Supplement of The Cryosphere, 17, 5435–5458, 2023
https://doi.org/10.5194/tc-17-5435-2023-supplement

The Cryosphere
Open Access

Supplement of

Annual to seasonal glacier mass balance in High Mountain Asia derived from Pléiades stereo images: examples from the Pamir and the Tibetan Plateau

Daniel Falaschi et al.

Correspondence to: Daniel Falaschi (dfalaschi@mendoza-conicet.gob.ar)

Supplementary material

3.1.10 Ice dynamics considerations

As stated in Sect. 1 of the main manuscript, geodetic mass balance assessments have been often used to calibrate contemporary glaciological measurements. Differences amongst them in relation to vertical surface elevation changes have been attributed to firn densification and vertical ice velocity. Whilst differencing of elevation changes from *dDEM* and glaciological observations should yield representative emergence and submergence velocities (Pelto et al., 2019), glaciological data is unfortunately unavailable as part of this study. Alternatively, Belart et al. (2017) implemented a full-Stokes model by ingesting glacier bedrock and surface DEMs, in situ GPS velocities, coupled with the firn densification model derived realistic emergence and submergence velocities. This, however, was beyond the scope of the present study, as the influence of ice dynamics on overall mass budget is usually very small (<5%) on a year-to-year basis and only significant when calculating mass budget over few decades (e.g. Mukherjee et al. 2022).

S3.3 Investigating the influence of climate (temperature and precipitation) on glacier mass balance

To understand how the precipitation and temperature may have influenced the response of the glaciers in the study sites, we used remotely–sensed daily Global Precipitation Measurement (GPM) IMERG late run precipitation observations (Hou et al. 2014, Huffman et al. 2015). We opted to use the GPM precipitation dataset over reanalysis data (e.g. APHRODITE, ERA5, HARv2), since they have proven to largely over- or underestimate precipitation over the Tibetan Plateau (Wortmann et al., 2018; Lin et al., 2021). We used monthly temperature estimates from ERA5 Land (Hersbach et al. 2020, Muñoz-Sabater et al. 2021), a gridded reanalysis data based on numerical weather prediction models.

We converted the daily GPM precipitation data to monthly data and calculated the monthly solid precipitation as all the precipitation when the corresponding temperature is less than 0°C. To estimate seasonal temperature and solid precipitation, we assumed May-October as summer months and November-April as winter months. We then obtained the total amount of solid precipitation for each year by matching with the dates/months of the geodetic data as shown in Table S1.

To determine the relation between glacier mass balance and climate variability, we first calculated the annual, winter and summer average temperature and snowfall over the 2001-2022 time periods and then calculated annual and seasonal mean temperature and total snowfall anomalies. Finally, we correlated the glacier-wide mass budgets with the annual and seasonal variations of temperature and snowfall. To do this, we used our mass budget estimates at annual scale, added the geodetic mass balance values in Bhattacharya et al. (2021), and performed a correlation analysis using the averaged climate records for analogous sub-periods. Whilst we focus on our shorter 2020-2022 period, our aim was to evaluate climate conditions of the last three years in a longer climate/mass balance context.

S4.3 Relation between climate (temperature and precipitation) and mass balance

In Muztag Ata, the summer (+0.5 °C to -1.1 °C) and winter (-0.9 °C and +0.3 °C) temperature anomalies were either positive or negative among the surveyed 2020 to 2022 hydrological years, and showed no prominence within the 2001-2022 period (Fig. S1c, e). In contrast, winter snowfall anomalies were all positive between 2020 and 2022, but still within the 2001-2022 range. It must be also noted that snowfall anomalies (either winter or summer) are of rather small magnitude, especially compared to those in Western Nyainqêntanglha. These results indicate that air temperatures and solid precipitation in the 2020 and 2021 surveyed years were representative of recent climate conditions in Muztag Ata. We were, however, unable to find any significant correlation between climate variability and mass balance in Muztag Ata (Fig. S1a-f). Winter snowfall showed the highest correlation coefficient ($r = 0.36$; $p = 0.47$; $\alpha = 0.05$) amongst the investigated seasonal variables in Muztag Ata.

In Western Nyainqêntanglha, the surveyed 2020-2022 hydrological years all had positive summer temperature anomalies (around +0.6 °C), which were at the same time amongst the highest in the last two decades (summer anomaly range: -1.2 °C to +0.7 °C). The 2021 and 2022 winter seasons also showed positive temperature anomalies (+1.6 °C and +0.6 °C; winter anomaly range: -3.3 °C to +3.0 °C; Fig. S1g-j). Of the last 16 years, 12 of them showed positive summer air temperatures anomalies. Likewise, the winter season has also shown positive temperature anomalies for 8 of the last 10 years. The years 2021 and 2022 were therefore among the warmest and driest in Western Nyainqêntanglha over approximately the last two decades. We found a strong correlation between temperature anomalies and mass balance at both annual ($r = 0.97$, $p = 0.03$) and seasonal (summer) scale ($r = 0.75$, $p = 0.08$). In regard to solid precipitation, our surveyed years showed highly negative summer anomalies of up to ~16 mm/year. This likely contributed to the overall negative annual snowfall anomalies, which have been negative since 2014. Overall, the correlation between mass balance and solid precipitation was weak ($r < 0.52$) and non-significant either at annual or seasonal scale.

Supplementary Tables:

Table S1: Months for different mass balance years to calculate snowfall

Region	Months and years for climate analysis		
	2020	**2021**	**2022**
Muztag Ata	Sep 2019 – Sep 2020	Oct 2020 – Sep 2021	Oct 2021 – Sep 2022
Western Nyainqêntanglha	Nov 2019 – Sep 2020	Oct 2020 – Sep 2021	Oct 2021 – Oct 2022

Table S2: Firn area- and wet snow area-ratios

	2019			**2020**			**2021**			**2022**		
	FR	**WR**	**GI**	**FR**	**WR**	**GI**	**FR**	**WR**	**GI**	**FR**	**WR**	**GI**
Muztag Ata												
Total glacier area	0.55	0.23	0.32	0.56	0.17	0.35	0.58	0.23	0.39	0.60	0.15	0.45
Kekesayi	0.34	0.17	0.17	0.35	0.14	0.21	0.36	0.14	0.22	0.37	0.09	0.28
No. 15	0.84	0.16	0.68	0.85	0.01	0.84	0.86	0.01	0.85	0.90	0.01	0.89
Western Nyainqêntanglha												
Total glacier area	0.28	0.66	-0.38	0.26	0.33	-0.07	0.27	0.57	-0.30	0.25	0.50	-0.25
Xibu	0.25	0.50	-0.25	0.25	0.29	-0.04	0.24	0.46	-0.22	0.23	0.37	-0.14
Zhadang	0.01	0.52	-0.51	0.01	0.06	-0.05	0.01	0.41	-0.40	~0	0.50	-0.50

Supplementary figures:

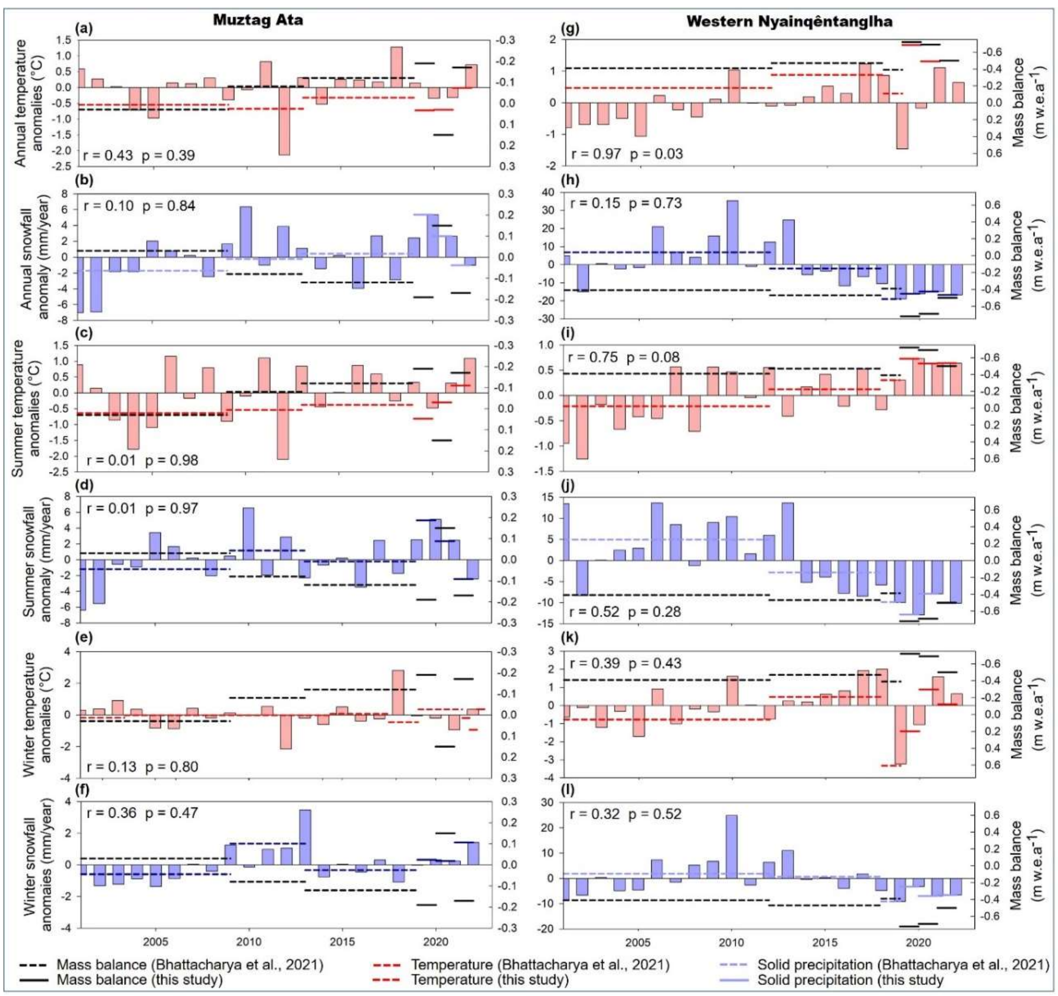

Figure S1. Evolution of geodetic glacier mass balance compared to annual and seasonal temperature and snowfall anomalies in Muztag Ata (a-f) and Western Nyainqêntanglha (g-l). In the temperature panels, the mass-balance values on the right axis have been reversed for a better interpretation.

References

Belart, J. M. C., Berthier, E., Magnússon, E., Anderson, L. S., Pálsson, F., Thorsteinsson, T., Howat, I. M., Aðalgeirsdóttir, G., Jóhannesson, T., and Jarosch, A. H.: Winter mass balance of Drangajökull ice cap (NW Iceland) derived from satellite sub-meter stereo images, Cryosphere, 11(3), 1501–1517, https://doi.org/10.5194/tc-11-1501-2017, 2017.

Bhattacharya, A., Bolch, T., Mukherjee, K., King, O., Menounos, B., Kapitsa, V., Neckel, N., Yang, W., and Yao, T.: High Mountain Asian glacier response to climate revealed by multi-temporal satellite observations since the 1960s, Nat. Commun., 12(1), 4133, https://doi.org/10.1038/s41467-021-24180-y, 2021.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., … Thépaut, J.: The ERA5 global reanalysis, Q. J. R. Meteorol. Soc., 146(730), 1999–2049, https://doi.org/10.1002/qj.3803, 2020.

Hou, A. Y., Kakar, R. K., Neeck, S., Azarbarzin, A. A., Kummerow, C. D., Kojima, M., Oki, R., Nakamura, K., and Iguchi, T.: The Global Precipitation Measurement Mission, Bull Am Meteorol Soc., 95(5), 701–722, https://doi.org/10.1175/BAMS-D-13-00164.1, 2014.

Huang, L., Hock, R., Li, X., Bolch, T., Yang, K., Wang, N., Yao, T., Zhou, J., Dou, C., and Li, Z.: Winter accumulation drives the spatial variations in glacier mass balance in High Mountain Asia, Sci. Bull., S2095927322003644, https://doi.org/10.1016/j.scib.2022.08.019, 2022.

Huffman, G. J., Bolvin, D. T., Braithwaite, D., Hsu, K., Joyce, R., Xie, P., and Yoo, S. H.: NASA global precipitation measurement (GPM) integrated multi-satellite retrievals for GPM (IMERG). Algorithm Theoretical Basis Document (ATBD) Version, 4(26), 2015.

Lin, Q., Chen, J., Chen, D., Wang, X., Li, W., and Scherer, D.: Impacts of bias-corrected ERA5 initial snow depth on dynamical downscaling simulations for the Tibetan Plateau, J. Geophys. Res. Atmos., 126(23), https://doi.org/10.1029/2021JD035625, 2021.

Mukherjee, K., Menounos, B., Shea, J., Mortezapour, M., Ednie, M., and Demuth, M. N.: Evaluation of surface mass-balance records using geodetic data and physically-based modelling, Place and Peyto glaciers, western Canada, J. Glaciol., 1–18, https://doi.org/10.1017/jog.2022.83, 2022.

Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G., Boussetta, S., Choulga, M., Harrigan, S., Hersbach, H., Martens, B., Miralles, D. G., Piles, M., Rodríguez-Fernández, N. J., Zsoter, E., Buontempo, C., and Thépaut, J.-N.: ERA5-Land: A state-of-the-art global reanalysis dataset for land applications, Earth System Science Data, 13(9), 4349–4383, https://doi.org/10.5194/essd-13-4349-2021, 2021.

Pelto, B. M., Menounos, B., and Marshall, S. J.: Multi-year evaluation of airborne geodetic surveys to estimate seasonal mass balance, Columbia and Rocky Mountains, Canada, Cryosphere, 13(6), 1709–1727, https://doi.org/10.5194/tc-13-1709-2019, 2019.

Wortmann, M., Bolch, T., Menz, C., Tong, J., and Krysanova, V.: Comparison and correction of high-mountain precipitation data based on glacio-hydrological modeling in the Tarim River headwaters (High Asia), J. Hydrometeorol., 19(5), 777–801, https://doi.org/10.1175/JHM-D-17-0106.1, 2018.