Glacier mass balance in High Mountain Asia inferred from a GRACE release-6 gravity solution for the period 2002–2016 postprint

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Abstract

We provide estimates of glacier mass changes in the High Mountain Asia (HMA) area from April 2002 to August 2016 by employing a new version of gravity solutions of the Gravity Recovery and Climate Experiment (GRACE) twin-satellite mission. We found a total mass loss trend of the HMA glaciers at a rate of -22.17 ($±1.96)$Gt/a.Thelargestmasslossratesof-7.02(\pm 0.94)and-6.73(\pm 0.78)Gt/aarefoundfortheglaciersinNyain$ Gt/a in Karakoram Mountains and West Kunlun Mountains, respectively. There is also a nearly zero mass balance in Pamirs. Our estimates of glacier mass change trends confirm previous results from the analysis of altimetry data of the ICESat (Ice, Cloud and Land Elevation) and ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) DEM (Digital Elevation Model) satellites in most of the selected glacier areas. However, they largely differ to previous GRACE-based studies which we attribute to our different post-processing techniques of the newer GRACE data. In addition, we explicitly show regional mass change features for both the interannual glacier mass changes and the 14-a averaged seasonal glacier mass changes. These changes can be explained in parts by total net precipitation (net snowfall and net rainfall) and net snowfall, but mostly by total net radiation energy when compared to data from the ERA5-Land meteorological reanalysis. Moreover, nearly all the non-trend interannual mass changes and most seasonal mass changes can be explained by the total net radiation energy data. The mass loss trends could be partly related to a heat effect due to increased net rainfall in Tianshan Mountains, Qilian Mountains, Nyainqentanglha Mountains and Eastern Himalayas. Our new results for the glacier mass change in this study could help improve the understanding of glacier variation in the HMA area and contribute to the study of global change. They could also serve the utilization of water resources there and in neighboring areas.

Full Text

Preamble

Glacier mass balance in High Mountain Asia inferred from a GRACE release-6 gravity solution for the period 2002–2016

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Abstract: We provide estimates of glacier mass changes in the High Mountain Asia (HMA) area from April 2002 to August 2016 by employing a new version of gravity solutions from the Gravity Recovery and Climate Experiment (GRACE) twin-satellite mission. We found a total mass loss trend of the HMA glaciers at a rate of –22.17 ($±1.96)$Gt/a. The largest mass loss rates of –7.02 (±0.94) and –6.73 (±0.78) Gt/a are found for the glaciers in Nyain$ Gt/a in Karakoram Mountains and West Kunlun Mountains, respectively. There is also a nearly zero mass balance in Pamirs. Our estimates of glacier mass change trends confirm previous results from the analysis of altimetry data of the ICESat (Ice, Cloud and Land Elevation) and ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) DEM (Digital Elevation Model) satellites in most of the selected glacier areas. However, they largely differ from previous GRACE-based studies, which we attribute to our different post-processing techniques of the newer GRACE data. In addition, we explicitly show regional mass change features for both the interannual glacier mass changes and the 14-averaged seasonal glacier mass changes. These changes can be explained in parts by total net precipitation (net snowfall and net rainfall) and net snowfall, but mostly by total net radiation energy when compared to data from the ERA5-Land meteorological reanalysis. Moreover, nearly all the non-trend interannual mass changes and most seasonal mass changes can be explained by the total net radiation energy data. The mass loss trends could be partly related to a heat effect due to increased net rainfall in Tianshan Mountains, Qilian Mountains, Nyainqentanglha Mountains and Eastern Himalayas. Our new results for the glacier mass change in this study could help improve the understanding of glacier variation in the HMA area and contribute to the study of global change. They could also serve the utilization of water resources there and in neighboring areas.

Keywords: glaciers; mass balance; GRACE; precipitation; snowfall; radiation energy; High Mountain Asia

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1 Introduction

In High Mountain Asia (HMA), glaciers are predominantly distributed across the Tianshan Mountains, Pamirs, Hindu Kush Mountains, Karakoram Mountains, Himalayas, and Nyainqentanglha Mountains. The total glacier area in HMA accounts for approximately 23% of the global mountain glacier area (Gardner et al., 2013) [Figure 1: see original paper]. Glacier mass balances (Cogley et al., 2011), also referred to as glacier mass changes in the space-gravimetry community (Kääb et al., 2012), are highly sensitive to long-term global warming. Understanding glacier mass changes is critical for water resource utilization in HMA and adjacent regions, as well as for global change studies (Brun et al., 2017; Pritchard et al., 2019). To this end, various survey techniques have been developed and deployed.

Glaciological methods can be used to evaluate glacier mass changes in the HMA area through measurements on the glacier surface (Cogley et al., 2011). Measured parameters typically include density in snow pits, changes in relative surface elevation from a network of stakes, and ice velocity and thickness near the glacier front and its frontal position (Gardner et al., 2013). However, such detailed measurements can only be implemented on a few glaciers in the HMA area due to their remote inland locations, harsh weather conditions, and challenging geography (Yao et al., 2012).

To overcome these challenges, satellite DEM (digital elevation model)-based methods are employed to derive glacier mass changes from repeatedly measured surface elevations, assuming that snow and ice density across the entire HMA are accurately determined. These methods utilize satellite altimetry such as ICESat (Ice, Cloud, and land elevation satellite; Zwally et al., 2002) and CryoSat-2 (Wang et al., 2015), optical stereo pairs such as ASTER (advanced spaceborne thermal emission and reflection radiometer; Brun et al., 2017), and bistatic SAR such as SRTM (Rodriguez et al., 2006). However, significant uncertainties affect mass changes derived from these data (Kääb et al., 2012, 2015; Gardner et al., 2013). For satellite altimetry in particular (Kääb et al., 2012; Gardner et al., 2013), several technique and environmental characteristics can impact measurements and results: (1) ground tracks cover only about half of the glaciers; (2) repeated ground tracks are commonly offset by 1–2 km; (3) the signal footprint is large, at about 70 m; (4) ground tracks are repeated only 2–3 times per year; (5) steep glacier slopes may be present; and (6) extensive debris cover and crevasse fields may exist on the ice surface.

Another option is the use of space gravimetry. Time-variable (usually monthly) gravity changes derived from continuous measurements of the Gravity Recovery and Climate Experiment (GRACE) twin-satellite mission from 2002 to 2017 can be used to infer monthly glacier mass changes in the HMA area (Bettadpur, 2012). GRACE data analysis offers several advantages compared to the glaciological methods and satellite altimetry mentioned above, including (1) full and homogeneous coverage over glaciers; (2) monthly resolved gravity changes and glacier mass changes; and (3) a long observation time span from March 2002 to June 2017. However, adequate post-processing—primarily filtering—of GRACE data must be performed to extract the signal of interest as accurately as possible. Most importantly, north-south-oriented stripes, which are sub-Nyquist artifacts arising from the oversampling of the Earth’ s low-frequency geoid in the east-west direction (Peidou and Pagiatakis, 2020), must be removed using so-called destriping filters.

Several studies have used GRACE gravity data to derive glacier mass changes in the HMA area over different time spans (Matsuo and Heki, 2010; Gardner et al., 2013). However, obvious differences exist in the estimates from different studies during approximately the same observation periods. For example, Jacob et al. (2012) provided trend rates of glacier mass changes for 2003-2010 of -5.0 ($±6.0) Gt/a in the Himalayas and Nyainqentanglha, −5.0 (±6.0) Gt/a in Tianshan, and −11.0 (±9.8) Gt/a for the to
Tibet Plateau and Qilian Mountains). Despite a slightly different observation period from 2003 to 2012, Yi and Sun
−20.5 (±3.0) Gt/a, −8.4 (±2.4) Gt/a, and −35.0 (±$4.6) Gt/a, respectively. They used the destriping filter P4M6 (Chambers, 2006), which apparently could not effectively reduce the north-south-oriented stripe noise in the Stokes coefficients of the GRACE gravity data, as shown in Figure 2c of Xiang et al. (2017). This emphasizes the importance of using adequate post-processing for GRACE data.

After the end of the GRACE mission in June 2017, gravity data solutions have been updated, and a new release-6 version was released by different institutions, including the Institute of Geodesy at Graz University of Technology (ITSG), Austria (Mayer-Gürr et al., 2016; Kvas et al., 2019), the Center for Space Research, USA (Bettadpur, 2012), the German Research Center for Geosciences (Dahle et al., 2012), the Jet Propulsion Laboratory, USA (Watkins and Yuan, 2012), Tongji University (Chen et al., 2015), and Huazhong University of Science and Technology (Zhou et al., 2016). Following Wahr et al. (1998) and Xiang et al. (2017), we calculated trend rates of gravity changes (in equivalent water height, EWH) from these different new gravity solutions in the HMA and adjacent areas, and found that the differences among the results from the models are far less than those from different destriping filters (not shown). Therefore, it seems reasonable to estimate glacier mass changes in the HMA area using only one of these new GRACE gravity solutions but with an effective destriping filter.

In this study, we investigate glacier mass changes in the HMA area derived from the ITSG release-6 solution together with meteorological reanalysis data, and analyze differences between our results and those from previous studies. Due to lower quality of the Stokes coefficients from the solutions near the end of the GRACE mission, the observation time span is limited to April 2002 to August 2016.

2.1 GRACE Gravity Data

The ITSG release-6 solution (i.e., ITSG-Grace2018; Kvas et al., 2019) is available as monthly Stokes coefficients from degree 2 to 96 from April 2002 to August 2016 (http://icgem.gfz-potsdam.de/series). Due to large errors in the higher degree/order Stokes coefficients, the maximum degree/order is set to 90. The degree-1 Stokes coefficients from Swenson' s GRACE-OBP approach (Swenson et al., 2008) are available from ftp://podaac.jpl.nasa.gov/allData/tellus/L2/degree_1/deg1_{coef}.txt. The C20 Stokes coefficients with large uncertainties (Chen et al., 2016) should be replaced with estimates from satellite laser ranging (Cheng and Tapley, 2004; Cheng et al., 2013), available from https://podaac-tools.jpl.nasa.gov/drive/files/allData/grace/docs/TN-11_{{{C20}}_{{SLR}}}.txt. Glacial isostatic adjustment effects are corrected in the monthly Stokes coefficients of the ITSG model using the GIA model ICE-6G_C(VM5a) (Peltier et al., 2015).

According to Xiang et al. (2017), the S&WP2M8 destriping filter (Swenson and Wahr, 2006) is recommended, as trend rates of mass changes in the HMA and adjacent areas derived from different GRACE release-5 solutions agree with increasing lake level and declining glacier mass trends observed by ICESat data (Gardner et al., 2013; Zhang et al., 2013) when this filter is applied. For the S&WP2M8 filter, a degree-2 polynomial is used in a window dependent upon the order, fitted to all Stokes coefficients of the same parity in degrees $ 8*foracertainorder*($8), and the coefficients used in fitting are subtracted by the fitting values so that striping errors can be reduced in the coefficients within the window.

Moreover, the effects of soil moisture changes must be further removed from the monthly Stokes coefficients. For this purpose, average grid soil moisture data from two land surface models—Noah and Variable Infiltration Capacity of the Global Land Data Assimilation System (Rodell et al., 2004)—are decomposed into spherical harmonic (SH) series using Equations 3–5 of Xiang et al. (2016). The calculated SH coefficients can be transformed into the related Stokes coefficients according to Equations 1 and 2 of Xiang et al. (2016). These Stokes coefficients can then be removed from the monthly destriped Stokes coefficients of the ITSG solution.

2.2 Computation of Mass Changes

First, we divide the HMA and adjacent areas into a series of mascon regions totaling 700, which include 14 irregular glacier mascons based on the Randolph Glacier Inventory 6.0 (RGI Consortium, 2017), regular 2°$×$2° mascons in other regions, and irregular mascons in their buffer zones. Note that the 14 irregular glacier mascons are allowed to be slightly larger than specified in the inventory since RGI 6.0 did not account for glacier retreat and glacier lake expansion from 2001 to 2016.

Second, we remove the average during the observation time span from the Stokes coefficients from the ITSG solution and denote the results as δc_{lm} and δs_{lm}. Supposing that each mascon has a uniformly distributed unit EWH, which can be decomposed into SH series, and that the SH coefficients (Δlms, i=1, 2, ···, M) can be calculated with Equations 3-5 of Xiang et al. (2016), then according to Jacob et al. (2012), the realistic EWH (ΔEWH_i) for the 700 mascons (i=1, 2, ···, M) can be expressed by:

$$\Delta EWH_i = \sum_{l=0}^{l_{max}} \sum_{m=0}^{l} \frac{a \cdot (1+k_l)}{3 \cdot \rho_{ave} \cdot \rho_w} \cdot w_l \cdot \left(\Delta c_{lm} \cdot A_{lm,i}^{-1} + \Delta s_{lm} \cdot B_{lm,i}^{-1} \right) \quad (1)$$

where a is the Earth' s radius; k_l is the degree-l elastic load Love number for potential perturbation (Wang et al., 2012); _{ave} is the average density of the Earth (5.517 g/cm^3); _w is the water density (1 g/cm^3); w_l is the degree coefficient of Jekeli's Gaussian averaging function for Legendre expansion (Jekeli, 1981); while $A_{lm,i}^{-1}$ and $B_{lm,i}^{-1}$ are elements of the inverse of matrix **A** given by:

$$A_{i,j} = \sum_{l=0}^{l_{max}} \sum_{m=0}^{l} \frac{a \cdot (1+k_l)}{3 \cdot \rho_{ave} \cdot \rho_w} \cdot w_l \cdot \left(\Delta c_{lm,i} \cdot \Delta c_{lm,j} + \Delta s_{lm,i} \cdot \Delta s_{lm,j} \right) \quad (2)$$

For a Gaussian filter with an averaging radius of 220 km, the summation of Equations 1 and 2 is truncated at l_{max}.

Third, the monthly mass changes expressed as EWH for each mascon are fitted to a trend, an annual, a semi-annual, and a 161-day aliasing variation (from the S2 semidiurnal solar tide) by linear regression, and are corrected for the S2 aliasing signals.

Furthermore, assuming that the EWH trend estimate at each mascon is disturbed by independent regression error and noise errors (i.e., measurement errors and remaining stripe noises), the uncertainty of the estimated EWH trend can include twice the regression standard deviation and the effect of the noise errors. For a target mascon, the effect of noise errors can be estimated using the ITSG solution-derived mass change trend magnitude over the ocean at the same latitude as the mascon, but excluding ocean areas within 800 km of continents to avoid land signal leakage (Chen et al., 2009; Longuevergne et al., 2010; Farinotti et al., 2015).

2.3 Meteorological Reanalysis Data

Since certain meteorological physical quantities—particularly total net precipitation (net snowfall plus net rainfall), net snowfall, and total net radiation—could be correlated with glacier mass changes, they can be used for comparison with estimated glacier mass changes in selected glacier areas. In this study, monthly total net precipitation is derived from monthly total precipitation (snowfall plus rainfall), total evaporation, and total runoff data. Monthly net snowfall is calculated from monthly snowfall, snow evaporation, and snowmelt data. Total net radiation is derived from surface net solar radiation and surface net thermal radiation data. We further compare our results to monthly air temperature, taken directly from the monthly temperature data of air at 2 m above the land surface.

We apply the ERA5-Land reanalysis dataset (Muñoz-Sabater, 2019; Hersbach et al., 2020), which combines model data with observations using the laws of physics. The horizontal resolution of the dataset is 0.1°$×$0.1° (native resolution is 9 km). This dataset contains all meteorological data used in this study and is available from https://cds.climate.copernicus.eu/cdsapp#!/home.

3.1 Glacier Mass Changes

The derived trend rates of gravity changes expressed in EWH from monthly Stokes coefficients (Fig. 1) show that north-south-oriented stripes are effectively suppressed. The negative signals along the mountains could be ad hoc related to glacier melting trends. The positive signals in the central Qinghai-Tibet Plateau are likely due to the rising trend of lake water level (e.g., lakes in the southern Qiangtang Basin, Zhang et al., 2013) and increasing groundwater trends in the Three Rivers Source area (Xiang et al., 2016). Significant negative signals are also found in Northwest India and the Bengal Basin, resulting from excessive groundwater use for agricultural irrigation (Rodell et al., 2009).

To reduce signal leakage effects among different glaciers and between glaciers and non-glacier regions, monthly mass changes are simultaneously calculated using Equation 1 at the 700 mascons. We focus on the 14 glacier mascons, where mascon 1 covers glaciers in Nyainqentanglha, mascons 2–3 cover Eastern Himalayas, mascons 4–5 cover Western Himalayas, mascon 6 covers Karakoram, mascon 7 covers Hindu Kush, mascon 8 covers Pamirs, mascons 9–12 cover Tianshan, mascon 13 covers West Kunlun, and mascon 14 covers Qilian.

We present the trend rates of monthly mass changes at the HMA mascons in Figure 2 and the time series for each of the 14 glacier mascons in Figure 3 [Figure 3: see original paper]. The mass change trend rates at the 14 glacier mascons and some mascon combinations are expressed in both EWH per year and mass budget per year (Fig. 3; Table 1). Although results are also available for non-glacier mascons, which may show, for example, declining groundwater storage changes in Northwest India in Figure 2, they are not discussed in this study.

All glaciers experience mass loss except for mascons 6 (Karakoram) and 13 (West Kunlun). As shown in Table 1, the largest ice melting trends appear at mascon 1 (Nyainqentanglha) and mascons 2–3 (Eastern Himalayas) with rates of -1.08 ($±0.14)$m/a(-7.02(\pm0.94)Gt/a) and -1.05(\pm0.12)m/a(-6.73(\pm0.78)Gt/a), respectively. Large ice melting trend$ $determined glacier melting trends are found at mascon 7 (Hindu Kush) and mascon 14 (Qilian) with rates of -0.23($ Gt/a.

As indicated by the mass trend results in Table 1, the glacier areas in Karakoram, West Kunlun, and Pamir in the northwestern HMA form a so-called "Karakoram anomaly" that indeed shows an almost zero or positive mass balance (de Kok et al., 2018; Farinotti et al., 2020). The other areas typically show significant mass loss trends (Yao et al., 2012).

4.1 Comparison with Previous Estimates

In Tables 2 and 3, the trend rates of GRACE-derived monthly glacier mass changes are calculated for different glacier mascons and glacier mascon combinations during different observation time spans to compare them with previous studies covering the same periods. Our results generally match those from ICESat DEM and ASTER DEM analysis at most glacier mascons or glacier mascon combinations, though some results show larger differences (Table 2).

As shown in Table 2, Kääb et al. (2015) provide a value of -3.1 ($±0.6)Gt/aformascon2(easternhalfoftheEaste
fourth.Thecombinedvalueformascons2and3together(−6.3(±1.1)Gt/a)agreeswithours(−4.94(±$2.39) Gt/a) within errors, as our estimate for mascon 3 is larger than that from Kääb et al. (2015). This may point to improvements in leakage correction.

Gardner et al. (2013) listed a value of -4.5 ($±3.3)Gt/aformascon1(Nyainqentanglha)from2003to2009, whileo
Gt/a is 40% larger for the same time span. Despite these differences, the values still agree within their errors. In particular, Gardner et al. (2013) generally provide larger errors than other studies or our GRACE-based results.

Brun et al. (2017) determined -4.0 ($±1.5)Gt/aformascon1(Nyainqentanglha)from2000to2016, whileourresu
Gt/a from 2002 to 2016 is 75% larger. Except for mascons 1-3, there is good agreement between our results and those from Brun et al. (2017). For mascons 2 and 3, we speculate that improved leakage correction in the GRACE data could reduce the differences, though it should also be investigated whether the ASTER DEM data are satisfactory. Similarly, for mascon 1, the apparent difference might relate to limitations in the ASTER DEM data, especially since our values for shorter time spans agree very well with two other studies.

We also evaluate how our results compare to combined regional results (Table 3).
Gardner et al. (2013) listed a value of -17.5 ($±4.4)Gt/aformascons1−5(NyainqentanglhaandHimalayas)fron
temporalresolution, andnoiseleveloftheothersatellitedata(Gardneretal., 2013; Brunetal., 2017).AccordingtoF
Gt/a.

Based on Gardner et al. (2013), all glaciers together had a mass loss trend of -
28.2 ($±8.3)Gt/afrom2003to2009, whichagreesverywellwithourestimateof−29.57(±$4.79)
Gt/a. Note that ASTER DEMs compute the mass balance for 92% of the glaciated area, while the remaining 8% including small glaciers were not processed (Brun et al., 2017), and thus might miss parts of the mass changes.

Table 3 also shows the comparison of our GRACE-based results to two previous GRACE-based studies (Jacob et al., 2012; Yi and Sun, 2014). Large differences are also found here. For example, Jacob et al. (2012) determined -5.0
($±6.0)Gt/aformascons1−5(NyainqentanglhaandHimalayas)from2003to2010, whileourresultof−21.88(±2.8
Gt/a, respectively—much smaller. These large differences between our results

and those from the two previous GRACE-based studies are attributed to different methods for suppressing north-south-oriented stripe noise and measurement errors, as well as different GRACE solutions.

4.2 Comparison with Changes in Meteorological Quantities

In Figure 3, the time series of monthly glacier mass changes show manifold time-variable features. We therefore calculate interannual (Figs. 4 and 5) and average seasonal mass changes (Fig. 6 [Figure 6: see original paper]) and compare them with corresponding total precipitation, snowfall, surface air temperature, and total radiation data at nine selected glacier areas approximately covering all HMA glaciers. Note that total precipitation contains snowfall and rainfall, with the latter being detrimental to accumulation as it carries heat.

4.2.1 Interannual Changes

An increase/decrease in snowfall could induce more/less glacier mass accumulation, while an increase/decrease in summer air temperature could cause more/less glacier mass ablation. Changes in these two quantities correspond to partial glacier mass changes or mass balances (Yao et al., 2012; Farinotti et al., 2020), and are thus tentatively used here to validate observed glacier mass changes. Additionally, we compare total precipitation measurements to our results. Our GRACE-derived monthly glacier mass changes and ERA5-Land monthly total precipitation and snowfall are averaged over 12 months to obtain annual averaged results for each quantity in nine selected glacier mascon areas. The ERA5-Land summer temperatures are averaged over the three summer months of a year (June, July, and August) to obtain three-summer-month averaged temperatures. These annual results are shown for comparison in Figure 4 [Figure 4: see original paper]. However, no significant trends are found for total precipitation, snowfall, or the difference between total precipitation and snowfall (i.e., rainfall). The maximal magnitudes for total precipitation and snowfall are not larger than 0.08 and 0.07 Gt/a, respectively, which are far less than the observed glacier mass changes (Table 1). In addition, increasing temperature trends could help explain the mass loss trends for mascon 1 (Nyainqentanglha), mascons 2–3 (Eastern Himalayas), mascon 7 (Hindu Kush), mascon 8 (Pamirs), mascons 9–12 (Tianshan), and mascon 14 (Qilian), but fail to do so for mascon 13 (Western Kunlun), which shows a mass gain trend. A decreasing temperature trend (-0.015°C/a) could correspond to a mass gain trend for mascon 6 (Karakoram), but it (-0.043°C/a) cannot support a mass loss trend in mascons 4–5 (Western Himalayas).

Given the unsatisfactory comparisons above, we additionally compare our annual glacier mass changes, as suggested in recent studies (de Kok et al., 2018; Farinotti et al., 2020), with changes in total net precipitation, net snowfall, and total net radiation energy (Fig. 5 [Figure 5: see original paper]). Net snowfall in the HMA is directly related to glacier mass change (Brock et al., 2010). Note that the discrepancy between total net precipitation and net snowfall is actually net rainfall, which may partly directly contribute to glacier mass change, and changes in net rainfall could also imply a heat effect on glacier mass change. Since the total energy balance largely controls glacier ablation, changes in total net radiation directly impact glacier mass balance (Brock et al., 2010).

The results of the three meteorological quantities are accumulated to enable precise comparison with the already accumulated mass changes derived from GRACE data. Before accumulating, the 14-year average is removed from the monthly net radiation energy. Still, the mass change results cannot be fully explained by these data. First, total net precipitation and net snowfall usually have the same trend signs except for mascons 9–12 (Tianshan) and mascon 14 (Qilian). Both could thus explain the mass gain trends at mascon 6 (Karakoram), mascon 8 (Pamir), and mascon 13 (Western Kunlun). The decreasing trend in net snowfall together with the increasing trend in net rainfall causing a heat effect could be related to the mass loss trend for mascons 9–12 (Tianshan) and mascon 14 (Qilian). Total net radiation energy shows an increasing trend for all glacier areas, which could imply a mass loss trend for mascon 1 (Nyainqentanglha), mascons 2–3 (Eastern Himalayas), mascons 4–5 (Western Himalayas), mascon 7 (Hindu Kush), mascons 9–12 (Tianshan), and mascon 14 (Qilian). It is confirmed that an increase/decrease in non-trend total net radiation energy can usually explain a decrease/increase in glacier non-trend mass change for each glacier area. In addition, due to the heat effect, the increasing trend in net rainfall could also cause a mass loss trend for mascon 1 (Nyainqentanglha) and mascons 2–3 (Eastern Himalayas).

For the glacier areas of the so-called "Karakoram anomaly," mass gain trends are usually thought to be mainly due to increased strength and frequency of westerlies-dominated total precipitation or snowfall during the last several decades (Cannon et al., 2015), and are also supported by increased summer snowfall caused by increased land irrigation in the lowlands (de Kok et al., 2018). Other mechanisms are not introduced (de Kok et al., 2018; Farinotti et al., 2020). For other glacier areas, mass loss trends could be mainly due to weakening Indian monsoon bringing reduced total precipitation. However, as stated above, there are no obvious trends in total precipitation and snowfall during the 14-year observation time that could support this view. Although we also tested accumulative total net precipitation, net snowfall data, and net radiation energy data, they could only explain mass changes for parts of the glacier regions. A possible reason for this is that the used meteorological reanalysis data have larger uncertainties, especially for trend estimates (Palazzi et al., 2013).

4.2.2 Average Seasonal Changes

We further calculate a 14-year average for each of the 12 months of a year from monthly glacier mass changes, ERA5-Land monthly accumulative total net precipitation, accumulative net snowfall, and accumulative total radiation energy results. Before accumulating, the 14-year average values are removed from the monthly net radiation energy results. Moreover, before averaging, we remove the corresponding interannual signals and trend signals for the four quantities. The comparison results are shown in Figure 6 [Figure 6: see original paper]. Seasonal mass changes peak in May–July and show a valley in October–November for mascon 1 (Nyainqentanglha), mascons 4–5 (Western Himalayas), mascon 6 (Karakoram), and mascon 13 (Western Kunlun). Similar seasonal mass changes are also found for mascon 7 (Hindu Kush) and mascon 8 (Pamir), but with a peak in April and a valley in August–September. These seasonal mass changes, except for mascon 13, agree with changes in accumulative total net precipitation and net snowfall and are anti-correlated with accumulative total radiation energy. Seasonal changes in accumulative net snowfall almost account for all those in total net precipitation. For mascon 13 (Western Kunlun), the seasonal mass change could be explained by both increased accumulative net snowfall in spring and increased accumulative net rainfall in summer. However, for other glacier areas—i.e., mascons 2–3 (Eastern Himalayas), mascons 9–12 (Tianshan), and mascon 14 (Qilian)—there are more peaks and valleys for the seasonal mass changes, resulting in a more complicated pattern that cannot be explained by changes in the three meteorological quantities. The reason for this is unclear and deserves further analysis.

5 Conclusions

We provided estimates of glacier mass changes in the HMA area from April 2002 to August 2016 by employing a new GRACE solution. The total mass loss trend for HMA glaciers is -22.17 (±1.96) *Gt/a. The largest glacier mass losses occur in Nyainqentanglha and the Easter* *called "Karakoram anomaly" have a nearly zero mass balance in the Pamirs and a slight mass gain trend in Karakor* Gt/a, respectively.

Our estimates of glacier mass change trends match results from previous studies based on ICESat and ASTER DEM analysis in most selected glacier areas where results are available over the same time periods for comparison. Larger differences in some glacier areas could be due to limitations in coverage, spatial-temporal resolution, and noise level of the other data. However, our results are very different from those of two previous GRACE-based studies, possibly due to our different post-processing techniques and the new GRACE solution used.

The 14-year estimates of glacier mass change for the nine selected glacier areas explicitly show different interannual mass changes and average seasonal mass changes, which can be partly supported by total net precipitation and net snowfall data, but mostly seem to correlate with total net radiation energy data. Almost all non-trend interannual mass changes and most seasonal mass changes can be explained by total net radiation energy data. The mass loss trends could be partly due to heat effects from increased net rainfall in some glacier areas such as Tianshan, Qilian, Nyainqentanglha, and Eastern Himalayas.

The new glacier mass change results in this study based on the latest GRACE solution can help serve water resource utilization in the HMA and adjacent areas and contribute to global change studies.

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Note: Figure translations are in progress. See original paper for figures.