The glacier geodetic mass balance and its hydrological contribution to runoff in the Yarlung Zangbo-Brahmaputra basin

中國科学院青藏高原研究所
Institute of Tibetan Plateau Research
Chinese Academy of Sciences

中国科学院大学
University of Chinese Academy of Sciences

Nauman Ali[1,2], Lan Cuo[1], Qinghua Ye[1], Xueqin Zhang[3], Yafan Hu[1,2], Xinhui Ji[1,2], Lei Wang[1], Junbo Wang[1], Liping Zhu[1]

[1]State Key Laboratory Tibetan Plateau Earth System, Environment and Resources (TPESER), Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China.
[2]University of Chinese Academy of Sciences, Beijing 100049, China.
[3]Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China.

Key points

- *The glacier area has decreased by 0.56 % a^{-1} from 1970s to 2020.*
- *Glacier mass balance (GMB) significantly changed.*
- *The GMB contribution to runoff increased from 0.05 % a^{-1} in 2000 – 2004 to 0.86 % a^{-1} in 2015 – 2019.*
- *The GMB validation was carried out with in-situ observations for six glaciers.*

Introduction

- High Mountain Asia (HMA), often known as the "**Third pole**" (Yao et al., 2012), has the most glaciers outside the polar zone (Consortium, 2017).
- **Glacier meltwater** increasingly affects streamflow that **feeds 1.5 billion downstream** (Yao et al., 2012).
- Over **15,000 glaciers** in the Yarlung Zangbo–Brahmaputra basin (YB) feed **a trans–boundary river** from **China** to **India** and **Bangladesh** into the **Indian Ocean**, supporting 80 million people.
- The impact of **glacier changes** on **YB catchment's** runoff is unknown.
- The **glacier inventory** requires urgent **updating** and revisions.
- Therefore, the research's primary objectives are:

(1) **Establish** a 2020 **glacier inventory** for debris-free glaciers in the YB;
(2) Study **glacier area changes** from **1970s** to **2020**;
(3) Calculate **glacier surface elevation change**, and **geodetic mass balance** in the YB and its catchments;
(4) Estimate **glacier meltwater contribution**.

Study area

- The Yarlung Zangbo–Brahmaputra basin (YB) stretches from **81.97°E to 97.87°E** east to west and **23.32°N to 31.48°N** from south to north.
- The Brahmaputra River **originates** from the **Angsi Glacier**, in **China**, and flows towards the southeast.
- It is a **trans–boundary** basin covering parts of **China, India, Nepal, Bhutan, and Bangladesh.**
- The YB is divided into **nine main catchments** (ICIMOD, 2021).
- The Yarlung Zangbo catchment (hereafter YZ_m) is largest catchment in the YB. It is further divided into **nine sub–catchments**.

Datasets and Methods

Datasets : We used the **Landsat 8 Operational Land Imager (OLI)** and the **Sentinel 2** images to update the glacier inventory in 2020. Further publicly available, **DEMs** including the **NASADEM** (JPL, 2020) and the **Copernicus DEM (GLO30)** (Agency, 2024), laser altimetry data from the **ICESat–2**, and **elevation change datasets from (Hugonnet et al., 2021)** were used to study GMB. In order to validate our GMB results we used **in–situ observations for the six selected glaciers** from literature. **Discharge data** was used with GMC data to estimate glacier meltwater contribution to runoff.

Dataset	Time	Spatial Resolution	Sources and references
Landsat images	2013–021	30 m	https://earthexplorer.usgs.gov (accessed on 10 March 2023)
Sentinel–2 images	2016–2021	10 m	https://browser.dataspace.copernicus.eu (accessed on 10 March 2023)
NASADEM	2000	30 m	https://portal.opentopography.org (accessed on 02 September 2024)
Copernicus DEM (GLO30)	December 2010–November 2015	30 m	https://portal.opentopography.org (accessed on 02 September 2024)
ICESat–2 ATL06	October 2018–June 2023	~17 m	https://nsidc.org/data/atl06/versions/5 (accessed on 10 November 2023)
Radar Penetration in snow.	2000	1° × 1°	(Jiang, 202)
The glacier surface elevation changes rate data (Dh_{ASTER})	2000–2019 [1]	100 m	(Hugonnet et al., 2021)
Discharge data (GloFAS-ERA5)	2000–2023	0.1° × 0.1°	(Harrigan et al., 2020)
GGI–18			(Consortium, 2023; Sakai, 2019)
TPG1976, TPG2001, TPG2013	1970s, 2001, 2013		(Ye et al., 2017)
TPG2018			(Ye, 2019)
CGI–2	2004–2011		(Guo et al., 2015)
Outline of basin, catchments and sub-catchments			(Guo et al., 2015; ICIMOD, 2021a, 2021b)

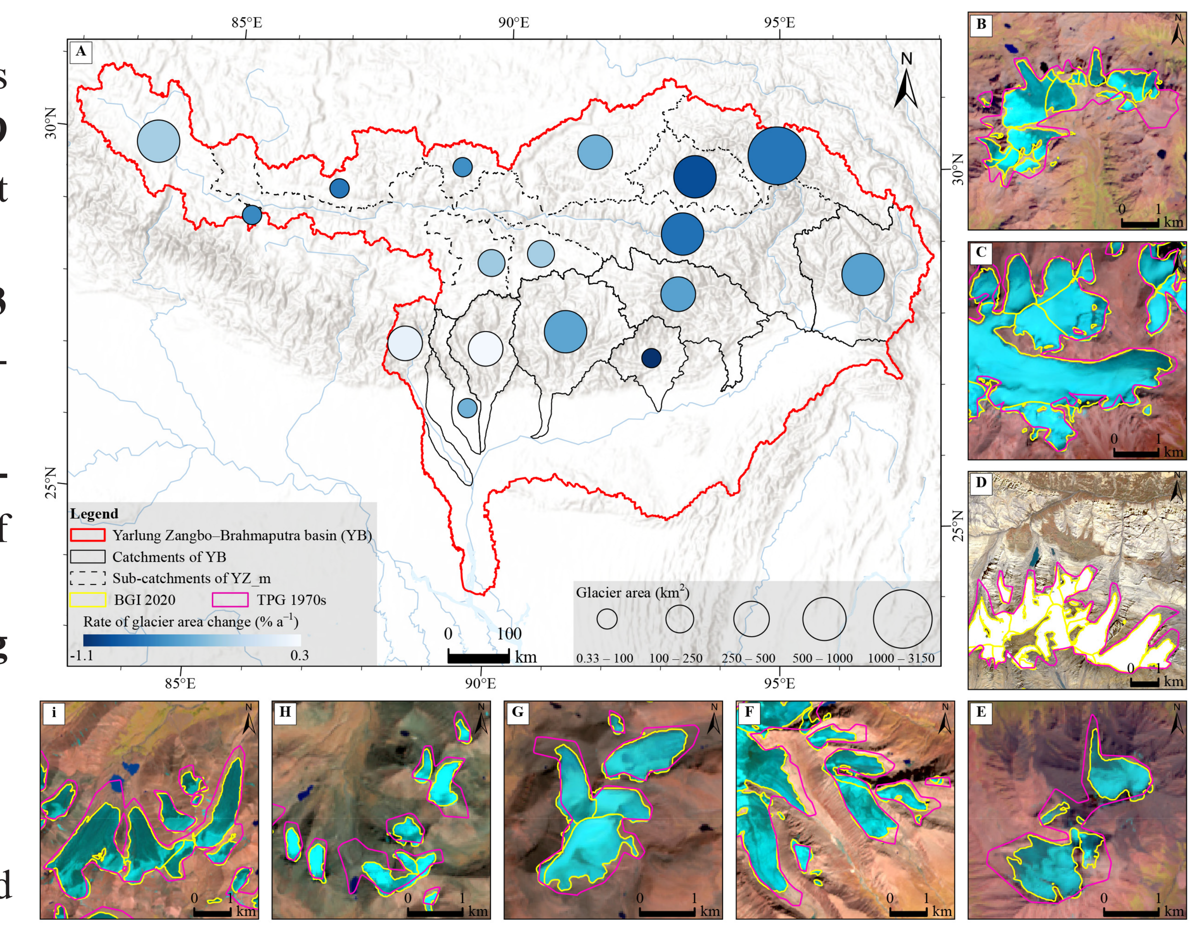
Methods

- **Glacier mapping :** The **band ratio** technique was used in the **Google earth engine** to map debris-free glaciers. The **TPG1970s** dataset was compared to know the area change from 1970s to 2020.
- **Geodetic glacier mass balance :** The geodetic glacier mass balance was estimated using **DEM differencing** and **altimeter** method. **In-situ observations** from **six glaciers** were used to validate the GMB results.
- **Glacier meltwater contribution** : The **glacier meltwater contribution** was estimated using the **discharge data** from **GloFAS-ERA5** on the **outlets of catchments** and the **glacier mass change** from geodetic mass balance.

Results

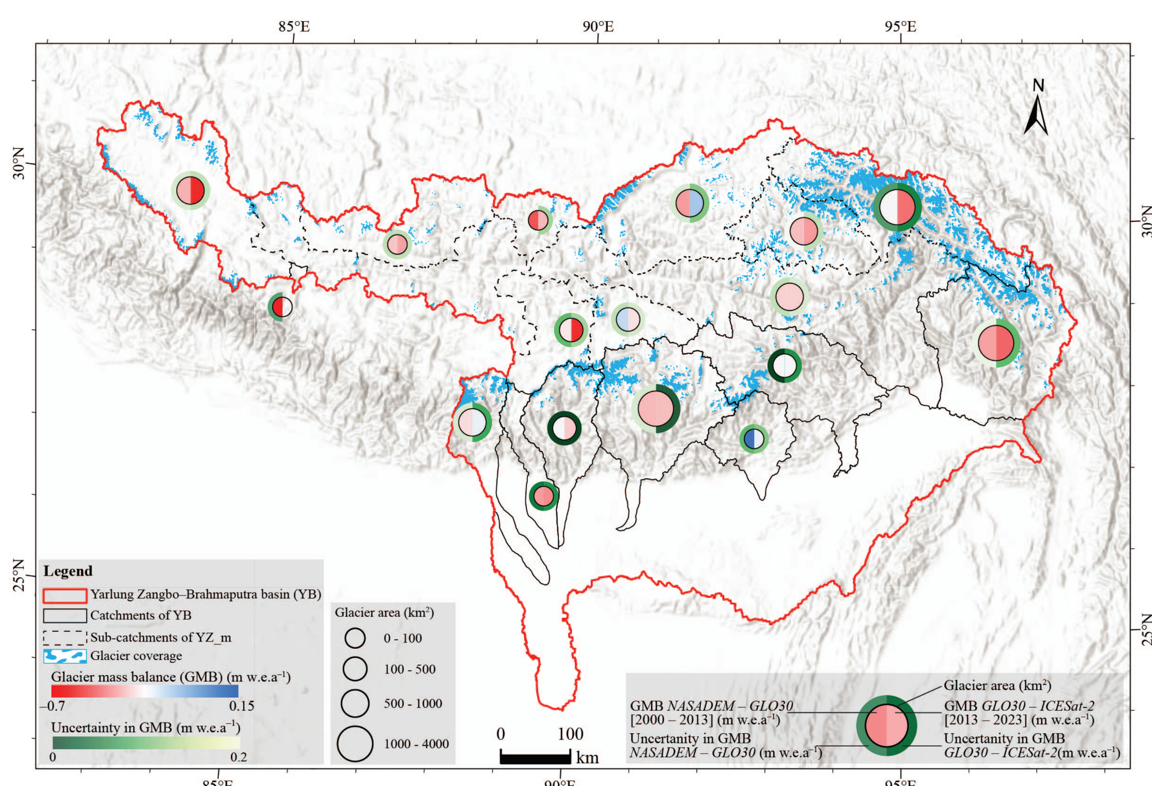
Glacier area change

- We identified **15,032** pieces of glaciers (> 0.01 km²) covering **9,081 ± 12.59 km²** of glacier area across different catchments of the YB.
- The glacier **area shrank** from **12,638.3 ± 758.3 km²** to **9,081 ± 12.09 km²** between **1970s** and **2020**.
- A total of **3,557.30 ± 758.39 km² glacier area lost**, with an **average rate** of **–0.56 % a^{-1}**.
- The glacier area in the YB is **shrinking** with **spatial heterogeneities**.



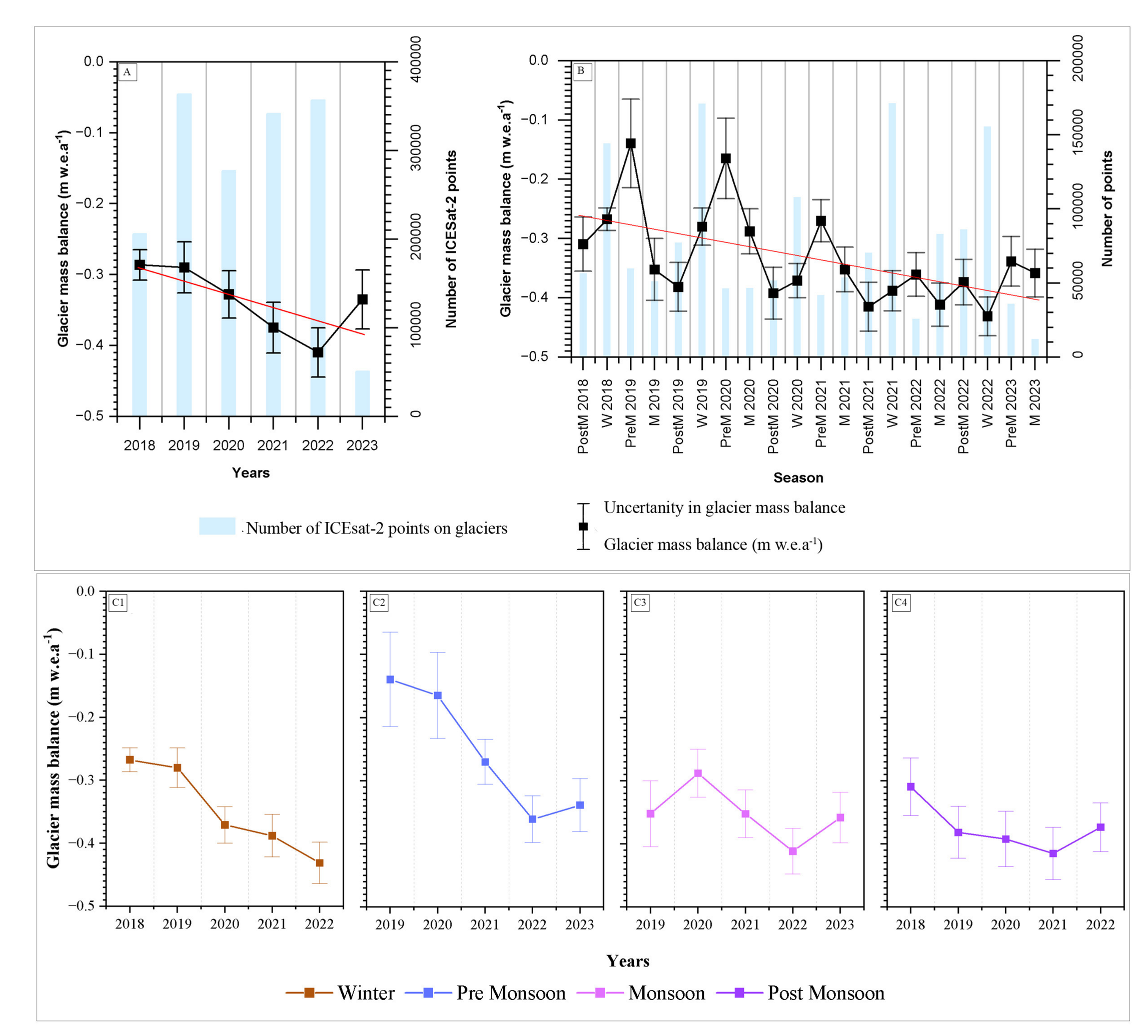
Glacier mass balance

- Glaciers located in the **Eastern** and **Southwestern** parts of the YB are experiencing **more negative** GMB than those on the western edges.
- The result derived from $\mathbf{Dh_{GLO30–NASADEM}}$ (2013 – 2013) shows, the GMB was **–0.42 ± 0.02 m w.e.a⁻¹**, and GMC was **–4.61 ± 0.41 Gt a⁻¹**.
- The results from $\mathbf{Dh_{ICESat–2–GLO30}}$ (2013 – 2023) show, the GMB was **–0.34 ± 0.03 m w.e.a⁻¹**, and the GMC was **–3.79 ± 0.29 Gt a⁻¹**.
- The **GMB** derived from $\mathbf{Dh_{ASTER}}$ for **2000–2004** was **–0.36 m w.e.a⁻¹** corresponding to **GMC –3.95 Gt a⁻¹**, which **increased** up to **–0.64 m w.e.a⁻¹ GMB**, corresponding to **–7.07 Gt a⁻¹ of GMC** in **2015–2019**.



Annual and seasonal glacier mass balances from 2018 to 2023

- The **annual and seasonal** GMB calculations from $\mathbf{Dh_{ICESat–2–GLO30}}$ show that **glacier recession increased** in the YB from 2018 to 2023.
- The **maximum glacier recession** was observed in **2022**, where GMB was –0.41 ± 0.03 m w.e.a⁻¹, the corresponding GMC was –4.54 ± 0.39 Gt a⁻¹.
- The glacier recession **increases from the pre–monsoon to the post–monsoon** season.
- The **seasonal variation** in the GMB shows most **significant increase in glacier mass loss** in the **pre–monsoon season.**



Glacier contribution to runoff

- The **glacier meltwater contribution** to runoff in the YB was **0.45% over 2000–2004**, while it **increased** dramatically to **1.05% between 2015 - 2019**.
- The **highest glacier melt contribution** to runoff was observed in the **Yarlung Zangbo catchment**.

Conclusion

- A total of 15,032 glaciers were identified in the YB, covering 9,081 ± 12.59 km² as of 2020.
- Over the past 50 years, the YB has lost 3,557.3 ± 758.39 km² of glacier area, at an average rate of –0.56% a^{-1}.
- Glacier shrinkage shows significant spatial heterogeneity across the basin, reflecting the influence of local topography and climatic conditions.
- Glaciers in the eastern and southwestern YB exhibit more negative glacier mass balance (GMB) compared to those in the western region.
- Seasonal analysis indicates greater glacier mass loss during the pre-monsoon season than in the post-monsoon, highlighting strong seasonal sensitivity.
- The contribution of glacier meltwater to runoff has increased in recent years.
- Overall, the findings highlight rapid and spatially variable glacier recession in the YB, underlining the need for continued monitoring and adaptive water resource management.

Refferences

- Agency, E. S. (2024). Copernicus GLO-30 Digital Elevation Model (OpenTopography. https://doi.org/https://doi.org/10.5069/G9028PQB
- Ali, N., Ye, Q., Zhang, X., Ji, X., Hu, Y., Zhu, L., & Ali, A. (2022). Glacier Changes in India's Dhauliganga Catchment over the Past Two Decades. Remote Sensing, 14(22). https://doi.org/10.3390/rs14225692
- Alifu, H., Hirabayashi, Y., Johnson, B., Vuillaume, J., Kondoh, A., & Urai, M. (2018). Inventory of Glaciers in the Shaksgam Valley of the Chinese Karakoram Mountains, 1970-2014 [Article]. Remote Sensing, 10(8), Article ARTN 1166. https://doi.org/10.3390/rs10081166
- Alifu, H., Johnson, B. A., & Tateishi, R. (2016). Delineation of Debris-Covered Glaciers Based on a Combination of Geomorphometric Parameters and a TIR/NIR/SWIR Band Ratio. Ieee Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 9(2), 781-792. https://doi.org/10.1109/Jstars.2015.2500906
- Alifu, H., Tateishi, R., & Johnson, B. (2015). A new band ratio technique for mapping debris-covered glaciers using Landsat imagery and a digital elevation model. International Journal of Remote Sensing, 36(8), 2063-2075. https://doi.org/10.1080/2150704x.2015.1034886
- Brun, F., Berthier, E., Wagnon, P., Kaab, A., & Treichler, D. (2017). A spatially resolved estimate of High Mountain Asia glacier mass balances, 2000-2016. Nature Geoscience, 10(9), 668-673. https://doi.org/10.1038/NGEO2999
- Brunt, K. M., Neumann, T. A., & Larsen, C. F. (2019). Assessment of altimetry using ground-based GPS data from the 88S Traverse, Antarctica, in support of ICESat-2. The Cryosphere, 13(2), 579-590. https://doi.org/10.5194/tc-13-579-2019
- Consortium, R. (2017). Randolph glacier inventory–a dataset of global glacier outlines: Version 6.0: technical report, global land ice measurements from space, Colorado, USA. (5).
- Fan, Y., Ke, C.-Q., Zhou, X., Shen, X., Yu, X., & Lhakpa, D. (2022). Glacier mass-balance estimates over High Mountain Asia from 2000 to 2021 based on ICESat-2 and NASADEM. Journal of Glaciology, 1-13. https://doi.org/10.1017/jog.2022.78
- 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., & Paul, F. (2013). A Reconciled Estimate of Glacier Contributions to Sea Level Rise: 2003 to 2009. Science, 340(6134), 852-857. https://doi.org/10.1126/science.1234532
- Guo, W., Liu, S., Wei, J., & Bao, W. (2017). The 2008/09 surge of central Yulinchuan glacier, northern Tibetan Plateau, as monitored by remote sensing. Annals of Glaciology, 54(63), 299-310. https://doi.org/10.3189/2013AoG63A495
- Guo, W., Liu, S., Xu, J., Wu, L., Shangguan, D., Yao, X., Wei, J., Bao, W., Yu, P., Liu, Q., & Jiang, Z. (2015). The second Chinese glacier inventory: data, methods and results. Journal of Glaciology, 61(226), 357-372. https://doi.org/10.3189/2015JoG14J209
- 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. N. (2020). The ERA5 global reanalysis. Quarterly Journal of the Royal Meteorological Society, 146(730).
- Hugonnet, R., McNabb, R., Berthier, E., Menounos, B., Nuth, C., Girod, L., Farinotti, D., Huss, M., Dussaillant, I., Brun, F., & Kaab, A. (2021). Accelerated global glacier mass loss in the early twenty-first century. Nature, 592(7856), 726-+. https://doi.org/10.1038/s41586-021-03436-z
- Huss, M. (2013). Density assumptions for converting geodetic glacier volume change to mass change. The Cryosphere, 7(3), 877-887. https://doi.org/10.5194/tc-7-877-2013
- ICIMOD. (2021). Sub-sub-basins of Hindu Kush Himalaya (HKH) Region (https://doi.org/https://doi.org/10.26066/RDS.7952
- Jacob, T., Wahr, J., Pfeffer, W. T., & Swenson, S. (2012). Recent contributions of glaciers and ice caps to sea level rise.