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# The shrinking crown of the tropics: A consistent accelerated trend of glacier retreat since the 1980s

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**Dear Editor,**

Glaciers are recognized as sensitive indicators of global climate change.[1] In recent decades, under the influence of global warming, most glaciers worldwide have experienced significant retreat.[2,3] Equatorial glaciers, in particular, have shown a high sensitivity to climate change and have generally experienced accelerated area reduction and mass loss.[2] However, the current understanding of glacier changes in equatorial regions remains limited. While previous studies have documented area changes of individual glaciers across different regions (e.g., Kilimanjaro, Mount Kenya),[4-9] these findings are spatially and temporally fragmented, lacking a comprehensive analysis of overall area change in equatorial glaciers. Likewise, although existing studies on mass balance have quantified the overall mass loss in low-latitude regions,[2,3,10] they have not specifically addressed the unique climatic and topographic conditions of equatorial glaciers, which may not fully capture the unique climate characteristics of the core equatorial zone. A systematic investigation of the overall evolution trend of glacier area and mass balance in the equatorial region is therefore essential to reveal their spatiotemporal change patterns, inform conservation strategies, and support climate change adaptation.

This study aims to systematically monitor the spatiotemporal evolution trends of glacier area and mass balance in the equatorial region (5°N-5°S) from the 1980s to 2024. Based on glacier inventories and existing research, all glaciers within this region are selected, exactly the 12 glaciers. By collecting multi-source optical remote sensing images and DEM products, we first extract glacier areas using the band ratio method, typically using data from visible and short-wave infrared bands to delineate glacier boundaries. The combination of bands utilized includes bands 3 and 5 from Landsat TM and ETM+ images, as well as bands 4 and 6 from Landsat OLI images. Glacier boundaries extracted for the early period (around the 1980s) and the recent period (the latest available year for each glacier) are combined with DEM to derive glacier area-elevation distributions by aggregating glacier area within fixed elevation intervals. The equilibrium-line altitude (ELA) is estimated on the Google Earth Engine (GEE) platform using the accumulation area ratio (AAR) method under a steady-state assumption. The AAR is determined as the ratio of the spectrally classified snow-covered area, identified via NDSI and NIR thresholds at the end of the ablation season, to the total glacier area. To account for the highly fragmented snow cover typical of equatorial glaciers, the effective ELA is mathematically derived from the hypsometric curve as the specific elevation contour that partitions an upper accumulation area equal to the observed AAR, ensuring strict geometric self-consistency. We then estimate the glacier elevation changes and mass balance in the near-equatorial region via the geodetic method (i.e., DEM differencing), utilizing the SRTM DEM (2000), Copernicus DEM (2012), and ASTER DEM (2021, 2024). On this basis, we conduct a long-term analysis of 12 glaciers across three major sub-regions, revealing the overall spatial pattern of trends of glacier retreat and mass loss in equatorial zones (Figure 1A). These findings will help fill the knowledge gap in comprehensively quantifying the changes of equatorial glaciers and provide a valuable data basis for the prediction of glacier melting in tropical regions.

Since the 1980s, glaciers in the equatorial region have shown an accelerating trend of area retreat (Figure 1A). The retreat rates of glaciers in South America are significantly higher than those in eastern Africa and Indonesia. The spatial heterogeneity of area loss is closely linked to the initial glacier size. As illustrated by the proportional symbols in Figure 1A, South American glaciers, which possess much larger initial areas, exhibit the highest absolute reduction. However, when normalized by initial extent, the relative retreat rates in East Africa and Indonesia are equally significant, reflecting a universal vulnerability of near-equatorial glaciers to recent climatic shifts. Among them, Nevado del Ruiz has experienced the fastest area loss (-0.49 $km^2$/a), followed by Chimborazo (-0.37 $km^2$/a) and El Altar (-0.36 $km^2$/a). In terms of the percentage of area reduction, Mount Kenya (79%) and Chimborazo (74%) show the most significant reductions, followed by Nevado del Ruiz (71%) and Ngga Pulu (69%), consistent with local observations reported by Prinz et al.[7] and Permana et al.[8] The rate of glacier area change in other regions ranges from -0.02 to -0.37 $km^2$/a, and the percentage of area reduction is between 14% and 44%.

In terms of glacier mass balance changes, equatorial glaciers have generally experienced sustained mass loss, although the rates vary significantly among individual glaciers (Figure 1A). During the 2000-2012 period, the most pronounced mass loss rates were observed at Santa Isabel (-1.62 ± 0.17 m w.e./a) and Chimborazo (-0.97 ± 0.08 m w.e./a), followed by El Altar (-0.71 ± 0.07 m w.e./a) and Kilimanjaro (-0.62 ± 0.13 m w.e./a). The slowest rates of mass loss occurred at Tolima (-0.03 ± 0.02 m w.e./a) and Mount Kenya (-0.09 ± 0.04 m w.e./a). Other glaciers exhibited moderate mass loss, with the rate of change ranging from -0.20 ± 0.04 to -0.62 ± 0.13 m w.e./a. From 2012 to 2024, the ablation rate generally increased and showed marked spatial heterogeneity. In this later period, glaciers in East Africa showed significantly intensified mass loss, with Kilimanjaro and Mount Kenya reaching -0.95 ± 0.18 m w.e./a and -0.75 ± 0.08 m w.e./a, respectively—representing increases of 53% and 733% compared to the previous period. In South America, the ablation rate of Nevado del Ruiz rose to -0.73 ± 0.07 m w.e./a, whereas Nevado Santa Isabel saw a decline to -0.45 ± 0.09 m w.e./a. Other glaciers experienced apparently negative mass balance ranging from -0.16 ± 0.05 to -0.73 ± 0.07 m w.e./a. The comparison between the two periods indicates that climate warming has a disproportionately greater impact on smaller glaciers, such as Mount Kenya, where topographic feedbacks, including reduced local albedo from exposed bedrock and the lowering of the glacier surface into warmer air layers, further amplify regional heterogeneity. Small glaciers are particularly vulnerable to climate change due to their low volume-to-area ratio, which translates surface melting into rapid relative mass loss. Furthermore, as these ice bodies shrink, the surrounding terrain's reduced albedo and increased sensible heat flux create a positive feedback loop that accelerates ablation. Unlike larger ice fields, these small remnants often lack a sufficient accumulation buffer, making them highly sensitive to even minor upward shifts in the ELA.

Based on multi-source remote sensing data, this study quantified the glacier area-elevation distribution and ELA for both study periods (Figure 1B). The comparison reveals a widespread and significant trend of glacier retreat across the region. Morphological analysis indicates that glacier area loss exhibits strong elevation dependence, with the vast majority of glaciers experiencing drastic area reduction at lower elevations. Notably, the glacier tongues of Nevado del Ruiz, Cayambe, and El Altar have almost completely disappeared, resulting in a significant rise in their terminus elevations. This

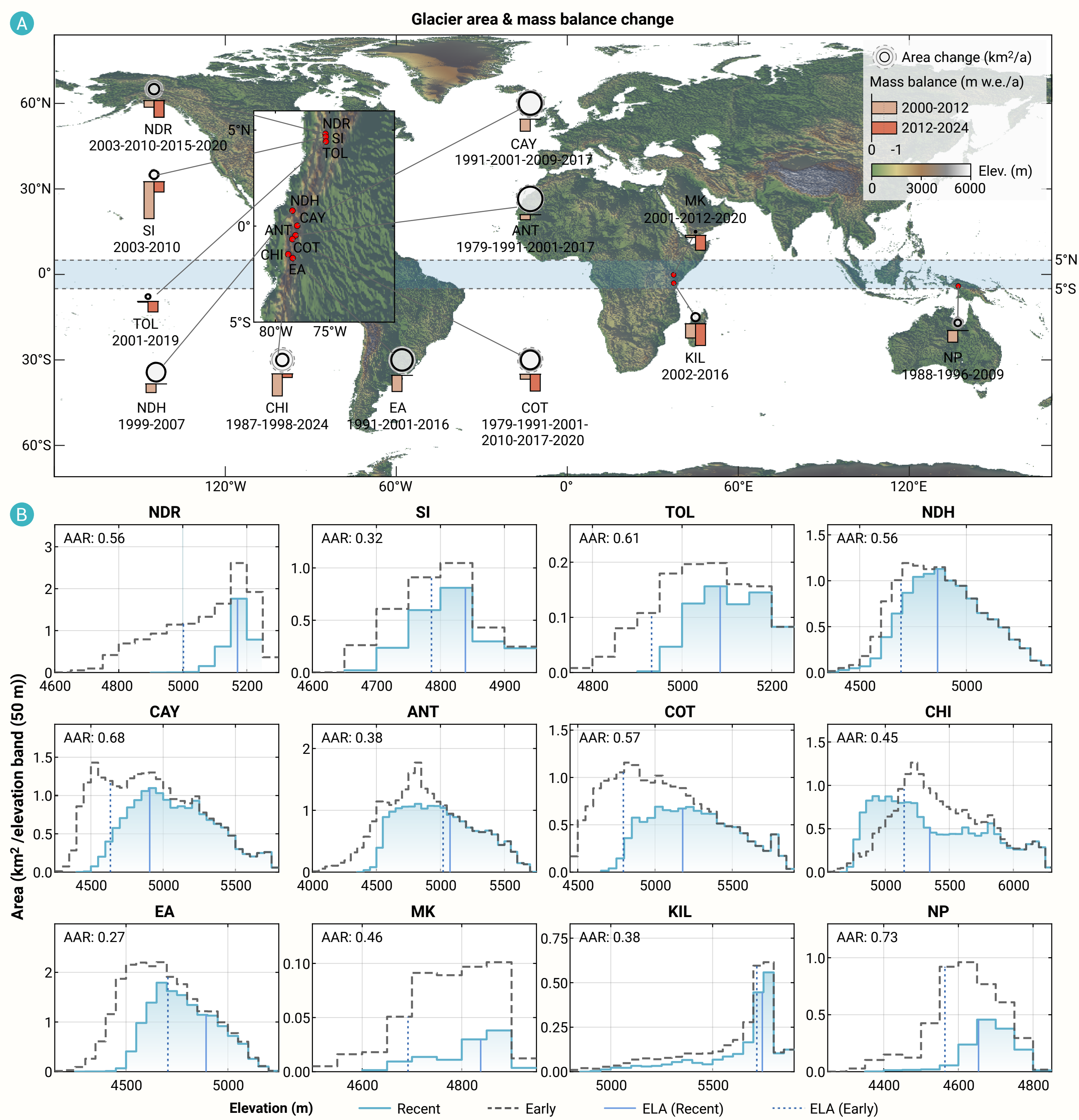


**Figure 1. Spatiotemporal changes in glacier area and mass balance in the equatorial region since the 1980s** (A) Changes in glacier area and mass balance, including nine glaciers in South America [Nevado del Ruiz (NDR), Santa Isabel (SI), Tolima (TOL), Nevado del Huila (NDH), Cayambe (CAY), Antisana (ANT), Cotopaxi (COT), Chimborazo (CHI) and El Altar (EA)], two in Africa [Mount Kenya (MK) and Kilimanjaro (KIL)], and one in Indonesia [Ngga Pulu (NP)]. Concentric circles indicate glacier area reduction at different years, with line styles transitioning from dashed to solid and line width increasing from the outer to the inner circle; the labels beneath the circles indicate the glacier and observation year. The dark yellow and dark orange rectangles represent glacier mass balance during 2000-2012 and 2012-2024, respectively. The base map is derived from the Copernicus DEM. (B) Variations in area-elevation distribution and ELA for the twelve representative glaciers. Dotted lines represent the area distribution of the early period, while colored solid lines with shading indicate the recent period. Vertical lines mark the ELA positions for the corresponding periods. The text of AAR refers to the recent period (around 2024).

overall contraction of the distribution curve towards higher altitudes and the reduction in curve amplitude reveal that glaciers have undergone significant areal retreat at their termini; when integrated with our geodetic mass balance results, it is evident that these glaciers are concurrently experiencing substantial thinning and spatial contraction. This reflects the dominant role of ablation at lower elevations under climate warming and its consequent reshaping of glacier geometry. This phenomenon is further corroborated by the evolution of the ELAs. The analysis shows that recent ELAs exhibit a distinct upward trend compared to the early period, indicating an upward migration of the ELA driven by rising air temperatures. Furthermore, we calculated the AAR of the 12 monitored glaciers (Figure 1B), revealing a mean AAR of 0.50 with significant heterogeneity. Six glaciers, including Nevado del Ruiz and Tolima, maintained a healthy status (AAR > 0.50), averaging 0.62 and peaking at 0.73, likely driven by local precipitation or topographic factors.

Conversely, the remaining six glaciers exhibited significant retreat. Notably, glaciers such as El Altar recorded some of the lowest AAR values in the region (AAR = 0.27), highlighting the heightened vulnerability to climate warming. If current trends continue, based on linear extrapolation, it is expected that glaciers on Nevado del Ruiz, Santa Isabel, Mount Kenya, and Ngga Pulu may disappear by 2030, and the others may disappear within this century. Such losses could lead to water shortages and ecological imbalance, and may also exacerbate regional climate warming and the occurrence of extreme weather events. And it has an impact on the development of tourism characterized by glaciers and related economic activities.

This study conducts a systematic analysis of the evolution of near-equatorial glaciers since the 1980s by integrating multiple-source satellite data and generates a dataset of glacier changes over more than 40 years, which offers a scientific basis for water resource management and climate policy formulation. The results show that the overall area of equatorial glaciers experienced an accelerated retreat and continuous mass loss, but there are significant regional differences. The glaciers in South America are shrinking at the fastest rate, with some glaciers losing over 70% of their area. Notably, since 2012, while the trend of glacier mass loss remains pervasive, the rate of loss shows significant spatial heterogeneity. Intensified mass loss is particularly evident in East African peaks and certain South American glaciers (e.g., NDR, COT), whereas other sites in South America exhibit a sustained but non-accelerated rate of thinning. This highlights the complex interplay between regional climate forcing and local topographic buffering. To address the challenge of the accelerated melting of equatorial glaciers, future research urgently needs to strengthen collaborative observations, deepen multi-scale coupled studies of climate, glaciers and ecosystems, and incorporate small glaciers (< 0.5 $km^2$) into the core framework of global cryosphere monitoring to mitigate the risks and impacts caused by their disappearance.

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## AUTHOR CONTRIBUTIONS

S.R. and X.L. designed the study with contributions from Y.Z. S.R. wrote the manuscript. X.L., D.Z., Y.Z., and Y.G. edited the manuscript. S.R., D.Z., M.F, and Y.G. interpreted the results, performed the analyses, and drafted the figures. All authors contributed to the final form of the study. All authors contributed to the manuscript and approved the final version.

## DECLARATION OF INTERESTS

The authors declare no competing interests.