two new studies.

Study "Zhang, G., Bolch, T., Chen, W., & Crétaux, J. F. (2021). Comprehensive estimation of lake volume changes on the Tibetan Plateau during 1976–2019 and basin-wide glacier contribution. Science of the Total Environment, 772, 145463. DOI: 10.1016/j.scitotenv.2021.145463" revealed that during 2000-2015, the glacier contribution for Selin Co is ~8.2%.

Study "Brun, F., Treichler, D., Shean, D., & Immerzeel, W. W. (2020). Limited contribution of glacier mass loss to the recent increase in Tibetan Plateau lake volume. Frontiers in Earth Science, 8, 495. DOI:

10.3389/feart.2020.582060" revealed that during the 2000s and 2010s, the glacier contribution for Selin Co is 8 ± 3%.

The sentence has been rephrased as follows "In addition, recent research has revealed that glacial meltwater has contributed ~ 10% of the total water input to Selin Co since the 1970s (Lei et al., 2013; Tong et al., 2016; Brun et al., 2020; Zhang et al., 2021a)."

- The weakening of lake evaporation has also contributed to the accelerated expansion of Serling Co lake. It is really weaking? It should be increasing as the warmer air temperature, and some studies have corrected this by Nam Co or different study period?

The statement is based on the work "Guo, Y., Zhang, Y., Ma, N., Xu, J., & Zhang, T. (2019). Long-term changes in evaporation over Siling Co Lake on the Tibetan Plateau and its impact on recent rapid lake expansion. Atmospheric research, 216, 141-150." This work found that "during the studying period of 1961–2015, the temporal variations in lake evaporation can be divided into three periods as follows: a significant increasing trend (12.3 mm yr-1) during the period 1961–1984, a significant decreasing trend (-10.2 mm yr-1) during the period 1985–2006, and a slightly increasing trend (4.3 mm) during the period 2007–2015. During the period of significant expansion of Siling Co Lake from 1972 to 2010, lake evaporation presented a significant decreasing trend (-4.7 mm yr-1)." The main factors that controlled the changes in evaporation were wind speed for the period 1961–2006. That explains although the air temperature is continuously increasing, the evaporations have variations.

To be clear, in the revised manuscript, we have rephrased the sentence to "The weakening of lake evaporation during 1972–2010 due to decreasing wind speeds also contributed to the accelerated expansion of Selin Co to some extent, but this contribution was reported to be very small (Guo et al., 2019)."

- Table 2. Ele. (m) to Ele. (m a.s.l.)

Corrected.

- Line 245: ERA-5 reanalysis data, how about ERA-6 data? It is better?

ERA5 is the fifth generation ECMWF atmospheric reanalysis of the global climate. The production of the next full-observing-system reanalysis, ERA6, is planned to start by 2023 according to the newsletter of ECMWF. The accurate description of vertical profiles of temperature, pressure, and water vapor partial pressure is good for the accurate estimation and correction of tropospheric delay in InSAR phase. When good atmospheric data is not available, if SAR acquisitions are adequate and interferogram pairs have some redundancy, the tropospheric disturbances could also be removed in a certain way by spatial filtering and time series inversion during the multi-temporal InSAR processing and this is the advantage of multi-temporal InSAR processing compared to D-InSAR.

- Line 445: compared to the values recorded in previous studies. The references are necessary.

The references have been added to the revised manuscript. We also took the reviewer's suggestion of including a comparison (lake level/volume changes) in the discussion. The contents are presented in Figure 10.

- Line 515: "in the northern two" to "in the two northern"

Corrected.

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