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Limited forcing of glacier loss through land-cover change on Kilimanjaro

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Global climate change is primarily linked to changes in greenhouse gases, but land-cover change (LCC) has increasingly been recognized as another forcing on the regional scale[1,2]. The related effects on alpine glaciers are, however, not yet known. Here we present the first quantification of the contribution of LCC-driven atmospheric change to glacier mass loss, illustrated by the well-studied case of Kilimanjaro in tropical Africa[3–5]. We employ a novel multi-scale modelling approach[6], which links atmospheric dynamics and local glacier mass balance in a fully physical way and is validated by *in situ* measurements. Using different model settings, this shows that local LCC since the 1970s has contributed 7 ± 6% (17 ± 12%) to mass loss of a southern slope glacier in the dry (wet) season, but this effect could reverse in the other mountain sectors and also decrease glacier mass loss. Thus, for the moment, the hypothesis that local LCC is another forcing of glacier loss on Kilimanjaro[7,8] cannot be corroborated. More generally, our results indicate that the impact of local LCC on mountain glaciers is constrained by regional circulation (moisture trajectories), altitude (distance to forest), and outside the tropics by precipitation mechanisms (frontal systems). We therefore argue that attribution of glacier change and variability to large-scale climate dynamics[3,9,10] is unlikely to be distorted by local LCC.

LCC affects climate through modifications of land surface–atmosphere interactions, which include fluxes of energy, mass, momentum, and associated changes in atmospheric boundary layer dynamics[1,2]. The loss of mountain glaciers has been traditionally investigated through the influence of large-scale climate on regional climate (for example, refs 3,11), but to our knowledge no study has yet attempted to isolate the 'home-made' effect (atmospheric changes through local LCC) on observed glacier shrinkage. This is important, as glacier loss affects sea-level rise[12], regional water resources[13] and landscape perception[7], and the signal glacier shrinkage provides about large-scale climate change could be blurred by local LCC.

In this study we quantitatively examine the hypothesis that local LCC is a contributor to the observed mountain glacier loss. The shrinking glaciers on Kilimanjaro[14] are an ideal test case, as our extensive research programme over recent years (Fig. 1a) has revealed the physics of climate impacts on glacier mass in detail. Scientifically, this place is fascinating, as the free-standing mountain resembles a laboratory setting: the glaciers act as a sampling location high in the atmosphere that captures both large- to local-scale climate change dynamics[3,4,15,16], and how the mesoscale atmospheric circulation over Kilimanjaro links these two scales[5,6]. Moreover, long-term LCC has been carefully documented[17,18]. Kilimanjaro's regional climate is characterized by precipitation seasonality, with the main wet season from March to May, a second one from October to December, and the main dry season from June to September[4,19]. Precipitation is mostly of convective nature[5,6], so LCC has a strong potential to impact the local atmosphere[1].

We use a novel methodology that enables us to downscale large-scale climate dynamics to glacier mass balance (MB) in a fully physical way, as presented in our most recent study[6]. Central to this is the linking of a process-based glacier MB model to a mesoscale atmospheric model (see Methods) without statistical downscaling at their interface. This interface is the local atmospheric surface boundary layer (SBL) over the glacier in which air temperature (T_a), relative humidity (RH), air pressure (p), and wind speed ($\mathbf{V}$) 2 m above the glacier surface, as well as precipitation and surrounding cloud-cover fraction (CCF), govern the glacier MB. On the basis of our *in situ* measurements (see Methods) we showed that (1) the glacier model successfully reproduces observed mass and energy fluxes on Kersten Glacier[4], if it is forced with SBL conditions recorded at automatic weather station 3 (AWS3) (Fig. 1a) between 2005 and 2008, and (2) the atmospheric model simulates the local SBL at Kilimanjaro's summit to a degree which, when applied directly as glacier model forcing, yields the same mass and energy flux characteristics[6]. This comprehensive validation work[4,6], which is summarized in the Supplementary Methods, qualifies the outlined models for the sensitivity analyses in the present paper.

The advantage of our multi-scale modelling approach is that regional and local drivers of glacier MB can be resolved together with the large-scale forcings. The latter are represented by the circulation over East Africa and the western Indian Ocean (Fig. 1b), but here we focus on the local/regional factor of LCC. The land-cover distribution on Kilimanjaro was thoroughly compiled by Hemp[17,18] for the years 1976 and 2000 (hereafter LC_{1976} and LC_{2000}), which revealed reductions in montane forests and particularly cloud forests (9 and 83%, respectively). We use the atmospheric model set-up of our previous study[6] for the reference experiment (EX-REF), and conduct one run with LC_{2000} and a second run with LC_{1976} as lower boundary condition in model domain 4 (Supplementary Fig. S1). This pair of runs serves to determine (1) the resultant changes in atmospheric state and dynamics over the mountain and (2) their effect on Kersten Glacier's mass budget. Supplementary Fig. S2 summarizes the methodology.

To investigate the robustness and uncertainty of the results we run the atmospheric model in three different settings, following other LCC studies[2]. Besides EX-REF, the second experiment pair (EX-SOI) is initialized with soil moisture adjusted to the differing land cover, and the third experiment pair (EX-LMO) uses these adjustments and a different land surface scheme (Supplementary Methods). Simulations are conducted for the two time slices of our previous study[6]: April 2006 (August 2005) as a typical month of the wet (dry) season (see Supplementary

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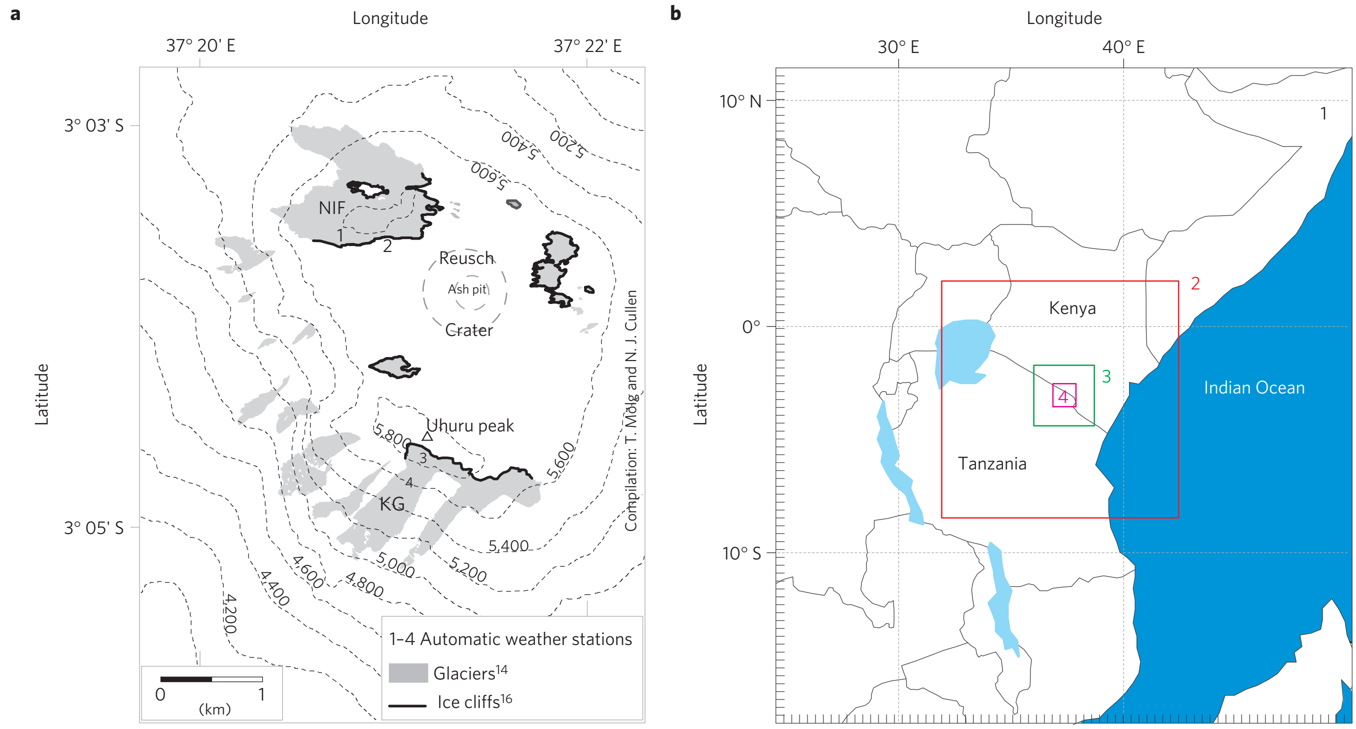

Figure 1 | The study region. a, Kilimanjaro's central part Kibo with automatic weather stations AWS1 (5,794 m, operational since 2/2000), AWS2 (5,730 m, 2/2005), AWS3 (5,873 m, 2/2005), and AWS4 (5,600 m, 10/2009). Kersten Glacier (KG) and the Northern Icefield (NIF) are indicated. **b**, Computational domain of the atmospheric model and the grid structure[6]. Horizontal resolution increases from grid 1 to 4 (39, 13, 3.25 and 0.81 km grid spacing, respectively).

Discussion). The MB of Kersten Glacier determined from AWS3 observations, $+39 \pm 8\,\mathrm{kg\,m^{-2}\,month^{-1}}$ in the wet season and $-35 \pm 7\,\mathrm{kg\,m^{-2}\,month^{-1}}$ in the dry season[4], can be reproduced for recent land-cover conditions (LC_{2000}) with all three settings using the atmospheric model output as the glacier model forcing (Supplementary Table S2).

The effect of LCC on atmospheric conditions in the summit zone (Fig. 2) is very small and statistically insignificant for mean CCF, **V** and p (Fig. 2d–f). Changes in T_a and RH over the glacier (Fig. 2b,c) are largest in EX-LMO owing to the stronger snow albedo effect on T_a in the land surface scheme employed (Supplementary Fig. S3). The most robust result is that precipitation decreases in all cases over Kersten Glacier owing to LCC over the past decades (Fig. 2a). We also tested if the change in glacier extent since the 1970s alone could control simulated changes at the summit, but this is not happening (Supplementary Discussion). Overall, changes in the dry season are clearly smaller than in the wet season (Fig. 2). A recent study also found negligible LCC impacts on Kilimanjaro's summit climate for the dry season 2007, using idealized scenarios and a different atmospheric model[20].

How do these atmospheric changes affect Kersten Glacier's mass? Table 1 compiles the results of the calculations, which consider changes in meteorological gradients along the glacier (Supplementary Table S3). We see a small increase in mass loss in the dry season and a more obvious impact in the wet season. Higher initial soil moisture in LC_{1976} than in LC_{2000} (EX-SOI, EX-LMO) strengthens the LCC impact. Such initialization seems reasonable but neglects negative vegetation–soil moisture feedbacks such as changes in soil properties[21]. Thus EX-SOI and EX-LMO do not necessarily represent the more realistic cases. The strongest response found in EX-LMO during the wet season (Table 1) is mainly a result of the strong precipitation reduction in Kersten Glacier's lower section (Fig. 2a), as elaborated by Fig. 3, which reveals the physical basis of the potential effect. Clearly, the MB change is dominated by the reduction in accumulation of solid precipitation, while melt and sublimation also increase slightly (Fig. 3a). Even if sublimation raises the energy expense, higher melt results from more energy input by net shortwave radiation due to reduced glacier albedo (another precipitation signature) or, in the case of the strong albedo effect on T_a (EX-LMO), by increased turbulent sensible heating as well (Fig. 3b). The mentioned changes are statistically significant (Fig. 3). Hence, the precipitation changes associated with LCC clearly govern the mass response of Kersten Glacier, which was expected given Kilimanjaro's glaciers show a very high sensitivity to precipitation[4,15].

However, the simulated precipitation reductions due to LCC are consistently less evident on the Northern Icefield (Supplementary Table S4), the second large ice entity on Kilimanjaro[14] (Fig. 1a). During the wet season in EX-LMO, the Northern Icefield and most of the summit zone even experience a precipitation increase (Supplementary Table S4), so local MB would profit from LCC. Kersten Glacier at the southern margin is the only exception (Supplementary Table S4). Such a small-scale contrast should always be deemed possible owing to the vicinity of moisture convergence/divergence zones[6] or convective/non-convective regions in high mountains[22], which are shifted by LCC (ref. 2). In summary, our results indicate that Kersten Glacier in the southern sector, where annual precipitation and upward moisture transport maximize[5,18,19], has suffered additional seasonal mass loss in the range 0–27% (Table 1) due to LCC since the 1970s. For the other ice fields the atmospheric changes are less consistent and do not rule out an opposite glacier response, so we cannot identify local LCC as a consistent contributor to glacier shrinkage since the 1970s for the mountain as a whole.

Thus, local changes in summit climate and glaciers seem to be controlled by the remote factors[3,5,23]. Among these, reduced moisture supply from the Indian Ocean dominates[3,4,24]; this has also weakened the mountain's regional circulation for uphill moisture

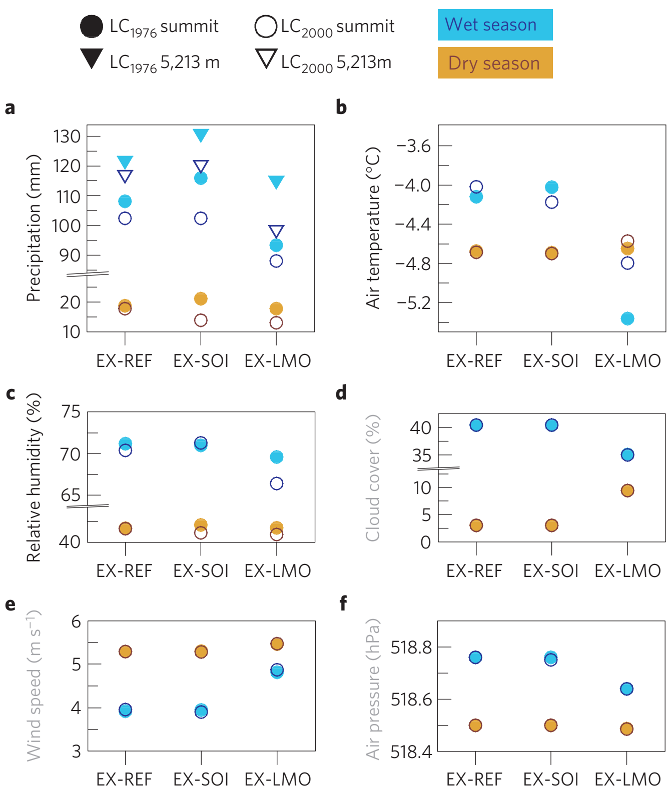

Figure 2 | LCC impact on atmospheric conditions at Kilimanjaro summit. Shown are the mean values (and sum for precipitation) in the three experiments for the six variables that drive the glacier model. Variables in grey signify variables where simulated differences in the mean values are statistically insignificant at 0.05 for all cases (assessed by a non-parametric U-test for cloudiness and precipitation, and analysis of variance for others). Precipitation results for the grid cell in Kersten Glacier's lower section (5,213 m) are also shown. Note the *y* axis breaks for the moisture variables owing to the large seasonal contrasts.

Table 1 | Effect of LCC on the southern slope glacier.

	EX-REF		EX-SOI		EX-LMO	
	LC_{2000}	LC_{1976}	LC_{2000}	LC_{1976}	LC_{2000}	LC_{1976}
Wet season	53.2	55.5	55.3	69.0	51.4	70.7
	−4% ←		**−20%** ←		**−27%** ←	
Dry season	−40.2	−40.4	−42.8	−38.5	−45.1	−40.5
	0% ←		**−11%** ←		**−11%** ←	

Glacier-wide specific mass balance on Kersten Glacier (kg m^{-2} month^{-1}) in the dry and wet season for the 1976 glacier extent[14] as the static reference surface[30] (as the present extent might already be a result of past LCC): LC_{2000} versus LC_{1976} as land-cover distribution in the three different experiments. Bold numbers give the change relative to LC_{1976} conditions, where wet-season (dry-season) mean and sigma yield −17±12% (−7±6%).

transport to the summit[5], and that, in turn, has dried the high-altitude microclimate and driven glacier retreat[4]. Previous results reveal a −31 ± 11 mm month^{-1} summit precipitation decline in the March–May wet season due to the remote large-scale climate forcing[4], compared with only −4 ± 8 mm month^{-1} from local LCC forcing (Supplementary Table S4). This clear difference indicates that local LCC does not have the potential to override the large-scale forcing of local climate (Supplementary Discussion).

One might expect a strong impact of downslope LCC on summit climate and glaciers, because the thermal circulation on tropical mountains[6] is characterized by upslope flow during daytime and, thus, 'export' of moisture from lower elevation zones

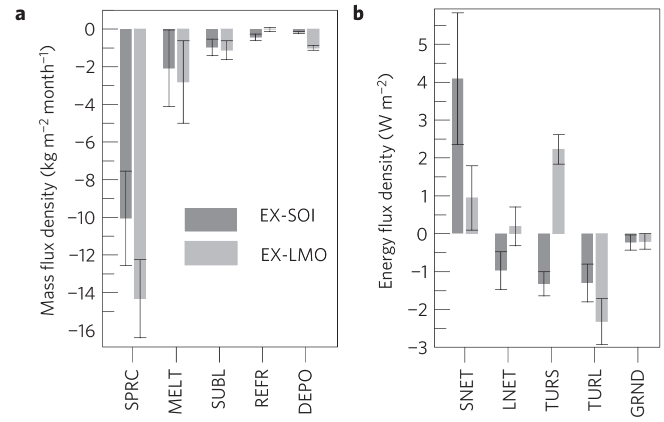

Figure 3 | Changes in mass and energy fluxes on Kersten Glacier due to LCC-forced atmospheric changes (difference to 1976). a, Mass balance: solid precipitation (SPRC), surface melt (MELT) and sublimation (SUBL), refreezing in the snow (REFR), and surface deposition (DEPO). **b**, Energy balance: net shortwave and longwave radiation (SNET, LNET), turbulent sensible and latent heat flux (TURS, TURL), and ground energy flux (GRND). Area-integrated values for the wet season and the two experiments with strongest glacier response; error bars are defined as the 95% confidence interval from a two-sided *t*-test. The sign indicates the direction of the flux change: negative (positive) means mass or energy removal from (addition to) the glacier.

(the forest belt) to the summit zone. Such processes are evident on Kilimanjaro from distributed measurements[8] and our cloud-resolving simulations[6]. However, moisture climate of the forest belt and vertical transport have non-local drivers as well: (1) as indicated above, dynamically generated flow patterns which are formed when approaching air masses impinge on the mountain, impact the daytime uphill flow and act on a regional scale[5]; (2) larger-scale moisture advection is known in general to have greater influence on local precipitation than local evaporation[25], which is also manifested by changed cloudiness over tropical mountains due to upstream environmental changes[26]. These two factors constrain the impact of local LCC on the high-altitude climate.

In a wider context, we demonstrate how large-, regional- and local-scale drivers can be resolved within one framework based exclusively on the governing physics. This approach[6] is computationally expensive, but in the form of time-slice experiments can be extended to any climate-driven local phenomenon for improving process-based attribution[6]. With respect to tropical glaciers, the vertical pattern of simulated precipitation change in a tropical convective climate[5,6] (Fig. 4a) indicates the LCC impact on glacier loss would be intensified only if the glacier descended close to, or into, the forest where wet-season precipitation decrease is equally important as in the moist high-altitude sector. This condition is rare nowadays.

We propose that the potential of local LCC as a driver for glacier loss is even more limited outside the tropics for two reasons. First, convective responses such as in Fig. 4 would occur less frequently, as extratropical precipitation is often generated by large-scale frontal systems, which reduces the impact of local LCC on climate[1]. Second, the precipitation-driven snow cover and albedo effect, which affects MB (Fig. 3) and near-surface T_a (Supplementary Fig. S3), is weaker[4]. Despite a greater sensitivity of glaciers to T_a outside the tropics[4], simulated magnitudes of T_a rise in the glacier zone (Fig. 4b) would be much reduced annually and hardly contribute to the +0.5 °C mean rise that has driven widespread glacier loss over recent decades[27]. Our results do not rule out that large-scale LCC upstream of mountains may be a stronger (remote[1]) forcing of alpine climate and glaciers than local

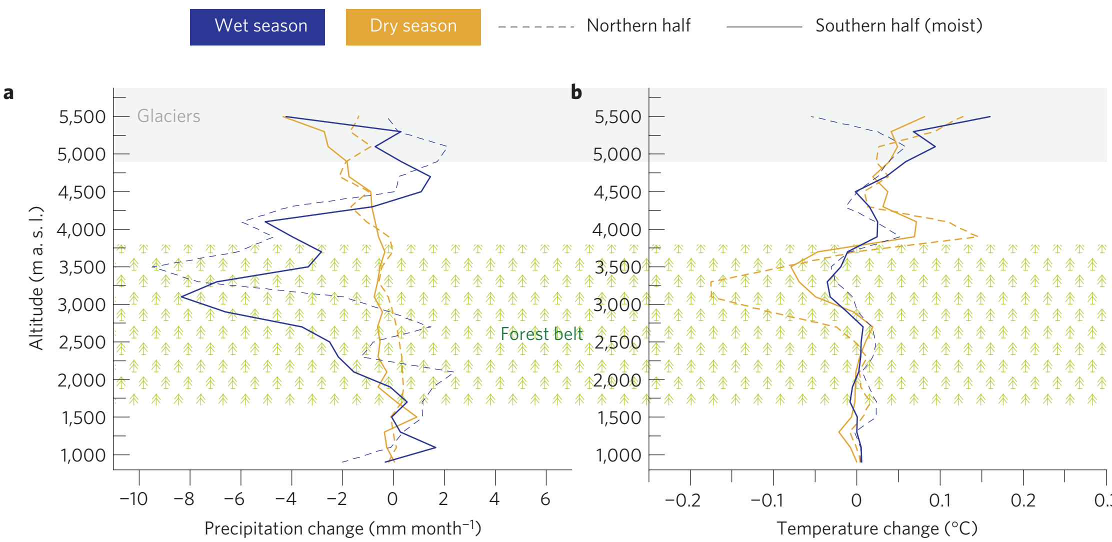

Figure 4 | Changes in precipitation and 2-m air temperature over Kilimanjaro due to LCC (difference to 1976). Shown are means for the ensemble of experiments and 200 m altitude bins in the northern half of the mountain and in the southern half of the mountain (maximum annual precipitation location). The altitude ranges of glacier and forest belt presence in 1976 are indicated.

LCC. Finally, the precipitation changes in Kilimanjaro's forest zone due to LCC (Fig. 4a) merit further investigation, as observations in other mountains of the Earth[28] indicate potential impacts on water reservoirs and runoff variability.

Methods

Automatic weather station measurements. AWS3 records T_a, RH, p, $\mathbf{V}$ and wind direction, surface height change (indicative of ablation and solid precipitation), and incoming and outgoing short- and longwave radiation. The effective CCF can be deduced from incoming radiation[4]. Details of AWS3 (instrument types, accuracy, sampling frequency, quality control of data) are in ref. 4 and references therein. Other measurements are detailed in refs 15,16.

Mass-balance modelling. From the mean hourly local SBL conditions the glacier model computes the specific MB ($\mathrm{kg\,m^{-2}\,h^{-1}}$) as the sum of solid precipitation, surface melt and sublimation, surface deposition, and refreezing of meltwater in the snow pack (here for 100 m grid cells in a digital terrain model of Kersten Glacier). The latter four components are solved from the energy budget at the glacier surface and the englacial temperature simulated in the subsurface, by applying the thermodynamic principle of energy conservation. The model is fully described and validated in ref. 4 and includes all important system feedbacks (for example, snowfall accumulation–albedo–surface temperature–melt and sublimation amounts).

Numerical atmospheric modelling. The Advanced Research Version of the Weather Research and Forecasting (WRF) Model, version 3.1, is based on fully compressible and non-hydrostatic equations[29]. It offers sophisticated parameterizations for cloud microphysics, cumulus processes, the land surface (Supplementary Discussion), surface and planetary boundary layers, and atmospheric radiation. Our runs are driven by reanalysis data at lateral boundaries (Supplementary Table S1), while multiple grid nesting increases horizontal resolution to 812 m over Kilimanjaro (Fig. 1b). Ref. 6 and Supplementary Table S1 summarize the model settings. Note that the model peak is slightly lower than the real peak (5,573 versus 5,895 m) owing to the required relief smoothing. Glacier cover can be defined in WRF (Supplementary Methods).

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Author contributions

T.M. designed the research, made the computations, participated in field work on Kilimanjaro, and wrote the paper. All co-authors helped with data preparation (reanalysis, vegetation) and continuously discussed the work.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/natureclimatechange. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to T.M.