Hydrol. Earth Syst. Sci. Discuss., referee comment RC1 https://doi.org/10.5194/hess-2022-179-RC1, 2022

Comment on hess-2022-179

Anonymous Referee #1

Referee comment on "Characterizing four decades of accelerated glacial mass loss in the West Nyainqentanglha Range of the Tibetan Plateau" by Shuhong Wang et al., Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2022-179-RC1, 2022

The manuscript quantified changes in glacier area, surface elevation and mass balance in the WNT over the past 44 years and investigated associated influence factors over 1976-2000 and 2000-2020, based on multi-source remote sensing datasets. It is important to well understand the importance of glacier changes and associated impacts in the WNT, where these glaciers play a critical role in regulating regional water resources through supplying meltwater to the densely populated Lhasa River basin and Nam Co. Overall, the science of the manuscript is very interesting, and the structure and writing of the manuscript are good, but there are some issues the authors should be considered.

Response: Many thanks for the positive comments and suggestions. We have addressed the reviewer's concerns and suggestions carefully. In the following, we provide point-by-point response to each reviewer comment (blue texts are our responses, while black texts are original comments). Note that we have also modified the color scales for some figures to meet the journal's requirement.

- The key purpose of this study is to provide an internally consistent dataset of glacier area and mass change in the WNT over the past 44 years. What is your purpose for obtaining this dataset? It should be the hydrological impacts of glacier changes in the basin. However, there is no discussion on hydrological impacts of glacier changes on water resources of the basin or Nam Co, so the authors can consider some discussion about the influence of glacier change on hydrology in the WNT. It is very important for the manuscript, also for HESS.

  Response: Many thanks for theses queries and suggestions. We agree that our motivation for compiling this dataset was to evaluate the hydrological effect of glacier changes on water resources downstream, and we have now added further information to section2.2.6 (Hydrological Data) and 4.4 (Hydrological Effect) as follows.

  Added to section 2.2.6:

  In order to assess hydrological changes under glacier retreat, we have collected runoff data of the Lhasa River station during 1976-2013 and the Yangbajain station during 1979-2013 from the Tibet Autonomous Region Hydrology and Water Resources Survey Bureau.

  We calculated the ratio of total glacier mass change to runoff in Lhasa River basin (R_r, %) and the total lake water storage change of Nam Co Lake (R_l, %) as follows:

$$R_\mathrm{r} = \frac{\Delta M * S_g}{S_r R_a} \qquad (9)$$

$$R_l = \frac{\Delta M * S_g}{\Delta V} \qquad (10)$$

Where ΔM, S_g, S_r, R_a, ΔV represent average annual glacier mass balance, glacier area, area of the Lhasa River basin, average runoff depth, lake water storage increase.

Added to section 4.4:

The glacier melt contribution to streamflow decreases significantly from the glacier terminus to the lowlands as it becomes diluted by other water sources (Kaser et al.,2010; Lutz et al., 2014; Pritchard, 2019) and this is reflected in our finding that the average annual glacier mass loss during 1976-2014 (-0.26±0.14 m w.e.a^{-1}) equates to 8.5±4.6% of the mean annual runoff depth for the Yangbajain basin, in the upper reaches of Lhasa River (location shown in Figure 1(a)), but only 1.6±1.0% for the Lhasa Riber basin as a whole.

Through this period, the annual runoff in the Yangbajain basin showed a significant increase trend of 1.32 mm a^{-1} and the Lhasa River basin a non-significant increase trend of 0.84 mm a^{-1} (Figure S4). Increasing runoff may in part be explained by a coincident 1.36 mm a^{-1} increase in precipitation observed over the Lhasa River basin (Figure 11(b)), though the glacier ablation increase in Lhasa River basin and Yangbajain basin (4.63±2.49 mm a^{-1} and 23.52±12.67 mm a^{-1} respectively) were substantially greater than the increase in precipitation, and evaporation losses from glacier melt water tend to be substantially smaller than those from evaporation of precipitation over the basin (Pritchard, 2019), suggesting that increased glacial meltwater primarily drove increased runoff. This is supported by Lin et al. (2020) who attributed increase streamflow at Yangbajain Station to accelerated glacier retreat, and Wang et al. (2021) who argued that glacier melt has increased its contributions to the surface runoff by 12%–43% among the sub-basins of the Yarlung-Zangpo River basin (the mainstream of Lhasa River) after 1997.

Some components of basin hydrology remain poorly observed, however we note that the combined increase in precipitation and ablation detailed above was much notably greater than the observed increase in runoff especially in the Yangbajain, a discrepancy that due to some combination of increased residential, industrial or agricultural water use (Pritchard, 2019), increased evaporation (Han et al., 2021), and possible deep seeps in upper Lhasa River (Lin et al., 2020).

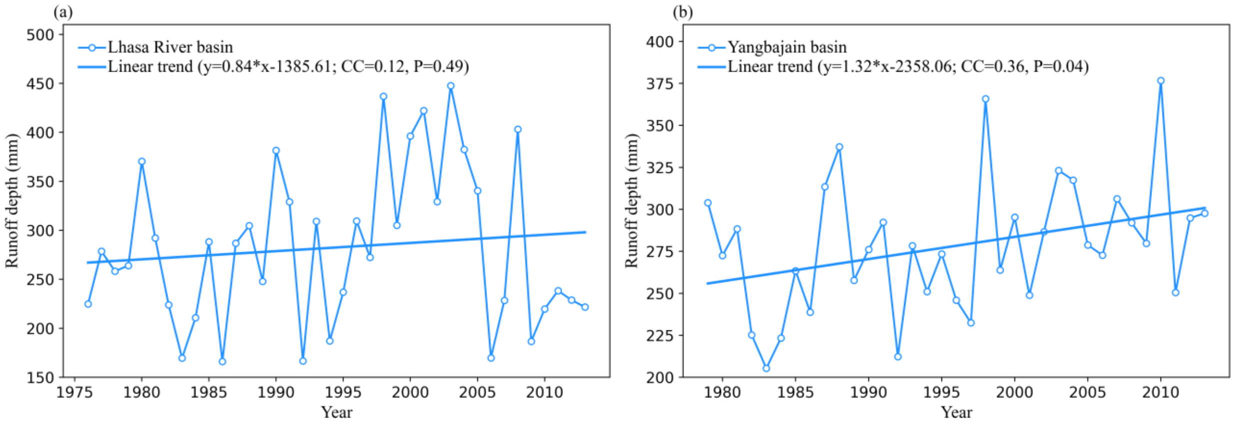

Figure S4 Variations in the annual runoff of (a) Lhasa River basin and (b) Yangbajain basin.

In the Nam Co basin, increase glacier runoff also appears to have been important in controlling the level of Nam Co Lake. The Nam Co basin glacier mass balance (0.32±0.16 m w.e.a^{-1}) that we find for 1976-2014, equates to 30.9 ± 15.4% of the reported increase in Nam Co Lake water storage (Zhang et al., 2011). This glacier contribution is comparable to previous estimates of 52.9% for the 1971-2004 period (Zhu et al., 2009), 28.7% for 1999-2010 based on a mass balance of 0.59 m w.e.a^{-1} (Zhadang glacier) (Lei et al., 2013), 10.50 ± 9.00% for 2003-2009 by based on a mass balance of -0.27±0.13 m w.e. a^{-1} (Li & Lin (2017), and 17.5±7.6% for 2000-2014 based on a mass balance of -0.32 m w.e. a^{-1} (Ke et al., 2022). Differences in these contributions of glaciers to increases in lake level reflect differences in the time periods studied and variability in the rate of change in the lake. For example, Ke et al. (2022) reported that their average lake level change of (0.26 ± 0.04 m a^{-1} for, 2000s–2014,) is substantially higher than 0.14± 0.18 m a^{-1} for 1994–2015 reported by Brun et al. (2020).

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Zhang, B., Wu, Y., Zhu, L., Wang, J., Li, J., & Chen, D.: Estimation and trend detection of water storage at Nam Co Lake, central Tibetan Plateau, J Hydrol, 405(1-2), 161-170, 2011.

Zhu, L., Xie, M., & Wu, Y.: Quantitative analysis of lake area variations and the influence factors from 1971 to 2004 in the Nam Co basin of the Tibetan Plateau, Chinese Sci Bull, 55(13), 1294-1303, 2010.

- Glacier outlines: Chinese Glacier Inventory (CGI) I and CGI II are available now. The authors generated new glacier boundaries of this region in the years of 1976, 2000, 2014 and 2020 from Landsat images obtained from various years. How about the differences between your results and previous datasets? What is the main reason why generate a new dataset? The authors may add some discussion or analysis in the manuscript or supplementary material.

  Response:

  The Chinese Glacier Inventory (CGI) I and CGI II of WNT represent extents in 1970 and 2009, so the time interval between the two periods of glacier inventories is relatively long. We wanted to show the process of glacier retreat under climate change. KH-9 (1976), SRTM (2000), and Aster Dems (2000-2020) are available in this area, this gave us a chance also to analyze the character of glacier thickness change for the 1976-2000 and 2000-2020 periods. Therefore, we extracted the areal extents of the same years 1976, 2000, 2020 to analyze changes in area and thickness together. Additionally, the glacier area in 2014 was extracted to test whether mass loss accelerated after 2014.

  In section 4.1.1, we have now added a comparison of glacier area in our study with the Chinese Glacier Inventory (shown in Table S3). The CGI II of WNT in 2009 are in good agreement with the areal retreat trend in our study (also shown in Figure 2). The CGI I of WNT in 1970 is slightly smaller than the glacier area in 1976 in our study, but it is within the margin of error. The CGI I was mapped based on the Chinese topographic maps, while glacier area in our study was mapped based on Landsat Images. The difference between them might come from this difference in data source used to extract the glaciers outlines. Besides, Frauenfelder & Kääb, (2009) reported that there are georeferencing errors in the areas in GGI I.

Table S3 Comparison of glacier area in this study with the Chinese Glacier Inventory

	Glacier Area (km^2)					
	1970	1976	2000	2009	2014	2020
Chinese Glacier Inventory	882.44	-	-	675.71	-	-
This study	-	884.90±29.71	770.03±33.44	-	648.55±30.88	589.17±31.72

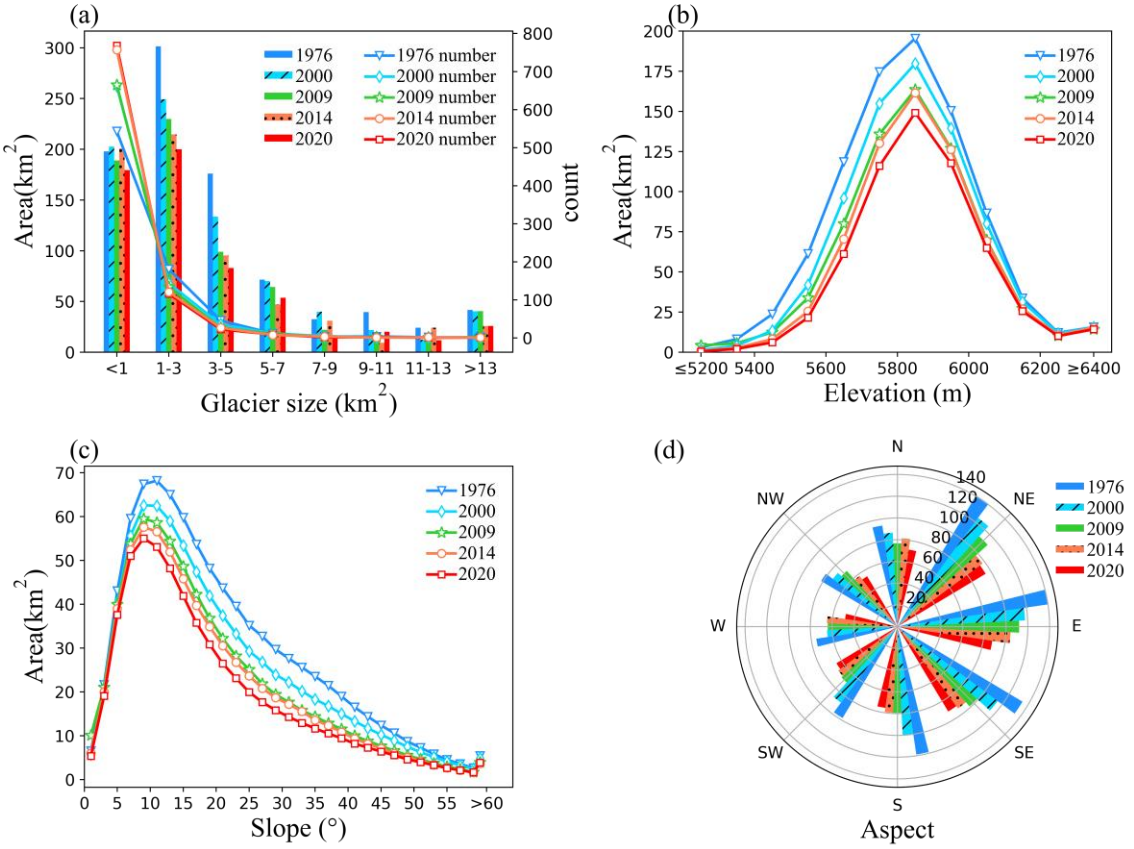

Figure 2 Glacier distribution in the WNT in 1976, 2000, 2009, 2014 and 2020. (a) Number and area of glaciers by size category. (b) Distribution of glacier area with altitude. (c) Distribution of glacier area with slope. (d) Distribution of glacier area with aspect. Data in 2009 came from Chinese Glacier Inventory II.

Frauenfelder, R., & Kääb, A.: Glacier mapping from multi-temporal optical remote sensing data within the Brahmaputra River Basin, In Proceedings of the 33rd International Symposium on Remote Sensing of Environment, 4-8, 2009.

- Meterological data: Please give the elevations of these meterological stations used in the manuscript.

  Response:

  There are three meteorological stations adjacent to the WNT, at Bange (31°23′N, 90°01′E, elevation of 4700 m), Lhasa (29°40′N, 91°08′E, elevation of 3648 m), and Damxung (30°29′N, 91°06′E, elevation of 4200 m).

  We have added these details to Section 2.2.5. (Meteorological data) in the manuscript.

- As shown in Table 3, the area of debris cover and lake terminating decreases between two periods, but thinning increases. Why? In particular, some current studies confirmed that the spatial expansion and thickening of the debris layer have been observed on different debris-covered glaciers with glacier shrinkage and sustained mass loss (e.g., Stokes et al., 2007; Kirkbride and Deline, 2013; Tielidze et al., 2020; Xie et al., 2020). Just as a matter of interest, what is the reason leading to the reduction of debris cover on glaciers of this region? In addition, between two periods, glacier number increases from 617 and 692 with an area decreasing. What happened?

  I didn't get a clue in glacier velocity that would answer that question, so I answered the question as follows.

  Response:

  We are sorry for the mistake we made. The debris cover and lake terminating in Table 3 referred to debris-covered glaciers and lake-terminating glaciers. We have revised the Table 3 and the corresponding descriptions in the manuscript including, Figure 1 and 9.

  The area of debris-covered glaciers and lake-terminating glaciers decreased, while surface lowering also accelerated, mainly driven by the continuous increase in temperature in the WNT region during 1976-2000, especially after 2014 (Figure 11 and Figure 12). In terms of the number and area of lake-termination, we identified glacier-marginal lakes as those lying within 50 m of a glacier boundary. As glaciers retreat, the distance between the end of the glacier and their proglacial lake increased, and some of lake-terminating glaciers in 1976 no longer belonged to lake-terminating class in 2000. This helps for explain the area decreased for this glacier class in Table 3.

  For debris-covered glaciers, the area of debris cover actually increased from 6.60±1.15 km^2 in 1976 to 7.37±1.48 km^2 in 2020 in our study (Table S6, new added), and we note that this is not necessarily inconsistent with an overall glacier retreat. This is because increased melt rates that lead to surface lowering drive retreat of the glacier front, while also promoting a greater concentration of debris on the wider surface of glacier ablation area as more debris melts out from ice below. A spatial expansion of the debris layer has, for example, been observed on different debris-covered glaciers during retreat and sustained mass loss. (Stokes et al., 2007; Kirkbride & Deline, 2013; Tielidze et al., 2020; Xie et al., 2020). Unfortunately, no data are available to changes in the change of the thickness of the debris cover itself, and we assume that all glacier thickness changes resulted from loss of ice, without considering the thickness change of the debris cover layer. We think that this is reasonable in because in most area, debris layers are typically thin (order of 1 meter or less) and compared to elevation changes we map, and because most debris cover in the ablatio area emerge from englacial transport rather than direct deposition by new, local rock fall(e.g., McCarthy et al. 2017), so changes in the debris-layer thickness represent a redistribution of existing glacier volume, not a change in volume. We have now modified Section 4.2 (The influences of debris-cover and proglacial lakes on glacier mass changes) in the manuscript.

Table S6 Area changes of debris cover over the WNT from 1976 to 2020

1976 Area(km^2)	2000 Area (km^2)	2020 Area (km^2)	1976-2000 △Area (% a^{-1})	2000-2020 △Area (% a^{-1})	1976-2020 △Area (% a^{-1})
6.60±1.15	6.90±1.34	7.37±1.49	0.20±1.12	0.28±1.45	0.24±0.65

The reason for the increased glacier number but decreased area is that intact glaciers break down into several smaller glaciers in the process of glacier ablation, e g., a large glacier in 1976 may become several smaller glaciers in 2020 (shown in Figure S3). We have added a comment on this to Section 3.1 (Glacier area change).

Kirkbride, M. P., & Deline, P.: The formation of supraglacial debris covers by primary dispersal from transverse englacial debris bands, Earth Surf Process Landf, 38(15), 1779-1792, 2013.

McCarthy, M., Pritchard, H., Willis, I. A. N., & King, E.: Ground-penetrating radar measurements of debris thickness on Lirung Glacier, Nepal, J Glaciol, 63(239), 543-555, 2017.

Stokes, C. R., Popovnin, V., Aleynikov, A., Gurney, S. D., & Shahgedanova, M.: Recent glacier retreat in the Caucasus Mountains, Russia, and associated increase in supraglacial debris cover and supra-/proglacial lake development, Ann. Glaciol, 46, 195-203, 2007.

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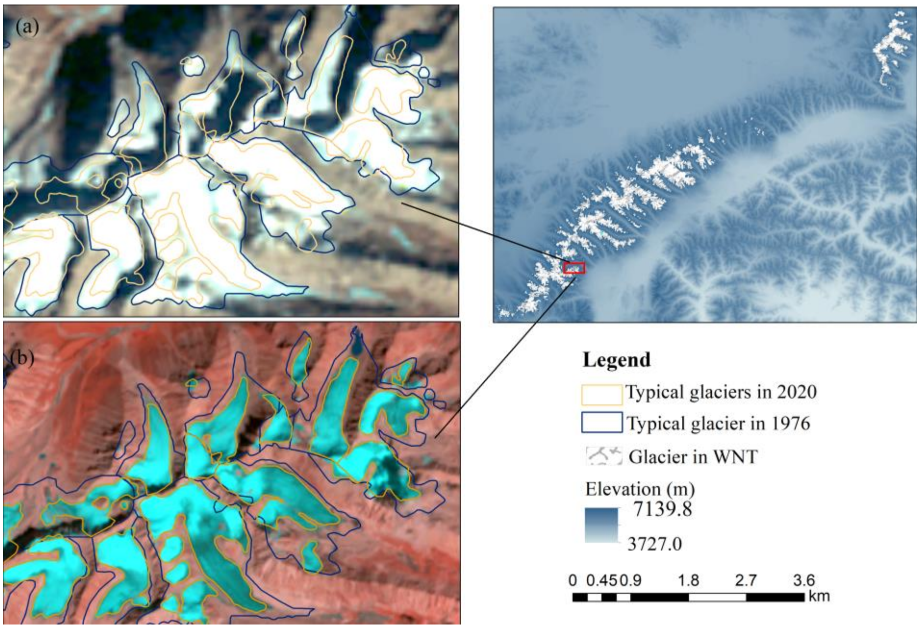

Figure S3 Large glaciers break down into several smaller glaciers due to retreat. (a) Glaciers in Landsat MSS images from 1976-12-17. (b) Glaciers in Landsat 8/OLI images from 2020-09-29 (false-color composite of bands 7, 5, 4 for R, G, B).

- The manuscript analyzed glacier area change and surface elevation change for the periods 1976-2000 and 2000-2020, how about the total changes in glacier area and surface elevation change between 1976-2020? The authors may add two figures in the manuscript or supplementary material that show changes between 1976-2020.

  Response: We thank the reviewer for this suggestion, and we find that for 1976-2020, the mean glacier areal retreat rate in the WNT is -0.76± 0.11% a^{-1} and surface lowering is -0.37 ±0.13 m a^{-1} (equal to a water-equivalent loss rate of -0.31 ± 0.12 m w.e. a^{-1} or a mass loss rate of -0.26 ± 0.09 Gt a^{-1}). We have added the area change of 2000-2020 in Figure 3, and surface change during 1976-2020 in Figure 5 and the corresponding description in line 235 and 252-253.

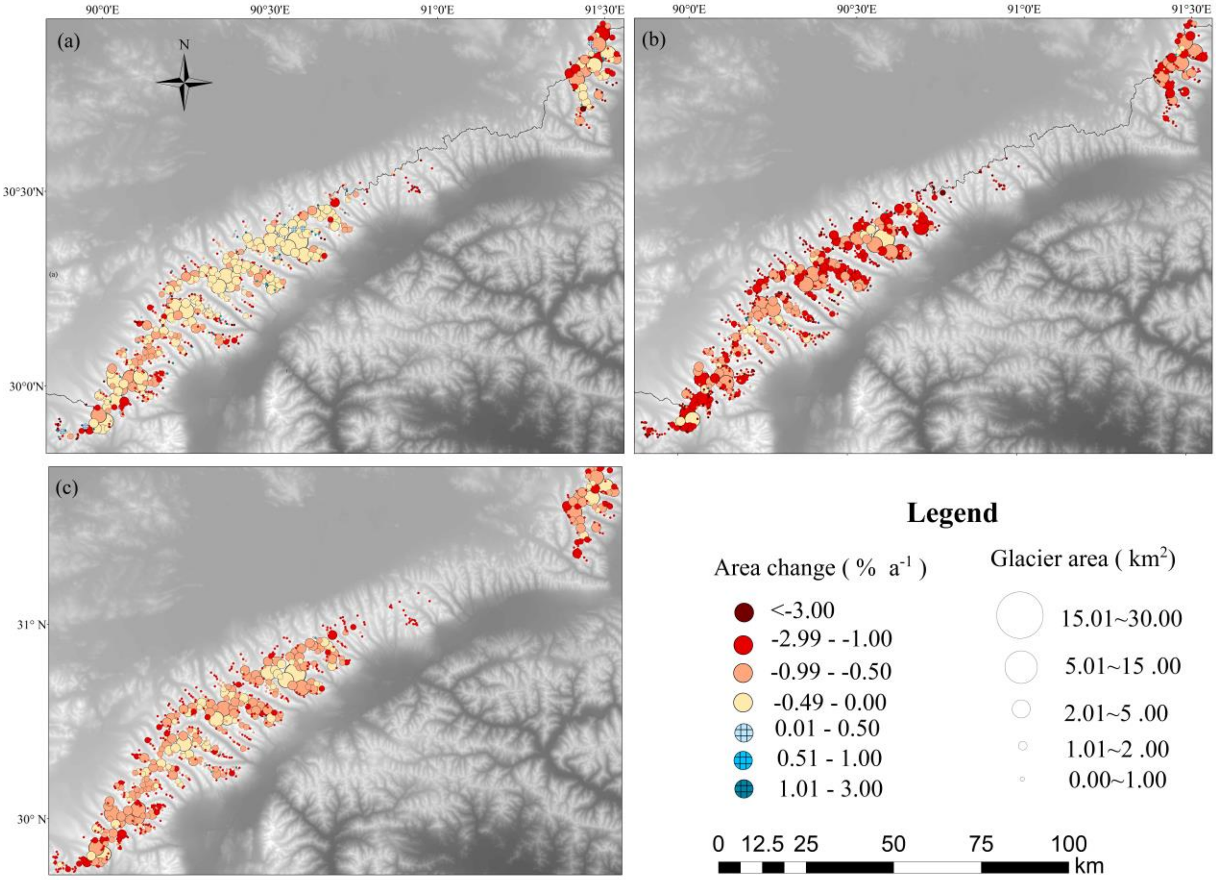

Figure 3 The distribution of glacier area change in the WNT from (a) 1976 to 2000, (b) from 2000 to2020, (c) 1976 to 2020.

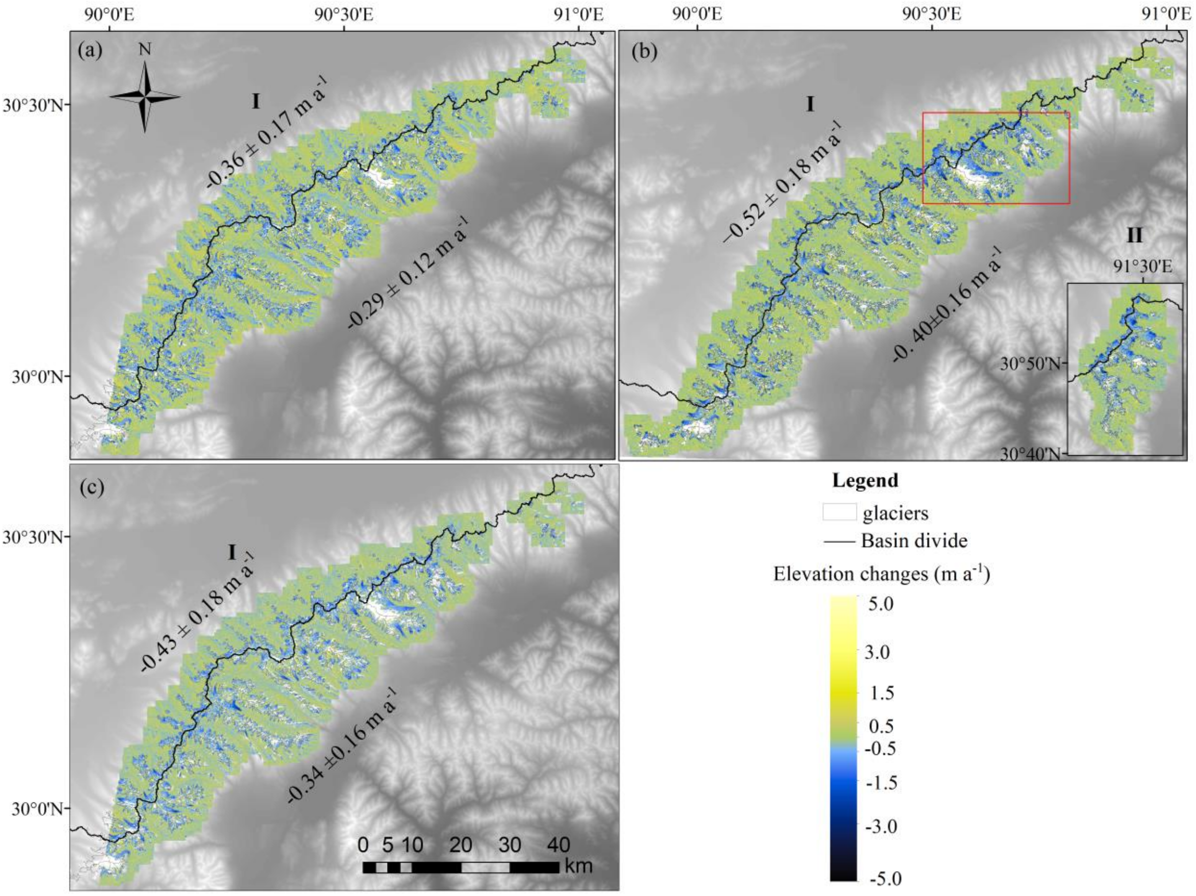

Figure 5 Mean annual glacier surface elevation changes in the WNT from (a) 1976 to 2000, (b) 2000 to 2020, and (c) 1976-2020. Label I in (a, b, c) represents the SW section and label II in (b) represents the NE section of the WNT (on the same scale). The red rectangular box in (b) shows an area of the centra WNT referred to in the paper.

- Minor comments:

1) Figure 1: Debris-cover is debris cover, Debris-cover glaciers is Debris-covered glaciers, and other glaciers is right?

Response: Actually, ‘Other glacier’ in Figure 1 corresponded to what we called ‘Regular glaciers’ in the text, and we have now corrected the terminology in Figure 1.

We have also corrected ‘Debris-cover’ to ‘Debris cover’, and ‘Debris-cover glaciers’ to ‘Debris-covered glaciers’.We have also added an inset map to show the relative positions of the glaciers in the WNT, Lhasa River basin, and Nam Co basin. [Revised Figure 1].

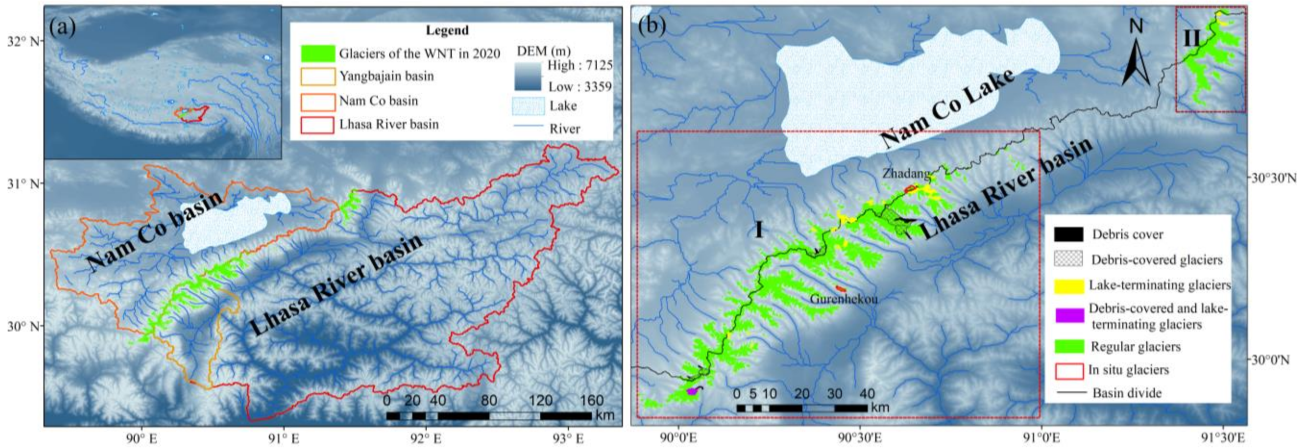

Figure 1 (a) Overview of study area. (b) Glacier distribution. Label I in the large, red dotted rectangle represents the SW section of the WNT and Label II in the small, dark red dotted rectangle represents the NE section.

2) Some units should be superscript.
Response: Thanks, we have corrected these accordingly.

3) Some References cited in the manuscript are missing in the Reference list. Please carefully check.
Response: We have now checked these and added the missing references.