

Spatially heterogeneous wastage of Himalayan glaciers

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We describe volumetric changes in three benchmark glaciers in the Nepal Himalayas on which observations have been made since the 1970s. Compared with the global mean of glacier mass balance, the Himalayan glaciers showed rapid wastage in the 1970s–1990s, but similar wastage in the last decade. In the last decade, a glacier in an arid climate showed negative but suppressed mass balance compared with the period 1970s–1990s, whereas two glaciers in a humid climate showed accelerated wastage. A mass balance model with downscaled gridded datasets depicts the fate of the observed glaciers. We also show a spatially heterogeneous distribution of glacier wastage in the Asian highlands, even under the present-day climate warming.

climate change | equilibrium line altitude

A recent study (1) has highlighted gross inadequacies both in our knowledge of important changes occurring to Himalayan glaciers and in two recent reports that have alternately overestimated (2) and seriously underestimated (3) the pace of shrinkage of Himalayan glaciers without, in either report (2, 3), offering a compelling basis. However, the rate at which Himalayan glaciers are shrinking remains poorly constrained because ground-based measurements are hampered by the high altitude and remoteness of the region. This lack of observational data has given rise to large uncertainties in both observation-based (4–6) and simulation-based (7–9) projections of global sea-level rise. These studies relied on relationships established for well-studied glaciers under a Euro-American climate. However, this approach may be inaccurate because the seasonal cycle of precipitation has a strong effect on the surface albedo and thus on glacier melt in the monsoonal Asian region (10).

In addition, much of the debate on the fate of Himalayan glaciers has missed an important consideration of the height and trend of the equilibrium-line altitude (ELA), which divides the glacier into areas of ablation and accumulation (11). The ELA is important because, for example, if the glacier has no accumulation area for a period because the ELA is located above the glacier, the glacier is destined to disappear over time (12). Unfortunately, observations of the mass balance and ELA of Himalayan glaciers have been made only in recent years (13, 14).

To address these problems, in the present study we update the elevation data for Himalayan benchmark glaciers, providing information for the past decades. We calculate changes in the mass balance and ELA of the three benchmark glaciers using an energy-mass balance model with downscaled gridded climate datasets, in order to describe the state and fate of glaciers. Further calculations are performed to assess the spatial representativeness of the observation-based results.

Locations and Method

The three benchmark glaciers [Rikha Samba (RS), Yala (YL), and AX010 (AX)] are situated at diverse locations in the Nepal Himalayas (Fig. 1A). Changes in the surface elevation of these glaciers have been observed intermittently by geodetic surveys between the 1970s and the 1990s (14–17) (Figs. S1–S3). In this study, we conducted carrier-phase global positioning system (GPS) surveys between 2008 and 2010 to provide up-to-date data

on changes in the elevations of the glacier surfaces since the most recent previous measurements in the 1990s (Figs. S4 and S5).

Results

Changes in Glacier Volume. Fig. 1B shows area-averaged mass balances (mass balance averaged for the entire glacier) calculated in this study along with those reported previously (14–17). Glacier wastage (negative mass balance) for the last decade is highly variable and is comparable to the global mean (6), whereas wastage in the previous two decades is much larger than the global mean. The RS glacier, in a comparatively arid area of western Nepal, shows suppressed wastage in the last decade compared with the previous two decades. In contrast, the two glaciers in a comparatively humid area of eastern Nepal show strongly accelerated wastage in the last decade.

A comparison of the mass balance results and annual precipitation reveals that glacier wastage has been accelerated in humid environments but suppressed in an arid environment (Fig. 1C). Previous observational (4, 16) and numerical (7, 10) studies have reported that glaciers respond more sensitively to warming in a humid environment in terms of mass balance. Glaciers in such an environment can exist at lower altitudes due to the large amount of snow accumulation, making them more sensitive to warming via changes in the fraction of precipitation occurring as rainfall (which affects accumulation) and changes in surface albedo (which affects ablation) (7, 10). Because the YL and AX glaciers are located in relatively humid environments and at lower altitudes (Fig. 1, Fig. S4, and Table S1), they are expected to show large amounts of wastage in response to recent warming.

Fate of Glaciers. To describe the fate of the three glaciers, we calculated their mass balance and ELA using an energy-mass balance model (18), employing recently archived gridded climate datasets (19, 20). We downscaled daily air temperature and precipitation in the datasets with those observed close to the glaciers for short periods (Table S2). Further calibration for air temperature was performed to yield the minimum rms error (rmse) against the surveyed area-averaged mass balance.

Fig. 2 shows the area–altitude distribution, calculated ELA, and preferable ELA for the present glacier extent (Fig. 2A–C) and the calculated and surveyed area-averaged mass balance for each glacier (Fig. 2D–F). Also shown are mass balances reconstructed from analyses of ice cores recovered from the RS and YL glaciers (21, 22). The preferable ELA is defined as the ELA in the case that its mass balance profile gives an area-averaged mass balance of zero; i.e., the glacier would retain its present extent if the ELA is located at the preferable altitude. All of the calculated

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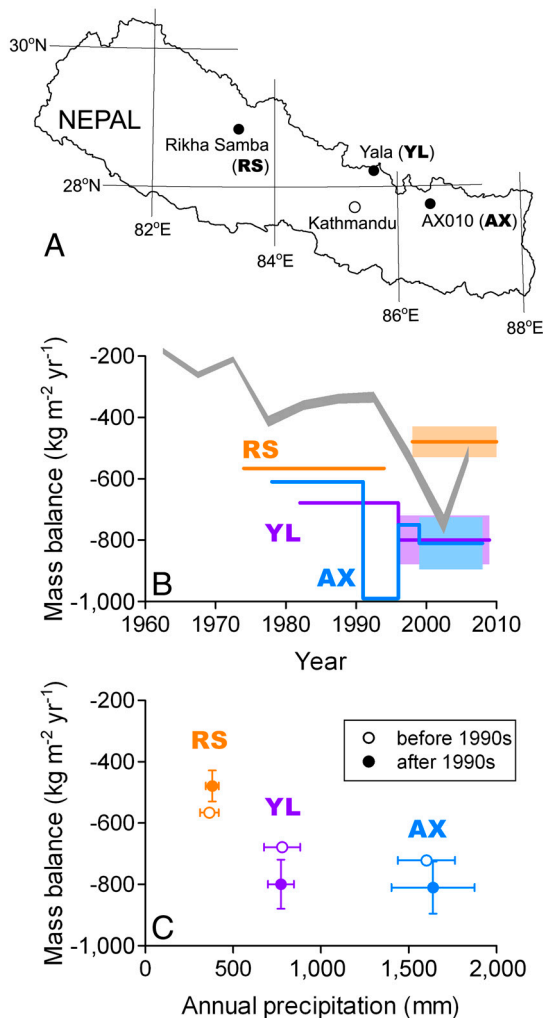


Fig. 1. Location of the three benchmark glaciers in Nepal (A), temporal changes in the area-averaged mass balances of the glaciers compared with the pentadal global mean (gray line) (6) (B), and mass balances compared with annual precipitation (C). Color shading in B and vertical bars in C denote measurement errors of mass balance. Horizontal bars in C denote variability of annual precipitation. See *SI Text* about the error evaluation and the downscaling.

ELAs are located above the preferable ELAs (Fig. 2 A–C); consequently, the area-averaged mass balances are all negative (except for the AX glacier in the 1970s and around 1990). However, the ELA for the RS glacier has fluctuated within the altitudinal extent of glacier and has descended since the 1990s, indicating that the glacier wastage has been suppressed in the last decade. If the present climate conditions persist, the RS glacier will approach an alternative equilibrium and will be maintained. In contrast, the ELAs of the YL and AX glaciers have been ascending and are now approaching the upper boundary of the glaciers, indicating accelerated glacier wastage. If the trend since the 1990s continues for the YL and AX glaciers, then the disappearance of these glaciers is inevitable because they are about to lose their accumulation areas; thus, no snow supply is expected for these glaciers. However, all three glaciers show decadal oscillations different from one another but broadly consistent with typical climate signals seen in glaciers worldwide. Rarely in the world are monotonic or steady exponential trends seen in glacier change and ELA records, and these three are no exception to the usual. On the longer time scale of the whole ELA records for the period 1970–2007, all three glaciers show a slight increasing trend (0.8 to 3.4 m yr⁻¹) of the ELA, thus projecting a long-term retreat

of all three but also slower long-term changes than the trends since the 1990s would suggest.

Spatial Distribution of ELA Trend. It is difficult to assess the spatial representativeness of the observed glacier wastage. To address this problem, we computed the mass balance for the Asian domain (25°–55°N, 60°–110°E; Fig. S6) using the same approaches as those employed above. However, the calculation did not involve downscaling or calibration, meaning that we are unable to discuss the location of the calculated ELAs in terms of the altitudinal extent of existing glaciers in the domain. Consequently, we focus on the trend in ELA during the last two decades (Fig. 3A).

In Fig. 3, statistically significant trends are colored. The variability of the calculated ELAs is consistent with that observed, though some biases are found (Fig. S7 and Table S3). If the ELA is located higher than the preferable ELA, as is the case for the three benchmark glaciers (Fig. 2 A–C), the ascending (descending) ELA results in acceleration (suppression) of glacier wastage. The available observational data reveal negative glacier mass balances and volumetric wastage, suggesting that the recent ELA fluctuates above the elevation of the preferable ELA in the domain (4–6). In Fig. 3, patchy areas of white and pale red in Nepal correspond, to the stable and acceleration of glacier wastage and are consistent with the observed glacier wastage, as outlined above. In addition, the accelerated wastage of glaciers in southeastern Tibet, as recently observed (23), also supports the ELA trend.

In Nepal, the distribution of the ELA trend appears to be influenced by the trend in summer mean temperature (June–August; Fig. 3B) rather than the trend in annual precipitation (Fig. 3C). Across the wider Asian domain, however, the warming trend in summer temperature does not always influence the ELA trend. For example, the descending ELA over western Tibet and the ascending ELA over Pamir (at the border between Afghanistan and Tajikistan) appear to reflect changes in annual precipitation (an increase in Tibet and a decrease in Pamir) rather than the trend in the summer mean temperature. In contrast to the occurrence of a dominant warming trend throughout the Asian domain (Fig. 3B), the ELA trend is spatially heterogeneous (Fig. 3A), probably due to spatial variations in the sensitivity of glacier mass balance to warming, which is strongly affected by the seasonality in precipitation (10). In addition, the ELA shows a significant descending trend for 1976–1995 in the Karakorum and Pamir regions (Fig. S8A). It is unknown whether the ELA in these regions was located above or below the preferable ELA during this period; consequently, we are unable to assess whether the glaciers were in a state of mass loss or gain. Nevertheless, this ELA trend supports at least that stable or advancing glaciers could have been driven by cooling and wetting in these regions (Fig. S8 B and C) (24, 25).

Discussion

We calculated the shrinkage rate of Himalayan glaciers based on in situ measurements. The wastage rates of the glaciers are equivalent to the global mean during the last decade, but are higher than the global mean during the previous two decades (Fig. 1B). Two glaciers located in humid environments (and thus at lower altitudes) showed accelerated wastage against a suppressed glacier wastage in an arid environment (and thus at a higher altitude) (Fig. 1C). Mass balance calculations indicate that the glacier in an arid environment will survive under the recent climate, whereas the other two glaciers, located in humid environments, are doomed to disappear over time (Fig. 2). It should be noted, however, that some glaciers with accumulation areas located at higher altitudes than those of the recent ELAs will not disappear, even in humid regions. Available in situ data have generally been obtained for glaciers that afford relatively easy

the radiation balance, sensible and latent turbulent heat fluxes, heat conduction into the glacier, and mass balance consisting of snow accumulation, melt, refreezing, and evaporation (see *SI Text*). We computed the mass balance at intervals of 50 m in altitude and then obtained the area-averaged mass balance using the area–altitude distribution. We calibrated the temperature offset to obtain the minimum rmse from the observed mass balance at each glacier (Fig. 2). ELA was calculated as the altitude where the mass balance profile crosses zero ($\text{kg m}^{-2} \text{yr}^{-1}$). We simultaneously calculated the preferable ELA for each glacier (i.e., the ELA that yields a zero area-averaged mass balance) by uniformly changing the air temperature throughout the calculated period. The amount and seasonality of precipitation affect the mass balance profile (10); consequently, the average and standard deviation of the preferable ELA were obtained for the 37 calculation results (i.e., for the 37 y between 1971 and 2007).

Because long-term climate data are unavailable for the Himalayan region, we used recently archived gridded climate datasets (19, 20) in which daily values of surface air temperature, solar radiation, and precipitation are available at a spatial resolution of $0.5^\circ \times 0.5^\circ$. We downscaled the daily air temperature and precipitation in the datasets by comparison with in situ meteorological observations taken near the glaciers for short periods, yielding statistically significant correlations (see *SI Text* and *Table S2*).

To obtain the spatial distribution of the ELA trend, air temperature, solar radiation, and precipitation were used from the datasets described above (19, 20). We did not employ downscaling of the input or calibration with

the mass balance except for air temperature, for which we reduced the annual variability of the gridded air temperature. We simply calculated the mass balance of each grid cell at altitude intervals of 50 m and then obtained the ELA for each year. We validated calculated ELAs with observed ones (see *SI Text*, and *Fig. S7, Table S3*). The obtained correlation coefficients (r in *Table S3*) indicate that the calculation performs well in reproducing the ELA fluctuations in the Asian domain, suggesting that it is valid to at least discuss the temporal trends. For all variables (ELA, summer mean temperature, and annual precipitation), we applied the Mann–Kendall trend test and excluded trends with a probability greater than 5% (*Fig. 3* and *Fig. S8*). Glacierized area and its neighboring area are shown in the figures.

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