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Comparison of glacier mass balance data in the Tien Shan and Pamir, Central Asia

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ABSTRACT

Glacier coverage and behavior are heterogeneous across Tien Shan and Pamir due to a climate gradient from west to east. Regional glacier mass balance data have previously been calculated using GRACE and hydrological models with differing results. In this study, in situ mass balance data of glaciers in the Tien Shan and Pamir, measured by the glaciological method between 2004 and 2012, are spatially extrapolated to the total glacier area by arithmetic averaging using (1) unfiltered balance data, and (2) a smoothing filter to the data in a way similar to that done for GRACE data. GRACE and the in situ data are the only methods that measure mass variations directly. A comparison of the extrapolated unfiltered and filtered in situ data is made with the difference between GRACE and the total water storage of the hydrological model Water Global Assessment and Prognosis Global Hydrology Model that represents glacier mass balance. The annual comparison between the extrapolated in situ and GRACE-related data does not fit very well, but the comparison of mass change rates shows quite good agreement. In comparison with GRACE-related results from the literature, the extrapolation of the unfiltered in situ glacier mass data performs best, especially in the Tien Shan.

INTRODUCTION

Several papers address the calculation of glacier mass balance in high-mountain Asia (HMA) by the Gravity Recovery and Climate Experiment (GRACE) satellites and other sources, with differing results (e.g., Matsuo and Heki, 2010; Jacob et al., 2012; Yao et al., 2012; Gardner et al., 2013; Yi and Sun, 2014). Glacial extent and behavior is highly variable throughout HMA. GRACE data and in situ mass balances measurements represent two methods of measuring mass balance directly. In situ glacier mass balance measurements by the glaciological method are sparse, often conducted on easy-to-reach glaciers, and biased toward small-to-medium-sized and debris-free glaciers (Hirabayashi et al., 2010; Gardelle et al., 2013). It is not known whether these glaciers are representative of the total glaciated area. Gardner et al. (2013) and Vincent et al. (2013) found a measurement bias towards glaciers with greater mass loss in HMA, suggesting a spatial extrapolation to an entire mountain range is questionable. Nevertheless, this has been done in several cases (e.g., Dyurgerov and Meier, 2005; Cogley, 2009; WGMS, 2013) as in situ data provide high temporal resolution (Huss et al., 2009). The aim of this paper is to use the in situ data in combination with GRACE global data on a regional scale. To use other data in comparison or combination with GRACE, the data should be preprocessed in a way similar to GRACE (Abelen and Seitz, 2013). Therefore, a filter similar to the GRACE smoothing filter is applied to the extrapolated in situ mass balance data to allow the comparison of extrapolated unfiltered and filtered in situ measurements with the GRACE-derived glacier mass balances.

STUDY AREA

This study focuses on the Tien Shan and Pamir regions, which form the northern end of HMA (Fig. 1). They are located in the dry mid-latitudes, in the Westerlies zone (Yao et al., 2012; Mölg et al., 2014, supplement; Yi and Sun, 2014). The Pamir is weakly influenced by the monsoon (Dyurgerov, 2010). The Tien Shan is the first mountain barrier for air masses from the north and west (Aizen et al., 1997; Bolch, 2005). Both mountain ranges show large vertical precipitation gradients (Bolch, 2005; Dyurgerov, 2010) and are quite variable in their climatic and orographic settings. This is reflected in the distribution of glacier change (Fujita and Nuimura, 2011). The study area covers a region of about 565,200 km^2 (black outline in Fig. 1) with a glacier area of about 26,800 km^2 and about 22,000 glaciers (Randolph Glacier Inventory [RGI] v4.0) (Arendt et al., 2014). The study area, also for Tien Shan and Pamir, is calculated using the 1980 Geodetic Reference System ellipsoid and the respective outline indicated in Figure 1.

Tien Shan

The area of the Tien Shan stretches from west to east and covers about 374,700 km^2. Maximum elevation is 7439 m a.s.l. (Jengish Chokusu, Kyrgyzstan). The glaciated area of the Tien Shan is 12,530 km^2 (Arendt et al., 2014) (equivalent of 3.3% of corresponding study area). There is a climate gradient from a more mild and temperate climate in the west and north to a continental climate in the inner and eastern Tien Shan (north–south, west–east gradients) (Dyurgerov et al., 1994; Bolch, 2006; Dyurgerov, 2010; Hagg et al., 2013a). Annual precipitation is 300 mm in the inner and eastern part (Bolch, 2006). As a result, maritime-type glaciers with maximum precipitation during winter are located in the west, whereas continental-type glaciers with maximum precipitation during summer are located in the inner and eastern parts (Bolch, 2005). Equilibrium line altitudes (ELAs) vary between 3500 and 3600 m a.s.l. in the western part, and are located at 4440 m a.s.l. in the center (Solomina et al., 2004). There are surging and debris-covered glaciers in the area (Kotlyakov et al., 2010; Pieczonka et al., 2013); for example, 3.5% of the total glacier area in the Big Naryn catchment, Central Tien Shan, are debris covered (Hagg et al., 2013b).

Pamir

The area of the Pamir (including Alai Range) is about 190,500 km^2. The highest peak is Kongur Shan, China, at 7719 m a.s.l. The glaciated area is 14,290 km^2 (Arendt et al., 2014) (equivalent of 7.5% of corresponding study area). The topography includes high peaks, steep slopes, and deep narrow valleys (Khromova et al., 2006; Dyurgerov, 2010). Many surge-type glaciers are located in the Pamir (Kotlyakov et al., 2010;

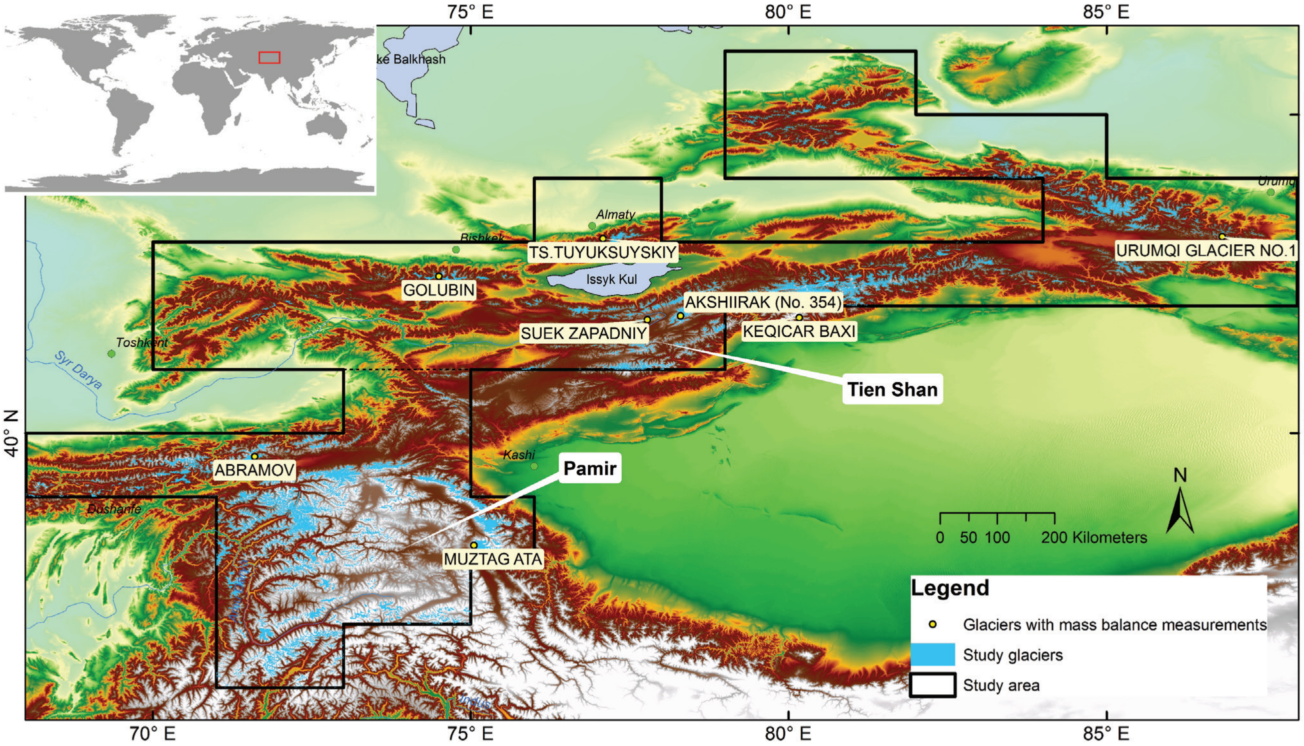

FIGURE 1. Location and map of study area. Glaciers with mass balance measurements used in the study are marked. Solid black line denotes the study area, dashed black line the border between Tien Shan and Pamir (Source world map: ESRI database, source digital elevation model [Jarvis et al., 2008]).

Gardelle et al., 2013), and about 11% of the glacier area is debris covered (Gardelle et al., 2013). There are dry conditions in the Pamir with a very low annual precipitation of 100–150 mm (Khromova et al., 2006; Hagg et al., 2013a). Continentality increases from west to east and is related to a shift in the precipitation maximum from winter to summer (Khromova et al., 2006) with a predominance of summer precipitation peaks (Dyurgerov, 2010). ELAs vary between 3600 and 4400 m a.s.l. (Barry, 2006).

The area between the Tien Shan and the Pamir mountains is the humid Alai Range. It is often considered as part of the Pamir area (e.g. Dyurgerov, 2002; Khromova et al., 2006). The glaciers are mostly valley and compound-valley glaciers with debris-covered glacier tongues (Kotlyakov et al., 2010).

METHODS AND MODELS

Analyses were carried out for the study area as a whole and for the Pamir and Tien Shan separately. Because of the resolution of GRACE, no analysis was performed in relation to the climate gradients within the two mountain areas.

GRACE

GRACE measures the gravity of the Earth using twin satellites following each other on the same orbital track and were launched in March 2002 (Tapley et al., 2004b). Changes in gravity cause changes in the distance of the satellites, measured by a very precise microwave ranging system (Wahr et al., 1998). These changes are directly related to changes in Earth's mass distribution. Most are related to changes in total continental water storage (TWS) compartments, moving ocean, and atmosphere (Wahr et al., 1998; Flechtner et al., 2010). Atmospheric pressure variations, ocean circulation, and ocean tides are corrected during preprocessing by background models in the GRACE data (Flechtner et al., 2010). TWS compartments consist of surface water, ground water, soil moisture, snow and ice, and canopy storage. Changes in nonhydrological compartments, for example erosion, play a negligible role compared to hydrological changes (i.e., Jacob et al., 2012; Schnitzer et al., 2013).

Monthly GRACE Release-05 level 3 (RL05-L3) data solutions from the Helmholtz Centre Potsdam, German Research Centre for Geosciences (GFZ) provided by GRACE Tellus, Jet Propulsion Laboratory (JPL), are used. Data range from October 2003 to September 2012, representing the hydrological years 2004–2012, the study period. In total these represent 105 months due to data gaps (January and June 2011, and May 2012). The spatial resolution of the GRACE data is 400 km (Tapley et al., 2004a), with an approximate accuracy of 2.5 cm w.e. for the total mass changes (Wahr et al., 2006). Preprocessing is carried out by GRACE Tellus, providing the data in 1° grid format. In the preprocessing they use the GRACE data given in spherical harmonic (Stokes) coefficients (SHC) up to degree and order 60 and a destriping least-squares polynomial Swenson filter (Swenson and Wahr, 2006) to remove longitudinal stripes. An isotropic Gaussian filter with a 300 km half-wavelength is applied to smooth short wavelength contents (Wahr et al., 1998) and to recover the set of masses on the Earth's surface that cause the gravity field seen by GRACE at its flying altitude (JPL, 2015a). The effects of glacial isostatic adjustment (GIA) are removed from the GRACE data using the model of Geruo et al. (2013). The long-term mean is subtracted from each month, and data are converted into 1° grid values. The unit is millimeters of water equivalent (w.e.). More information about the preprocessing is given in JPL (2015b). Apart from background model errors, the remaining GRACE signal is related to changes in TWS.

To compare GRACE with the extrapolated in situ mass balance data, annual values according to the hydrological year are calculated as the sum of the respective months within a hydrological year (sum of months from October previous year until September present year represents annual value of present year). A trend is fitted to the monthly data through linear regression, adjusted for seasonality and insufficient ocean tides corrections with sine and cosine waves applying periods of 1 year, 161 days, and 3.73 years (Ray et al., 2003). Error calculation is performed for measurement and leakage errors as suggested by GRACE Tellus for correlated pixels (pseudocode given in JPL, 2015b). The linear trend of the mass variations, including standard deviation, is obtained by least squares adjustment and error propagation.

WGHM

It is not possible to detect changes in individual storage compartments by GRACE alone. Therefore, all storage compartments that influence the signal have to be assessed by other methods or models. For this purpose, the Water Global Assessment and Prognosis (GAP) Global Hydrology Model (WGHM) 2.2 provided by Andreas Güntner (personal communication) was used (Döll et al., 2003; Müller Schmied et al., 2014). WGHM-TWS is the sum of soil moisture, ground water, inland waters, and snow water equivalent. Con-

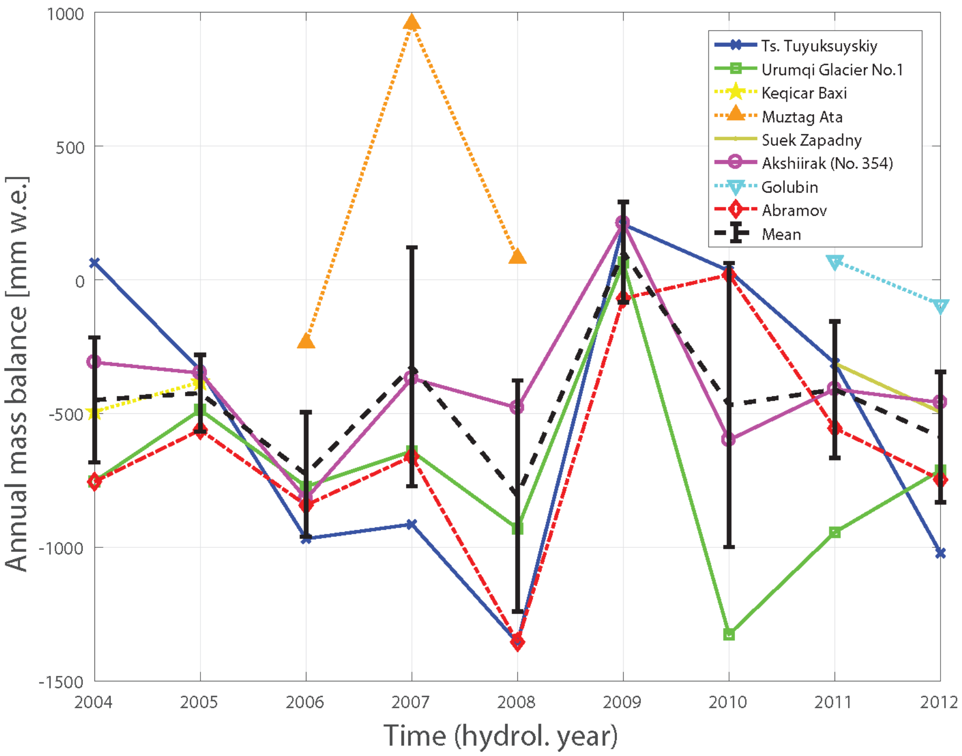

FIGURE 2. Annual in situ mass balance data in the Tien Shan and Pamir measured and reconstructed (see text) between 2004 and 2012. The dashed line gives the annual mean for the total study area with the standard deviation in black. Location of the glaciers given in Figure 1.

tributions from ice and permafrost are not accounted for in WGHM (Hunger and Döll, 2008), but the impact of surface water and groundwater withdrawals on water storage variations in the different compartments are estimated (Döll et al., 2012). WGHM has a daily temporal and 0.5° spatial resolution for the whole land area except Antarctica (Müller Schmied et al., 2014). The global hydrology and water-use model WaterGAP (including the hydrology component WGHM) was calibrated against average river discharge at 1319 gauging stations (Müller Schmied et al., 2014).

Data used here are from the same time period as GRACE. The unit is millimeters of w.e. WGHM grids were averaged over months and preprocessed in a way similar to GRACE, to be comparable with the GRACE data (Longuevergne et al., 2010; Abelen and Seitz, 2013). They were converted into SHC, and a Gaussian filter with a 300 km half-wavelength was applied in the same way as for GRACE. A destriping filter was not used because this filter only marginally influences data sets not affected by correlated errors (Abelen and Seitz, 2013; Farinotti et al., 2015, supplement). The mean was subtracted from all months to resolve WGHM-TWS anomalies. By re-converting the data into 1° grid format they are truncated at degree and order 60. A linear trend was calculated including error propagation using the variance–covariance matrices. Annual values are the sum of the respective months within a hydrological year.

In Situ Mass Balance Data

In situ mass balance data from eight glaciers were investigated by the glaciological method in the Pamir and Tien Shan during the study period (Fig. 2). General information about the glaciers is given in Table 1. Six of the measurement series are from glaciers in the Tien Shan; Abramov and Muztag Ata Glacier are located in the Pamir (see Fig. 1). Mass balance data from Ts. Tuyuksuyskiy Glacier, located in the Tien Shan, were also included in the Pamir data because of a significant correlation between Ts. Tuyuksuyskiy and Abramov Glacier (Dyurgerov and Meier, 2005; Dyurgerov, 2010). For Abramov Glacier and Akshiirak Glacier (No. 354), reconstructed mass balance data series were used (Barandun et al., 2015; Kronenberg et al., 2016). All other mass balance data were from the World Glacier Monitoring Service (WGMS, 2013, updated and earlier issues), from Zhang et al. (2006), and from Yao et al. (2012, supplement). The spatial resolution of each value is one glacier. For each area, at least one mass balance time series was available covering the total study period. In several cases the accuracy of the net mass balance was given with the mass balance data. It ranged from 20 to 1043 mm w.e. with a mean and standard deviation of 361 ± 222 mm w.e. If the accuracy was not available, the mean of the accuracy of each respective year for each area was applied as an error value for the respective glacier.

TABLE 1

General information about the glaciers used for in situ glacier mass balances. Data from WGMS (2013), updated and earlier issues.

Glacier \ Parameter	State	Lat. (°)	Long. (°)	Max. elevation	Min. elevation	Area (km^2)	Length (km)	Year inv.
Abramov	KG	39.63	71.60	4918	3659	24.1	7.8	2013
Akshiirak (No. 354)*	KG	41.84	78.30	4680	3750	6.4	n/a	2012
Golubin	KG	42.46	74.50	4350	3338	5.6	4.7	2013
Keqicar Baxi**	CN	41.81	80.17	6342	3020	83.6	25	n/a
Muztag Ata	CN	38.23	75.05	5940	5235	1.0	n/a	n/a
Suek Zapadny	KG	41.78	77.78	4471	3944	1.1	2.2	2014
Ts. Tuyuksuyskiy	KZ	43.05	77.08	4219	3483	2.3	2.6	2014
Urumqi Glacier No. 1	CN	43.08	86.82	4445	3752	1.6	2.1	2012

*Data from Kronenberg et al. (2016).
**Data from Xie et al. (2007).
Maximum (max.) and minimum (min.) elevation in m a.s.l., Year inv. = year of investigation.
KG = Kyrgyzstan, CN = China, KZ = Kazakhstan.

Two different methods were used to spatially interpolate and extrapolate the glacier mass balance data across the study area:

(1) arithmetic averaging of all measured mass balances for each year, and
(2) preprocessing of all measured mass balance data similar to WGHM-TWS, and arithmetic averaging of the result.

Method (1): The arithmetic mean method was applied after Huss (2012). All available annual net mass balance data from each respective year and area were used to calculate the arithmetic mean and the standard deviation for each year. The total error of each annual value is the sum of the standard deviation and the above mentioned accuracy (measurement error) using the rules of Gaussian error propagation. The mass change rate over the total time period and the corresponding error were calculated by arithmetic averaging of the annual values.

Method (2): Analogous to the WGHM data, extrapolated in situ glacier mass balances were preprocessed in a way similar to GRACE (Abelen and Seitz, 2013), using a comparable process to the WGHM data with the same processing setup. They were computed over the study area on a 1° grid and converted into SHC. A Gaussian filter with a 300 km half-wavelength was applied. The SHC were truncated at degree and order 60 and reconverted into 1° grid format. The resulting annual value is the mean over all grid cells in the study area. Unfiltered error values were preprocessed in the same way. The mass change rate and the corresponding error were calculated as in method (1).

Assumption

The basic assumption of this approach is that both the difference between GRACE and WGHM-TWS (further called Diff GW) and in situ mass balance measurements represent glacier mass changes. This means that the remaining signal of GRACE minus WGHM-TWS should only contain mass anomalies caused by glaciers. The same assumption with its corresponding uncertainties was already made by, for example, Jacob et al. (2012), Gardner et al. (2013), and Yi and Sun (2014). Annual data of Diff GW are the sum of the monthly values over each hydrological year. The trend was fitted through linear regression and adjusted for seasonality and ocean tide, as indicated for the GRACE data (see above). Data gaps were linearly interpolated. The uncertainty is the standard deviations for the mass variations of the linear trend from Diff GW obtained by error propagation.

The Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970) and the percent bias (PBIAS) (Moriasi et al., 2007) were used for evaluating the agreement between the annual data of Diff GW and the extrapolated in situ glacier data, taking Diff GW as simulated and the extrapolated in situ data as observed. The NSE is a normalized statistic that indicates how well the observed data fit to the simulated. It ranges from $-\infty$ to 1, where 1 is the optimal value, and values smaller than 0 indicate poor performance. PBIAS measures the tendency of the simulated data to be larger or smaller than the observed

TABLE 2

Annual mass balance of extrapolated in situ glacier data calculated with the two different methods for (a) the total area, (b) the Tien Shan, and (c) the Pamir. Filtered data is truncated at degree and order 60 and a Gaussian filter of 300 km half-wavelength is applied. Negative annual values are red and positive are blue.

(a) Total study area

Year / Method	Annual mass balance (mm w.e.)								
	2004	2005	2006	2007	2008	2009	2010	2011	2012
Unfiltered	–451	–425	–729	–326	–809	102	–469	–411	–589
Error	233	144	233	447	432	188	531	255	243
Filtered	–163	–154	–264	–118	–292	37	–170	–149	–213
Error	84	52	84	162	156	68	192	92	88
# MB Series	5	5	5	5	5	4	4	6	6

(b) Tien Shan

Year / Method	Annual mass balance (mm w.e.)								
	2004	2005	2006	2007	2008	2009	2010	2011	2012
Unfiltered	–374	–391	–854	–642	–923	160	–632	–382	–557
Error	228	87	145	240	322	108	595	270	269
Filtered	–112	–117	–256	–193	–277	48	–190	–115	–167
Error	68	26	44	72	97	32	179	81	81
# MB Series	4	4	3	3	3	3	3	5	5

(c) Pamir

Year / Method	Annual mass balance (mm w.e.)								
	2004	2005	2006	2007	2008	2009	2010	2011	2012
Unfiltered	–347	–451	–683	–207	–878	68	25	–434	–886
Error	542	316	370	759	780	371	351	364	349
Filtered	–99	–129	–195	–59	–251	19	7	–124	–253
Error	155	90	106	217	223	106	100	104	100
# MB Series	2	2	3	3	3	2	2	2	2

MB Series = number of mass balance series.

data. The optimal value is 0; small absolute values indicate accurate modeling.

RESULTS

Total Study Area

The minimum balance year is 2008 with –809 mm w.e., the maximum is 2009 with +102 mm w.e. for the extrapolated unfiltered data and –292 mm w.e. and +37 mm w.e. for the filtered in situ data (Table 2a). The only positive balance year (2009) shows the highest relative error value (nearly twice as much as the mass balance value). The minimum number of glacier mass balance measurements per year is four and the maximum is six. The mass change rate is –456 ± 301 mm w.e. a^{-1} for the extrapolated unfiltered data and –165 ± 109 mm w.e. a^{-1} for the filtered data. Overall, the mass balance estimates from the unprocessed data are larger in absolute value than from the processed data (Table 2a) due to data smoothing by the filters applied. The extrapolated in situ data show the same sign in three of nine years compared to the annual mass balances from Diff GW (Fig. 3, parts a and b). Diff GW has five positive mass balance years during the study period. The correlation coefficient between the extrapolated in situ data and Diff GW is –0.45 suggesting an anti-correlation (Fig. 3, parts a and b). The mass change rate of Diff GW is –202 ± 53 mm w.e. a^{-1}. By comparing the change rates, the rate of the extrapolated filtered in situ data fits quite well to Diff GW (Fig. 4, part a).

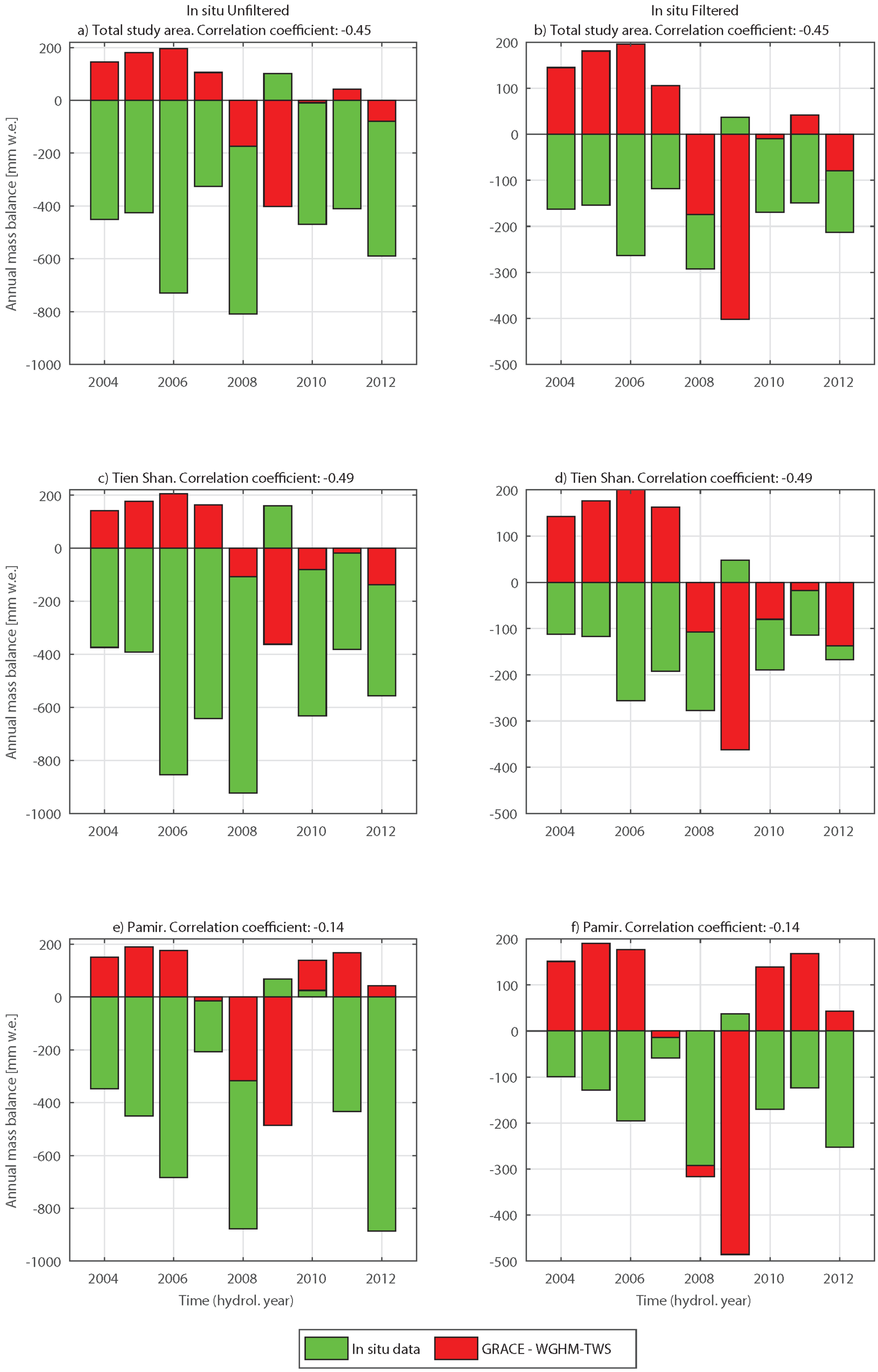

FIGURE 3. **Annual mass balance data of Diff GW and the extrapolated in situ glacier data separated for method (1) (left column) and method (2) (right column). (a) and (b) The total study area; (c) and (d) the Tien Shan; and (e) and (f) the Pamir.**

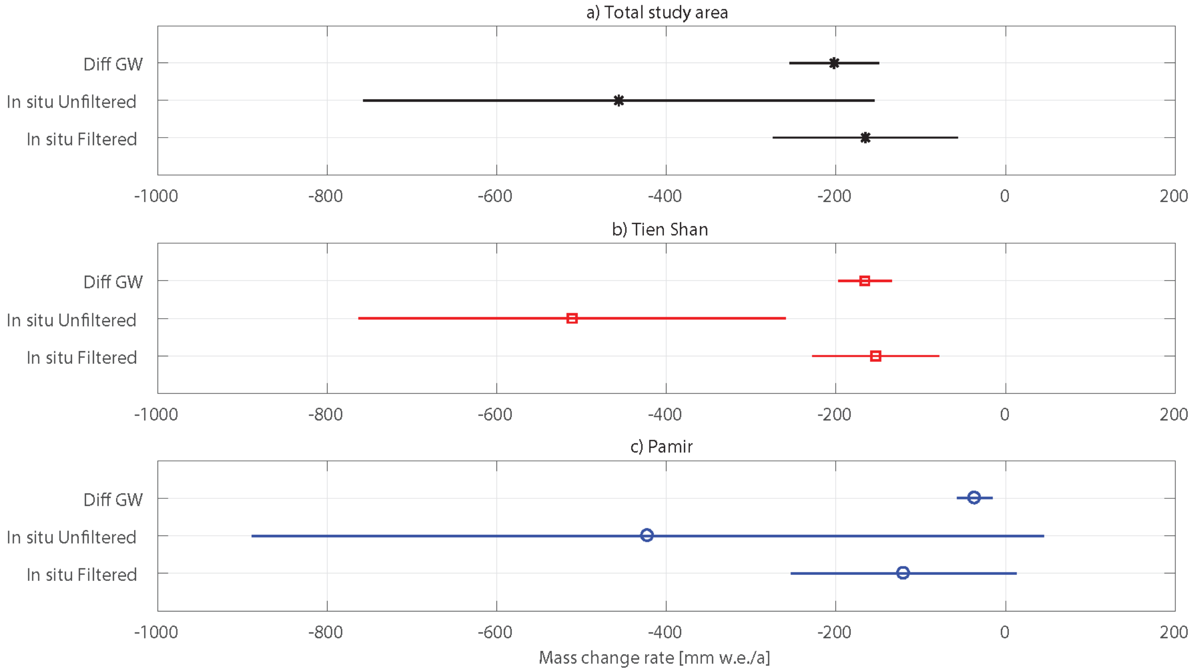

FIGURE 4. Comparison between the mass change rate in mm w.e. a^{-1} of the extrapolated in situ glacier data and Diff GW separated for methods (1) and (2) for (a) the total area, (b) the Tien Shan, and (c) the Pamir.

Tien Shan

The minimum balance year is 2008 with –923 mm w.e., the maximum is 2009 with +160 mm w.e. for the extrapolated unfiltered data and –277 mm w.e. and +48 mm w.e. for the filtered in situ data (Table 2b). The sign and pattern of the extrapolated in situ annual data are the same as for the total area. The error values are about half of the mass balance values. The minimum number of glacier mass balance measurements per year is three, and maximum is five; that is, all six mass balance series are not available for any one year. The extrapolated in situ mass change rate is –511 ± 252 mm w.e. a^{-1} for method (1) and –153 ± 75 mm w.e. a^{-1} for method (2), showing lower error values compared to the total study area. Comparing annual values, the sign of Diff GW corresponds in three of nine years to the extrapolated in situ data. Diff GW shows four positive balance years during the study period. The correlation coefficient between Diff GW and the extrapolated in situ data is –0.49 and shows an anticorrelation (Fig. 3, parts c and d). The mass change rate of Diff GW is –166 ± 32 mm w.e. a^{-1}. As for the total study area, the change rate of method (2) fits better to Diff GW (Fig. 4, part b).

Pamir

The minimum balance year is 2012 with –886 mm w.e., the maximum is 2009 with +68 mm w.e. for the extrapolated unfiltered data and –253 mm w.e. and +19 mm w.e. for the filtered in situ data (Table 2c). There are two positive mass balance years in 2009 and 2010, both accompanied with very high error values. In most cases, there are two mass balance series per year available and only for three years are there three. Mass change rate of the extrapolated unfiltered data is –422 ± 467 mm w.e. a^{-1} and –120 ± 133 mm w.e. a^{-1} for the filtered data. The pattern of annual extrapolated in situ mass values is different compared to both other regions (see Fig. 3). The extrapolated in situ data show the same sign in three of nine years compared to the annual mass balances from Diff GW (Fig. 3, parts e and f). Diff GW has six positive balance years during the study period. The correlation coefficient between the two data sets is –0.14 and indicates no correlation. The mass change rate of Diff GW is –36 ± 21 mm w.e. a^{-1}. As for both other areas, the rate of method (2) fits better to Diff GW (Fig. 4, part c).

The sign and pattern of the extrapolated in situ annual mass balance data are the same for both methods in each region (see Fig. 3). For both methods a more negative rate is obvious in the Tien Shan compared to the Pamir. In all three areas, the rate of method (2) corresponds better to the rate of Diff GW.

The analysis of the annual data with NSE and PBIAS (Table 3) shows that in all regions, there is no relationship between Diff GW and the extrapolated in situ glaciers. Despite the differences in the annual values, the rate of Diff GW and the extrapolated in situ glacier data fits reasonably well.

TABLE 3

Nash-Sutcliffe efficiency (NSE) and percent bias (PBIAS) between annual mass balance data of Diff GW and the extrapolated in situ glacier data calculated with the two methods for the total area, the Tien Shan, and the Pamir. The in situ glacier data are taken as observed.

Index / Method	Total study area		Tien Shan		Pamir	
	NSE	PBIAS	NSE	PBIAS	NSE	PBIAS
Unfiltered	–4.65	100	–3.76	100	–2.35	101
Filtered	–9.53	100	–8.59	99	–8.41	105

Diff GW = the difference between GRACE (Gravity Recovery and Climate Experiment) and WGHM-TWS (the sum of soil moisture, groundwater, inland waters, and snow water equivalent in the Water Global Assessment and Prognosis Global Hydrology Model).

DISCUSSION

The acquisition dates of glacier outlines range between 1959 and 1980, but a high number of outlines are undated. An area change assessment would not have been possible with this data set because no multitemporal information is stored in RGI, but it is available from the Global Land Ice Measurements from Space (GLIMS) platform. This database is still incomplete for the study area, and currently there is also no multitemporal information available. Therefore, no area change assessment is undertaken, and the same glacier area is applied for every year to calculate glacier mass balance. Furthermore, annual areal data would have been useful for the conversion of the specific unit (mm w.e. a^{-1}) to Gt a^{-1}. Dyurgerov (2010) found a weighted area change rate of –0.37% a^{-1} in the Tien Shan from 1964 to 2004 and an area change rate of 0.88% a^{-1} in the Pamir from 1991 to 2006. This error from omitting adjusted area information seems very small compared to the interpolation and extrapolation error of the in situ mass balances, and it is ignored in the error calculation.

Another error source might be the small size of the Pamir area. It is quite close to the minimum resolution of GRACE and therefore could contribute to the high uncertainty value in the GRACE data. As the area increases, leakage decreases (cf. Swenson and Wahr, 2002). A larger area would have resulted in lower error values concerning leakage. In other publications using GRACE, the Pamir is not taken as single area but as combination of, for example, Pamir, Hindu Kush, and Karakoram (Yi and Sun, 2014). Nevertheless, neighboring glacier areas are not included in the current study because the lack of in situ mass balance measurements would have increased the uncertainty of the in situ data. In the future, data from the GRACE Follow-on mission, planned for launch in 2017, could be used as this might have a higher spatial resolution (JPL, 2015c).

To prove the main assumption of the working hypothesis that Diff GW captures most of the mass signal except from glaciers, Diff GW was calculated for a part of the Sahara desert (20.5°–28.5°N, 7.5°–16.5°E). The area covers about 434,000 km^2, which is slightly smaller than the total study area. This area was chosen due to the high probability of the absence of unmodeled processes in WGHM and its high correlation coefficient between GRACE and WGHM-TWS (Abelen and Seitz, 2013). The mass change rate of Diff GW is very low with 9 ± 24 mm w.e. a^{-1}, suggesting the application of Diff GW is reasonable (cf. Farinotti et al., 2015).

As it is difficult to assess the accuracy of hydrological models in many studies (e.g., Jacob et al., 2012; Yi and Sun, 2014), the mean and standard deviation of two or more models were used. This method illustrates the variability of possible results, but not the accuracy of the respective models and so only one model is used in the current study. Döll et al. (2003) reported good model results from WGHM 2.1d with respect to interannual variability for the Amu Darya basin (draining from Pamir), but not for Syr Darya (draining from Tien Shan) (Fig. 1) and most basins in Africa north of the equator (including the part of the Sahara chosen for validation). In WGHM 2.1f, the groundwater recharge algorithm is modified so that an unbiased estimate of groundwater recharge in semiarid areas is obtained (Döll and Fiedler, 2008). But in (semi-)arid, mountainous, and Asian Monsoon regions, groundwater recharge accounts for a lower fraction of total runoff, which makes these regions particularly vulnerable to seasonal and interannual precipitation variability (Döll and Fiedler, 2008). Therefore, in semiarid and arid regions, this model modification probably leads to an underestimation of runoff generation (Döll and Fiedler, 2008), and, additionally, there are large uncertainties in the precipitation and climate input data (Döll and Fiedler, 2008; Müller Schmied et al., 2014). Nonetheless, these modifications result in improvements for semiarid and snow-dominated regions (Hunger and Döll, 2008; Werth and Güntner, 2010) compared to older model versions. The Indus basin is the closest large river basin to the study area and is dominated by snow storage in the northern mountain area and high evaporation rates in the desert region of the lower Indus (Werth and Güntner, 2010). These two parameters show the highest sensitivity in this region and a sensitivity analysis for 2008 was undertaken resulting in a root mean square error for WGHM-TWS 2.1f of about 28 mm w.e. in this area (Werth and Güntner, 2010). Müller Schmied et al. (2014) compared, observed, and simulated (with WGHM 2.2) discharge data separately for, among others, several calibration basins. The basins that are part of this study area have a NSE lower than 0.5.

In summary, the study area is part of regions that are difficult to model (e.g., snow-dominated, arid, mountainous) and shows low validation results compared to observed data. Additionally, glaciers are not included in WGHM modeling. Therefore, the uncertainty for the study area is expected to be larger than 28 mm w.e. as calculated for the Indus basin in 2008. Compared to the change rate of 31 mm w.e. a^{-1} of WGHM-TWS, this uncertainty would result in 90% of the calculated value if the time period is the same. Hence, the uncertainty of WGHM-TWS is probably larger than 90% and thus one of the largest factors of uncertainty in the whole calculation.

In Situ Mass Balance Data

In situ mass balance data is sparse in the study area, especially in the Pamir. As indicated in Table 2c, annual mass balance has been calculated over only six years with two mass balance series. These two series are from Abramov Glacier and Ts. Tuyuksuyskiy Glacier, which is similar to Abramov Glacier. Both are more representative of west Pamir. Due to the climate gradient, glaciers in east Pamir are very different and, thus, are omitted from the extrapolation (cf. Dyurgerov, 2010). Additionally, in years with three balance series, too much weight is given to the western glaciers, and the results in this area can change remarkably by adding or omitting single balance series. In all cases shown here, the error value for the Pamir is larger than the respective mass change rate. Two or three measurement series per year are not a reliable data basis for regional extrapolations and are probably the main reason for the high error values.

Gardelle et al. (2013) found no difference concerning glacier mass balance using DEM differentiation between debris-covered and debris-free areas in the same altitude range and also between surge-type and nonsurge-type glaciers in the Pamir. Kääb et al. (2015) calculated glacier volume changes using the Ice, Cloud, and Land Elevation Satellite. Their volume change for the Pamir seems especially uncertain due to the heterogeneous behavior of individual glaciers, for example, from glacier surges. In the Tien Shan, debris-covered glaciers behave differently (Pieczonka et al., 2013). Pieczonka et al. (2013) measured the highest mass loss rates for debris-covered glaciers; however, the number of debris-covered glaciers in the area is quite low. Hence, no error was assumed due to omitting debris cover in the extrapolation (cf. Farinotti et al., 2015, supplement).

Applying the arithmetic average of the mean specific mass balance of the measured glaciers to all unmeasured ones in the study area is a very simple method and accounts for the limited data basis (Huss, 2012). By applying this method, differences in glacier size, hypsometry, exposure, and geographic location are not accounted for (Huss, 2012). The mass balance of a few monitored glaciers should represent an entire mountain range (Huss, 2012). This is quite uncertain and makes the error of the extrapolated in situ measurements larger than indicated. Furthermore, in situ data are not always measured according to the hydrological year, that is, measurements according to the stratigraphic and fixed date system either are mixed or neither date nor system is indicated (cf. WGMS, 2013, updated and earlier issues). The stratigraphic, measurement period, and fixed data net and winter balance of Silvrettagletscher, Switzerland, were calculated by Huss et al. (2009) for three years. The net balance ranged between 82% and 114% from the mean of all three methods for each year. These values can be assumed as additional error values for the extrapolated in situ data in the current study that was not measured in the time frame of the hydrological year.

Comparison with Previous Studies on Mass Balance in the Pamir and Tien Shan Area

Comparison of the annual values for the GRACE and extrapolated in situ data is slightly anticorrelated or shows no correlation (Fig. 3). Therefore, the annual values are compared with data from the literature to prove values and pattern. For the GRACE data, there is only one annual data set from the Pamir with which to compare but only the pattern without values was given (Yi and Sun, 2014). The pattern of the Pamir data from this study shows a good agreement with data from Yi and Sun (2014); that is, the patterns of the annual cycle correspond except for 2009. The extrapolated unfiltered in situ data are compared with regional data from the Tien Shan from the Mass Balance Bulletin (WGMS, 2013) (available until 2011), which is the main source

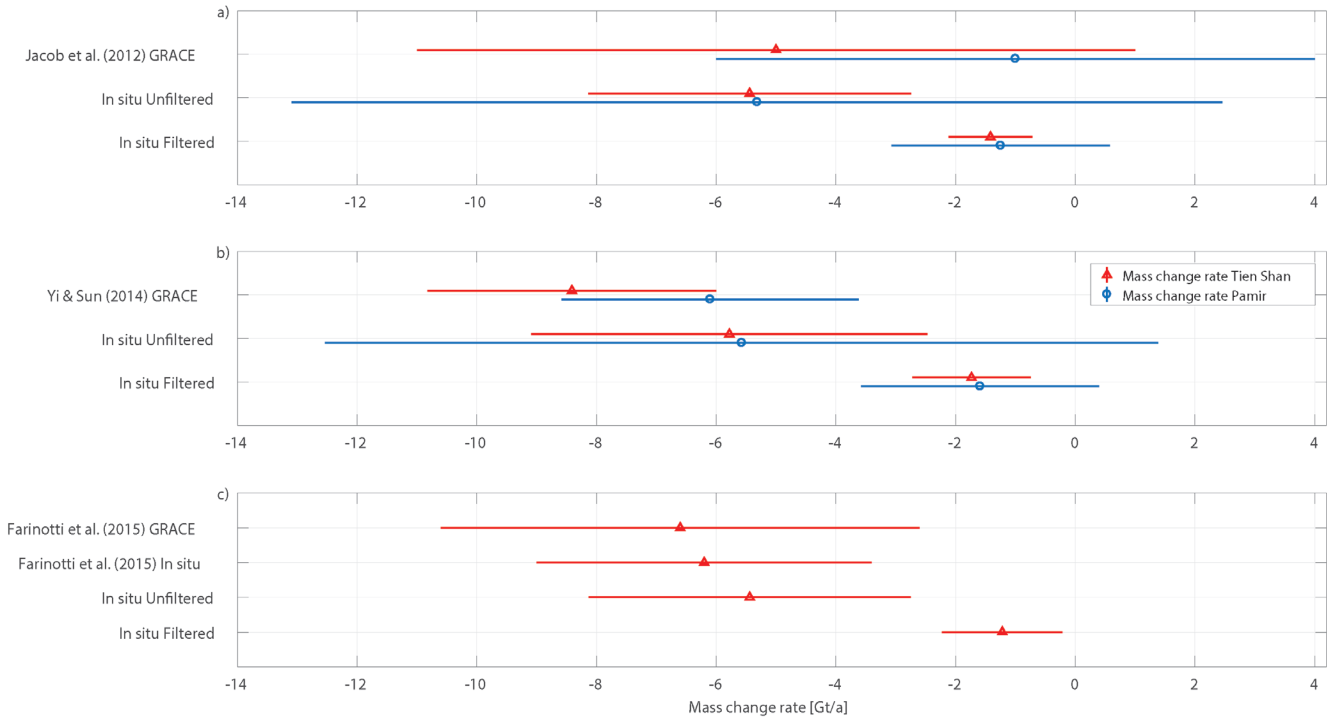

FIGURE 5. Comparison between mass change rates of the current and of three previous studies in Gt a^{-1}. Data from Tien Shan are given in red and from Pamir in blue. Triangles denote values of Tien Shan, circles values of Pamir with corresponding error range. Due to the different settings (see text), extrapolated in situ mass change rates are recalculated for the comparison with (a) Jacob et al. (2012), (b) Yi and Sun (2014), and (c) Farinotti et al. (2015). In addition to GRACE-related data, Farinotti et al. (2015) published a mass change rate based on in situ glacier mass balance data, both for Tien Shan.

of the annual in situ values for this study. Not surprising, both extrapolations show a good agreement except for 2011. As far as the data could be compared, the annual GRACE as the extrapolated in situ data are at least correct in their pattern and there is no explanation for the unsatisfying matching between the annual values.

For further evaluation of the results, the mass change rates of this study are compared with three previous studies using GRACE in the same area (Fig. 5). The extrapolated in situ mass balance data had to be recalculated according to the setting used in the respective studies and converted to Gt a^{-1} by multiplication with the glacier area. Jacob et al. (2012) used University of Texas Center for Space Research (CSR) GRACE RL04 data from January 2003 to December 2010, which corresponds roughly to the hydrological years 2003–2010. They applied a Gaussian filter with a 350 km half-wavelength and truncated the SHC at degree and order 60. Their Tien Shan area corresponds to the area used here, but the Pamir area is larger and includes the Kunlun Shan and Karakoram (Kääb et al., 2015). Therefore, there is limited comparability with this data set because of the different change rates (more balanced or slightly positive at least during 2003–2008) in these two additional regions (Kääb et al., 2015). Their result is –5 ± 6 Gt a^{-1} for the Tien Shan and –1 ± 5 Gt a^{-1} for the Pamir area. The extrapolated unfiltered in situ mass change rate (–5.44 ± 2.70 Gt a^{-1}) fits quite well to their result for the Tien Shan and the filtered rate (–1.25 ± 1.82 Gt a^{-1}) to their result for the Pamir (Fig. 5, part a), despite the different glacier areas of the Pamir. GRACE RL04 data overestimate the glacier melt rate in these two regions compared to GRACE RL05 (Yi and Sun, 2014). The overestimation of about 30% (estimated after data comparison from Yi and Sun [2014]) would reduce the results from Jacob et al. (2012) to –3.5 ± 4.2 Gt a^{-1} for the Tien Shan and –0.7 ± 3.5 Gt a^{-1} for the Pamir area but would not change the result of the comparison with the extrapolated in situ data.

Yi and Sun (2014) used CSR GRACE RL05 data from January 2003 to December 2012, approximately corresponding to the hydrological years 2003–2012. They used the same preprocessing setup as the current study. Their Tien Shan area corresponds roughly to the area used here, but the Pamir area is also larger and includes the Hindu Kush and Karakoram. Their results are –8.41 ± 2.41 Gt a^{-1} for the Tien Shan and –6.10 ± 2.48 Gt a^{-1} for the Pamir area. The extrapolated unfiltered in situ mass change rates fit better to their result for both areas with -5.78 ± 3.31 Gt a^{-1} for the Tien Shan and -5.57 ± 6.96 Gt a^{-1} for the Pamir (Fig. 5, part b).

Farinotti et al. (2015) used an ensemble approach of different GRACE solutions and processing methods for the Tien Shan. Their Tien Shan area corresponds roughly to the area used here. Their GRACE period ranges from January 2003 to December 2009, approximately corresponding to the hydrological years 2003–2009. They also used an ensemble approach to calculate glacier mass balance based on in situ data. For comparison, an ensemble approach is used to calculate the extrapolated filtered in situ data, that is, the mean of three different processing setups for the same time frame. Processing setups are:

- a Gaussian filter with a 350 km half-wavelength, SHC until degree and order 60,
- a Gaussian filter with a 300 km half-wavelength, SHC until degree and order 60,
- a Gaussian filter with a 400 km half-wavelength, SHC until degree and order 50.

The result from Farinotti et al. (2015) for the ensemble GRACE data is -6.6 ± 4.0 Gt a^{-1} and -6.2 ± 2.8 Gt a^{-1} for the ensemble in situ data. The result from the extrapolated unfiltered in situ data with -5.44 ± 2.69 Gt a^{-1} fits quite well to their results (Fig. 5, part c).

When comparing our results with results from previous studies, extrapolation of the unfiltered in situ data fits better for all cases in the Tien Shan and for two of three cases in the Pamir.

CONCLUSION

In this study a methodology is presented to compare the in situ glacier mass balance data measured by the glaciological method with mass balance data derived by GRACE and WGHM-TWS. The in situ data are averaged arithmetically (1) taken as they are, and (2) preprocessed with the same smoothing filter as the GRACE and WGHM-TWS data. In the comparison of the resulting glacier mass balances, the extrapolated in situ data and GRACE minus WGHM-TWS (Diff GW) do not agree very well on an annual basis. Comparing the mass change rates, the extrapolated filtered in situ data fit quite well to Diff GW. In a further comparison with data from literature, the extrapolated unfiltered in situ data perform well. In conclusion, the extrapolation of the unfiltered in situ data shows better results compared with GRACE-derived results.

More in situ measurements, especially in the Pamir, would be necessary to strengthen the reliability of the results for the study area. Additionally, the methodology presented in this study could be applied to other regions with denser glacier measurements to confirm the result from this area—for example, to Iceland (cf. Gardner et al., 2013).

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REFERENCES CITED

Abelen, S., and Seitz, F., 2013: Relating satellite gravimetry data to global soil moisture products via data harmonization and correlation analysis. *Remote Sensing of Environment,* 136: 89–98.

Aizen, V. B., Aizen, E. M., Melack, J. M., and Dozier, J., 1997: Climatic and hydrologic changes in the Tien Shan, Central Asia. *Journal of Climate,* 10(6): 1393–1404.

Arendt, A. A., Bliss, A., Bolch, T., Cogley, G., Gardner, A. S., Hagen, J. O., Hock, R., Huss, M., Kaser, G., Kienholz, C., Pfeffer, W. T., Moholdt, G., Paul, F., Radić, V., Andreassen, L. M., Bajracharya, S., Barrand, N., Beedle, M., Berthier, E., Bhambri, R., Brown, I., Burgess, E., Burgess, D., Cawkwell, F., Chinn, T. J. H., Copland, L., Davies, B., De Angelis, H., Dolgova, E., Filbert, K., Forester, R. R., Fountain, A. G., Frey, H., Giffen, B., Glasser, N. F., Gurney, S., Hagg, W., Hall, D., Haritashya, U. K., Hartmann, G., Helm, C., Herreid, S., Howat, I., Kapustin, G., Khromova, T., König, M., Kohler, J., Kriegel, D., Kutuzov, S., Lavrentiev, I., Le Bris, R., Lund, J., Manley, W., Mayer, C., Miles, E. S., Li, X., Menounos, B., Mercer, A., Mölg, N., Mool, P., Nosenko, G., Negrete, A., Nuth, C., Pettersson, R., Racoviteanu, A., Ranzi, R., Rastner, P., Rau, F., Raup, B., Rich, J., Rott, H., Schneider, C., Seliverstov, Y., Sharp, M. J., Sigurðsson, O., Stokes, C., Wheate, R. D., Winsvold, S., Wolken, G. J., Wyatt, F., and Zheltyhina, N., 2014: *Randolph Glacier Inventory—A Dataset of Global Glacier Outlines: Version 4.0.* Boulder, Colorado: Global Land Ice Measurements from Space Technical Report, http://www.glims.org/RGI/00_rgi40_TechnicalNote.pdf.

Barandun, M., Huss, M., Sold, L., Farinotti, D., Azisov, E., Salzmann, N., Usubaliev, R., Merkushkin, A., and Hoelzle, M., 2015: Re-analysis of seasonal mass balance at Abramov Glacier 1968–2014. *Journal of Glaciology,* 61(230): 1103–1117.

Barry, R. G., 2006: The status of research on glaciers and global glacier recession: a review. *Progress in Physical Geography,* 30(3): 285–306.

Bolch, T., 2005: Rezenter Gletscherschwund und Klimawandel im nördlichen Tien Shan (Kasachstan / Kyrgyzstan). *Mitteilungen der Fränkischen Geographischen Gesellschaft,* 52: 157–174.

Bolch, T., 2006: *GIS- und fernerkundungsgestützte Analyse und Visualisierung von Klima- und Gletscheränderungen im nördlichen Tien Shan (Kasachstan/Kyrgyzstan) mit einem Vergleich zur Bernina-Gruppe/Alpen*. PhD thesis, Naturwissenschaftliche Fakultäten, Friedrich-Alexander-Universität Erlangen-Nürnberg, Nürnberg-Erlangen, Germany, 216 pp.

Cogley, J. G., 2009: Geodetic and direct mass-balance measurements: comparison and joint analysis. *Annals of Glaciology,* 50(50): 96–100.

Döll, P., and Fiedler, K., 2008: Global-scale modeling of groundwater recharge. *Hydrology and Earth System Sciences,* 12(3): 863–885.

Döll, P., Kaspar, F., and Lehner, B., 2003: A global hydrological model for deriving water availability indicators: model tuning and validation. *Journal of Hydrology,* 270(1-2): 105–134.

Döll, P., Hoffmann-Dobrev, H., Portmann, F. T., Siebert, S., Eicker, A., Rodell, M., Strassberg, G., and Scanlon, B. R., 2012: Impact of water withdrawals from groundwater and surface water on continental water storage variations. *Journal of Geodynamics,* 59: 143–156.

Dyurgerov, M. B., 2002: *Glacier Mass Balance and Regime: Data of Measurements and Analysis*. Boulder: University of Colorado, Institute of Arctic and Alpine Research, Occasional Paper 55, https://instaar.colorado.edu/other/download/OP55_glaciers.pdf.

Dyurgerov, M. B., 2010: Reanalysis of glacier changes: from the IGY to the IPY, 1960–2008. *Data of Glaciological Studies,* 108: 1–116.

Dyurgerov, M. B., and Meier, M. F., 2005: *Glaciers and the changing Earth system: a 2004 snapshot*. Boulder: University of Colorado, Institute of Arctic and Alpine Research, Occasional Paper 58, https://instaar.colorado.edu/uploads/occasional-papers/OP58_dyurgerov_meier.pdf.

Dyurgerov, M., Mikhalenko, V., Kunakhovitch, M., Ushnurtsev, S., Liu, C., and Xie, Z., 1994: On the cause of glacier mass balance variations in the Tian Shan Mountains. *GeoJournal,* 33(2): 311–317.

Farinotti, D., Longuevergne, L., Moholdt, G., Duethmann, D., Molg, T., Bolch, T., Vorogushyn, S., and Güntner, A., 2015: Substantial glacier mass loss in the Tien Shan over the past 50 years. *Nature Geoscience,* 8(9): 716–722.

Flechtner, F., Thomas, M., and Dobslaw, H., 2010: Improved non-tidal atmospheric and oceanic de-aliasing for GRACE and SLR satellites. *In* Flechtner, F., Gruber, T., Güntner, A., Mandea, M., Rothacher, M., Schöne, T., and Wickert, J. (eds.), *System Earth via Geodetic-Geophysical Space Techniques*: Berlin: Springer, 131–142.

Fujita, K., and Nuimura, T., 2011: Spatially heterogeneous wastage of Himalayan glaciers. *Proceedings of the National Academy of Sciences,* 108(34): 14011–14014.

Gardelle, J., Berthier, E., Arnaud, Y., and Kääb, A., 2013: Region-wide glacier mass balances over the Pamir-Karakoram-Himalaya during 1999–2011. *The Cryosphere,* 7(4): 1263–1286.

Gardner, A. S., Moholdt, G., Cogley, J. G., Wouters, B., Arendt, A. A., Wahr, J., Berthier, E., Hock, R., Pfeffer, W. T., Kaser, G., Ligtenberg, S. R. M., Bolch, T., Sharp, M. J., Hagen, J. O., van den Broeke, M. R., and Paul, F., 2013: A reconciled estimate of glacier contributions to sea level rise: 2003 to 2009. *Science,* 340(6134): 852–857.

Geruo, A., Wahr, J., and Zhong, S., 2013: Computations of the viscoelastic response of a 3-D compressible Earth to surface loading: an application to Glacial Isostatic Adjustment in Antarctica and Canada. *Geophysical Journal International,* 192(2): 557–572.

Hagg, W., Hoelzle, M., Wagner, S., Mayr, E., and Klose, Z., 2013a: Glacier and runoff changes in the Rukhk catchment, upper Amu-Darya basin until 2050. *Global and Planetary Change,* 110(A): 62–73.

Hagg, W., Mayer, C., Lambrecht, A., Kriegel, D., and Azizov, E., 2013b: Glacier changes in the Big Naryn basin, Central Tian Shan. *Global and Planetary Change,* 110(A): 40–50.

Hirabayashi, Y., Döll, P., and Kanae, S., 2010: Global-scale modeling of glacier mass balances for water resources assessments: glacier mass changes between 1948 and 2006. *Journal of Hydrology,* 390(3-4): 245–256.

Hunger, M., and Döll, P., 2008: Value of river discharge data for global-scale hydrological modeling. *Hydrology and Earth System Sciences,* 12(3): 841–861.

Huss, M., 2012: Extrapolating glacier mass balance to the mountain-range scale: the European Alps 1900–2100. *The Cryosphere,* 6(4): 713–727.

Huss, M., Bauder, A., and Funk, M., 2009: Homogenization of long-term mass-balance time series. *Annals of Glaciology,* 50(50): 198–206.

Jacob, T., Wahr, J., Pfeffer, W. T., and Swenson, S., 2012: Recent contributions of glaciers and ice caps to sea level rise. *Nature,* 482: 514–518.

Jarvis, A., Reuter, H. I., Nelson, A., and Guevara, E., 2008: Hole-filled SRTM for the globe (Version 4). http://srtm.csi.cgiar.org, accessed 31 March 2015.

JPL, 2015a: Overview—Monthly Mass Grids. http://grace.jpl.nasa.gov/data/monthly-mass-grids/, accessed 12 August 2015.

JPL, 2015b: Monthly Mass Grids—Land. http://grace.jpl.nasa.gov/data/get-data/monthly-mass-grids-land/, accessed 12 August 2015.

JPL, 2015c: GRACE-FO. http://grace.jpl.nasa.gov/mission/grace-fo/, accessed 13 August 2015.

Kääb, A., Treichler, D., Nuth, C., and Berthier, E., 2015: Brief Communication. Contending estimates of 2003–2008 glacier mass balance over the Pamir–Karakoram–Himalaya. *The Cryosphere,* 9(2): 557–564.

Khromova, T. E., Osipova, G. B., Tsvetkov, D. G., Dyurgerov, M. B., and Barry, R., 2006: Changes in glacier extent in the eastern Pamir, Central Asia, determined from historical data and ASTER imagery. *Remote Sensing of Environment,* 102(1-2): 24–32.

Kotlyakov, V. M., Dyakova, A. M., Koryakin, V. S., Kravtsova, V. I., Osopova, G. B., Varnakova, G. M., Vinogradov, V. N., Vinogradov, O. N., and Zverkova, N. M., 2010: Glaciers of Asia—Glaciers of the former Soviet Union. *In* Williams, R. S. J., and Ferringo, J. G. (eds.), *Satellite Image Atlas of Glaciers of the World*. U.S. Geological Survey Professional Paper 1386-F, chapter F-1, https://pubs.usgs.gov/pp/p1386f/.

Kronenberg, M., Barandun, M., Hoelzle, M., Huss, M., Farinotti, D., Azisov, E., Usubaliev, R., Gafurov, A., Petrakov, D., and Kääb, A., 2016: Mass balance reconstruction for Glacier No. 354, Tien Shan, from 2003 to 2014. *Annals of Glaciology,* 57(71): 92–102.

Longuevergne, L., Scanlon, B. R., and Wilson, C. R., 2010: GRACE Hydrological estimates for small basins: evaluating processing approaches on the High Plains Aquifer, USA. *Water Resources Research,* 46(11): W11517, doi http://dx.doi.org/10.1029/2009WR008564.

Matsuo, K., and Heki, K., 2010: Time-variable ice loss in Asian high mountains from satellite gravimetry. *Earth and Planetary Science Letters,* 290(1-2): 30–36.

Mölg, T., Maussion, F., and Scherer, D., 2014: Mid-latitude westerlies as a driver of glacier variability in monsoonal High Asia. *Nature Climate Change,* 4(1): 68–73.

Moriasi, D. N., Arnold, J. G., Liew, M. W. V., Bingner, R. L., Harmel, R. D., and Veith, T. L., 2007: Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the American Society of Agricultural and Biological Engineers,* 50(3): 885−900.

Müller Schmied, H., Eisner, S., Franz, D., Wattenbach, M., Portmann, F. T., Flörke, M., and Döll, P., 2014: Sensitivity of simulated global-scale freshwater fluxes and storages to input data, hydrological model structure, human water use and calibration. *Hydrology and Earth System Sciences,* 18(9): 3511–3538.

Nash, J. E., and Sutcliffe, J. V., 1970: River flow forecasting through conceptual models part I—A discussion of principles. *Journal of Hydrology,* 10(3): 282–290.

Pieczonka, T., Bolch, T., Junfeng, W., and Shiyin, L., 2013: Heterogeneous mass loss of glaciers in the Aksu-Tarim Catchment (Central Tien Shan) revealed by 1976 KH-9 Hexagon and 2009 SPOT-5 stereo imagery. *Remote Sensing of Environment,* 130: 233–244.

Ray, R. D., Rowlands, D. D., and Egbert, G. D., 2003: Tidal models in a new era of satellite gravimetry. *In* Beutler, G., Drinkwater, M. R., Rummel, R., and Von Steiger, R. (eds.), *Earth Gravity Field from Space—From Sensors to Earth Sciences*: Dordrecht: Netherlands, Springer, 271–282.

Schnitzer, S., Seitz, F., Eicker, A., Güntner, A., Wattenbach, M., and Menzel, A., 2013: Estimation of soil loss by water erosion in the Chinese Loess Plateau using Universal Soil Loss Equation and GRACE. *Geophysical Journal International,* 193(3): 1283–1290.

Solomina, O., Barry, R., and Bodnya, M., 2004: The retreat of Tien Shan glaciers (Kyrgyzstan) since the Little Ice Age estimated from aerial photographs, lichenometric and historical data. *Geografiska Annaler: Series A, Physical Geography,* 86(2): 205–215.

Swenson, S., and Wahr, J., 2002: Methods for inferring regional surface-mass anomalies from Gravity Recovery and Climate Experiment (GRACE) measurements of time-variable gravity. *Journal of Geophysical Research: Solid Earth,* 107(B9): ETG 3-1–ETG 3-13.

Swenson, S., and Wahr, J., 2006: Post-processing removal of correlated errors in GRACE data. *Geophysical Research Letters,* 33(8): L08402, doi http://dx.doi.org/10.1029/2005GL025285.

Tapley, B. D., Bettadpur, S., Ries, J. C., Thompson, P. F., and Watkins, M. M., 2004a: GRACE measurements of mass variability in the Earth System. *Science,* 305(5683): 503–505.

Tapley, B. D., Bettadpur, S., Watkins, M., and Reigber, C., 2004b: The Gravity Recovery and Climate Experiment: mission overview and early results. *Geophysical Research Letters,* 31(9): L09607, doi http://dx.doi.org/10.1029/2004GL019920.

Vincent, C., Ramanathan, A., Wagnon, P., Dobhal, D. P., Linda, A., Berthier, E., Sharma, P., Arnaud, Y., Azam, M. F., Jose, P. G., and Gardelle, J., 2013: Balanced conditions or slight mass gain of glaciers in the Lahaul and Spiti region (northern India, Himalaya) during the nineties preceded recent mass loss. *The Cryosphere,* 7(2): 569–582.

Wahr, J., Molenaar, M., and Bryan, F., 1998: Time variability of the Earth's gravity field: hydrological and oceanic effects and their possible detection using GRACE. *Journal of Geophysical Research,* 103(B12): 30205–30229.

Wahr, J., Swenson, S., and Velicogna, I., 2006: Accuracy of GRACE mass estimates. *Geophysical Research Letters,* 33(6): L06401, doi http://dx.doi.org/10.1029/2005GL025305.

Werth, S., and Güntner, A., 2010: Calibration analysis for water storage variability of the global hydrological model WGHM. *Hydrology and Earth System Sciences,* 14(1): 59–78.

WGMS, 2013: *Glacier Mass Balance Bulletin No. 12 (2010–2011)*, Zurich: University of Zurich, http://wgms.ch/downloads/wgms_2013_gmbb12.pdf.

Xie, C., Ding, Y., Caiping, C., and Han, T., 2007: Study on the change of Keqikaer Glacier during the last 30 years, Mt. Tuomuer, western China. *Environmental Geology*, 51(7): 1165–1170.

Yao, T., Thompson, L., Yang, W., Yu, W., Gao, Y., Guo, X., Yang, X., Duan, K., Zhao, H., Xu, B., Pu, J., Lu, A., Xiang, Y., Kattel, D. B., and Joswiak, D., 2012: Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings. *Nature Climate Change,* 2(9): 663–667.

Yi, S., and Sun, W., 2014: Evaluation of glacier changes in high-mountain Asia based on 10 year GRACE RL05 models. *Journal of Geophysical Research: Solid Earth,* 119(3): 2504–2517, doi http://dx.doi.org/10.1002/2013JB010860.

Zhang, Y., Liu, S., Ding, Y., Li, J., and Shangguan, D., 2006: Preliminary study of mass balance on the Keqicar Baxi Glacier on the south slopes of Tianshan Mountains. *Journal of Glaciology and Geocryology,* 28(4): 477–484.

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