Characterizing four decades of accelerated glacial mass loss in the West Nyainqentanglha Range of the Tibetan Plateau

Hi, Professor Pritchard, I switched the order of the second and third paragraphs and want to delete the red words. The text in blue is my new addition.

Abstract:

Glacier retreat is altering the water regime of the Tibetan Plateau (TP) as the region's climate changes, but there remain substantial gaps in ~~quantification~~ our knowledge of recent ~~regional~~ glacier loss in this region due to the difficulty of making~~-~~ direct high-mountain observations and this limits our ability to predict the future of this important water resource. Here, we assess 44 years of glacier~~s~~ area and volume change~~s~~ in the major West Nyainqentanglha Range (WNT) that supplies meltwater to the densely populated Lhasa River basin and Nam Co, the second largest endorheic lake on the TP. Between the two periods 1976-2000 and 2000-2020, ~~and compared the effects of topography, debris-cover and proglacial lake on glacier change during 1976-2000 and 2000-2020 in the West Nyainqentanglha Range (WNT) that supply meltwater to the densely populated Lhasa River basin and Nam Co, the second largest endorheic lake on the TP. We mapped glacier extent in 1976, 2000, 2014, and 2020 based on Landsat MSS/ETM+/OLI scenes and quantified changes in ice thickness during the intervals 1976-2000 and 2000-2020 using declassified KH-9 images, the Shuttle Radar Topography Mission DEM (2000), and modern stereo satellite imagery.~~we find that ~~Results show that~~ the glacier areal retreat rate more than doubled ~~between the periods 1976-2000 and 2000 to 2020, (~~from -0.54 ± 0.21 % a^{-1} to -1.17 ± 0.30 % a^{-1}~~.~~) and ~~Similarly, the glaciers experienced an~~ surface lowering also accelerated~~ion in surface lowering (, with thickness change of~~ from -0.26 ± 0.09 m w.e.a^{-1} ~~increasing~~ to -0.37 ± 0.15 m w.e.a^{-1} ~~between these two~~

~~periods,~~), with particularly intense melting after 2014. This acceleration is similar in both timing and magnitude to that observed for Himalayas glaciers farther south. ~~This supports previous less comprehensive studies that indicated accelerating mass loss.~~ To understand the sensitivity of WNT glaciers to climate forcing, we examine the effects of topography, debris-cover and the presence of proglacial lakes on our observed changes. We find consistently faster areal retreat but slower thinning rates on ~~On average,~~ steeper slopes ~~were associated with faster areal retreat but slower thinning rates~~, and an inconsistent relationship with ~~while the influence of~~ aspect.~~ on retreat and thinning was inconsistent through tim~~ We conclude that~~e.~~ ~~T~~our observed~~he~~ spatial and temporal ~~heterogeneity of glacier~~ patterns of glacier change ~~can~~ are ~~likely be explained~~ dominated by observed local variations in precipitation and temperature ~~in this region~~, ~~an apparent reduction in~~ the melt-reducing role of supraglacial debris ~~cover~~, and ~~an~~ the increasing influence of ice-~~-~~marginal lakes on glacier retreat.

1. Introduction

The Tibetan Plateau (TP) known as the “Water Tower of Asia”, is the source of several of Asia’s major rivers (Bolch et al., 2010) and glacial melt on the TP plays an important role in water supply for downstream populations, agriculture and industries along these rivers (Pritchard, 2019; Viviroli et al., 2007). Climate change over recent decades has boosted river discharge by increasing runoff from shrinking glaciers (Lin et al., 2020; Yao et al., 2007; Zhang et al., 2011), but this boost will eventually decrease as glacier area declines (Zhao et al., 2019). The sensitivity of ice loss to climate change is variable, however, and often poorly known, being a function of glacier size, hypsometry, aspect, debris cover, and the presence of proglacial lakes and ice cliffs, for example. Combined with uncertainties in ice thickness and future climate scenarios, the timing of peak water runoff and the rate of its subsequent decline remain key unknows (Maurer et al., 2019; Nie et al.,2021; Su et al., 2016; Zhao et al., 2019). It is therefore critical to monitor and analyze glacier change to improve our understanding of its climate drivers, and to assess its impacts on glacier-fed river basins.

Compared with the interpolation of sparse in-situ measurements, satellites can observe glacier change over much larger areas of remote terrain (Wang et al., 2021). In recent years, our understanding of the state of TP glaciers has been greatly improved by the increasing coverage and accuracy of multi-source remote sensing observations of glacier area, volume and mass change from KH-9 (Hexagon military satellites), Landsat, ASTER, ICESat altimetry, and other Digital Elevation Models (DEMs) constructed by geodetic techniques, and from GRACE gravimetry (Guo et al., 2015; Kääb et al., 2012; Wang et al., 2021; Zhou et al., 2018). Based on the KH-9 images and SRTM, for example, Zhou et al. (2018) found that from the mid-1970s to 2000, glaciers in the northwest TP thinned at −0.11 ± 0.13 m w.e. a^{-1} to 0.02 ± 0.10 m w.e. a^{-1} while those in the southeast part thinned faster at −0.30 ± 0.12m w.e. a^{-1} to −0.11 ± 0.14m w.e. a^{-1}. Brun et al. (2018) employed ASTER DEMs from 2000-2006 and showed that glacier mass balance~~s~~ in High Mountain Asia var~~y~~ied from -0.62 ± 0.23 m w.e. a^{-1} in eastern Nyainqentanglha to +0.14 ± 0.08 m w.e. a^{-1} in the Kunlun M~~m~~ountains, and averaged -0.14± 0.14 m w.e. a^{-1} over the large Inner TP that includes WNT. Maurer et al. (2019) found a doubling of the Himalayan average loss rate between the periods 1976-2000 (−0.22 ± 0.13 m w.e. a^{-1}) and during 2000–2016 (−0.43 ± 0.14 m w.e. a^{-1}) using KH-9 and ASTER DEMs. These studies showed that glacier changes on and around the TP have marked spatial and temporal heterogeneity, likely associated in part with variable glacial sensitivity to climate change (Yao et al., 2012).

The drivers of regional glacier loss include, for example, a jump in mean annual temperature and precipitation in the Yarlung-Zangpo River basin around 1997 (Wang et al., 2021) and an accelerating warming trend over the TP between the periods 1980–1997 and 1998–2013 (from 0.21 °C to 0.25 °C decade^{-1}) (Duan & Xiao, 2015). Modulating the effect of these climatic drivers are ~~Besides, the~~ local ~~influence~~ factors ~~of~~ including glacier topography, debris-cover and~~,~~ glacial lakes ~~and so on at local scales is also included~~ (Brun et al., 2018,2019; Ke et al., 2020; Maurer et al., 2019; Yao et al., 2012~~). Among these influencing factors, the glacier topography is the controlling factors which modulate the changes (~~; Pandey et al., 2017). ~~Wang et al (2021) showed that the mean annual temperature and precipitation in the Yarlung-Zangpo River basin jumped around 1997and Duan & Xiao (2015) showed the warming trend accelerated over the TP during 1998–2013 (0.25 °C decade^{-1}) compared with that during 1980–1997 (0.21 °C decade^{-1}).~~ There are, however, few ~~comparative~~ studies on the influence of ~~topography, debris-cover, and proglacial lakes~~these modulating factors on TP glacier change~~-~~. ~~before and after 1997 in the more than 40 years of remote sensing records, although s~~Some studies have analyzed the melt-inhibiting~~tory~~ effect of debris cover and ~~the~~ melt-promoting effect of pr~~e~~oglacial lakes on glacier ablation since 2000 (Ke et al., 2020; Vincent et al., 2016), but with the potential for ~~. DEM of TP in 1997 is difficult to collect, but~~ detailed topographic (~~SRTM of 2000 in combination with~~ KH-9 in 1976, SRTM in 2000, ASTER ~~DEMs in~~in 2000-2020) and aerial mapping ~~and~~ (Landsat, ~~data during~~ 1976-2020) through time, we are now ~~can~~ able to ~~provide a comparison of~~ assess glacier area and mass change ~~and mass balance before and after 2000 (which is near 1997), as well as a comparative study of factors effects~~in the WNT in relation to both regional climatic drivers and local modulating factors.

The WNT, in the south-eastern TP (Figure 1), is located in the transition zone between the two large-scale atmospheric circulation patterns characterized respectively by dominant westerlies and the Indian summer monsoon. It holds an abundance of glaciers and glacial-fed lakes, notably Nam Co Lake (Figure 1), whose rising water levels indicate a water imbalance primarily due to recently intensified glacier melting (Bolch et al., 2010), as supported by mass balance data from Zhadang Glacier and other hydrological observations from 2007 to 2011 (Zhou et al., 2013). The number and area of supraglacial lakes (of >0.0036 km2) in the WNT also increased between 1976 and 2018 by 56% and 35% respectively due to the increase in glacial meltwater (Luo et al., 2020). In the relatively densely-populated Lhasa Basin to the southeast of WNT, Lin et al. (2020) found that a water imbalance also existed using the first and second Chinese Glacier Inventory in 1960 and 2009. Despite these extensive changes and large affected population, logistical constraints have meant that in situ glacier mass balance records are limited to a few low-lying, small glaciers that are unlikely to be representative of the broader region (Kääb et al., 2012; Li & Lin, 2017; Yao et al., 2012).Similarly, glacier volumes in the Chinese Glacier Inventory were primarily calculated indirectly by area-volume scaling, and limited direct observations mean that these volume have larger uncertainty (Bahr et al., 1997; Bahr et al., 2015). Detailed investigation of the WNT glacier area change and mass balance on a longer time scale is therefore a high priority.

~~Detailed, spatially-comprehensive and long-running observations of area and volume change for the WNT are still lacking, however, resulting in many gaps in our knowledge and understanding of regional glacier behaviour, and considerable uncertainty in predicting future glacier area and volume and their runoff yield (Bhattacharya et al., 2021; Immerzeel et al., 2020; Maurer et al., 2019).~~

Investigations of ~~the~~ WNT glacier area have so far focused on the period before 2014 (~~-~~Bolch et al., 2010; Wu et al., 2016). For glacier mass balance, most studies focus on after

2000 (Li & Lin, 2017; Neckel et al., 2014; Ren et al., 2020; Zhang & Zhang, 2017). There are limited discussions on local glacier changes in the WNT region from before 2000, although Zhou et al. (2018) included this area in his study of glacier mass balance on the TP and its surroundings from the mid-1970s to 2000 and did not ~~show~~ present the characteristics of glacier change~~s~~ in detail. Furthermore, the warming rate of the TP is heterogeneous both spatially and temporally in recent decades (Duan & Xiao, 2015; Wu et al., 2015). Under a changing runoff regime (Lin et al., 2020), the lack of a detailed survey of glacier changes over a long time scale is a major impediment to water resource management and decision-making (Lutz et al., 2014).

The key purpose of this study is therefore to provide an internally consistent dataset of glacier area and mass change in the WNT over the past 44 years, and comparative analysis of the impact of topography, debris and proglacial lakes on glacier change during 1976 - 2000 and during 2000 - 2020. Although the area of both debris-cover and lake terminating glaciers are relatively small, the characteristics of their influence on individual glaciers can be used as a reference for glacier changes in other regions. We have compiled a complete glacier inventory in the years 1976, 2000, 2014 and 2020 with the Landsat and KH-9 images and quantified the geodetic glacier mass balance during 1976–2000 and 2000–2020 with DEMs derived from KH-9, ASTER and SRTM3.0. We report area and mass changes for periods 1976 to 2000 and from 2000 to 2020, and we examine and compare the influence of topographic, climatic and glaciological factors on these changes during 1976-2000 and 2000-2020.

5. Conclusions

Based on KH-9, Landsat, SRTM and ASTER satellite data, we have quantified the changes of glacier area, surface elevation and mass balance in the WNT over the past 44 years and compared the effects of topography, debris-cover and proglacial lakes on glacier change during 1976-2000 and 2000-2020. Our major conclusions are:

(1) Glaciers in the WNT retreated by 295.73 ± 43.45km^2, or 33.42 ± 4.9% of their area, from 1976-2020, at a mean rate of -0.76 ± 0.11 % a^{-1}. Over this time, they lost a total of 11.56 ±0.12 Gt of ice.

(2) The average retreat rate from 2000 to 2020 (1.17 ± 0.30 % a^{-1}) was more than twice that from 1976 to 2000 (0.54 ± 0.21 % a^{-1}). Similarly, the mean glacier mass balance from 2000 to 2020 (-0.37 ± 0.12 m w.e.a^{-1}) was more negative than that from 1976 to 2000 (-0.26 ± 0.09 m w.e.a^{-1}) (though the change is within the uncertainties). The more rapid ice loss from 2000 to 2020 was mainly due to intensified glacier melting after 2014, which was likely associated with particularly strong warming of the region after that year.

(3) In the WNT the spatial and temporal patterns of glacier loss can largely be explained by the observed patterns of regional climate change. Locally, the mass balance varied between different types of glaciers with proglacial lakes associated with the most rapid loss, particularly during 2000-2020. The mass balance of debris-covered glaciers was similar to debris-free glaciers during 2000-2020.

(4) Topographic setting influenced retreat and thinning, with lower loss rates ~~decreasing~~ at ~~with increasing~~ higher elevations. The rate of both glacier retreat and thinning decreased with elevation, but the relationship between the parameters of slope and aspect with thinning rates differed from their relationship with retreat rates, spatially and through time. For slopes of 8-40° (which includes most glaciers), for example, the retreat rate increased with slope while the thinning rate decreased.

In this study, we observed accelerated glacier loss in the WNT on multi-year time scales. However, factors such as precipitation, temperature and altitude could not yet fully explain the heterogeneity of glacier changes. Thus, more detail data and glacier ablation models are needed to fully understand the mechanism of glacier change in the future.

~~change during specific time periods.~~