

Glaciology: Mass Balance of Very Small Glaciers on Mount Kenya During 2016–2018



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Three-dimensional (3D) topographic model of Mount Kenya generated using structure from motion multi-view stereo (SfM-MVS) photogrammetry software and digital images captured from a Cessna aircraft on August 19, 2018

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Abstract In 1929, 17 glaciers were identified on Mount Kenya. Later, the glacier inventory of 2004 reported the presence of only 10 glaciers, which were reduced to only 9 in 2016 as documented in the revised glacier inventory published in 2018. In this study, we confirm the existence of eight glaciers by comparing changes in the surface elevation of digital surface models (DSMs). The models are created based on Pleiades satellite images from February 17, 2016 and on digital images acquired from a Cessna aircraft on August 19, 2018. Although the revised glacier inventory of 2016 included Northey Glacier, we are not able to confirm any change in the surface elevation of this glacier. Therefore, it is likely that Northey Glacier could represent a seasonal snow patch without an ice body. The comparison between the DSMs of 2016 and 2018 shows that the surface area of all eight glaciers had declined, indicating a negative mass balance. The average annual mass balance of the six glaciers is found to be -1.4 m w.e./a. The significantly smaller Darwin (0.0039 km²), Heim (0.0025 km²), and Diamond (0.00034 km²) glaciers might represent disappearing glaciers with stagnant ice, which have transitioned from active glaciers.

Keywords Very small glacier · Mass balance · Digital surface model · Structure from motion · Mount Kenya

1 Introduction

Glaciers located close to the equator are found in three mountain regions worldwide: the Ecuadorian Andes, the cordilleras of New Guinea, and the high mountains of East Africa (Hastenrath 1983). The monitoring of equatorial glaciers is an important research topic because equatorial glaciers are indicators of climate changes in the major climate zones (Kaser 2001; Hastenrath 2010). In East Africa, glaciers are distributed on Mount Kilimanjaro (5,895 m) and Mount Kenya (5,199 m), both of which are volcanoes, as well as in the Rwenzori Mountains (5,109 m). In 1991, the total glacier areas were 0.4 km² on Mount Kenya, 4.9 km² on Mount Kilimanjaro, and 1.7 km² in the Rwenzori Mountains (Kaser and Osmaston 2002). These glaciers are expected to disappear in the next few decades as a result of climate warming. Although drastic ice shrinkage is apparent on all of the above-mentioned tropical high mountains, the available evidence for mountains other than that for Mount Kenya is largely lacking (Hastenrath 2005).

Although 18 glaciers on Mount Kenya were confirmed at the end of the nineteenth century (Hastenrath 1983), some glaciers have since disappeared. The total number of glaciers on Mount Kenya was 17 in 1929, decreasing further to 12 in 1947–1963, and to 11 in 1978–1987. In 2004, only 10 glaciers were identified (Charnley 1959; Hastenrath 1983, 2005; Hastenrath and Kruss 1992), and only 9 were listed in the revised glacier inventory of 2016 (Prinz et al. 2018). The number of glaciers and their

areas were identified mainly based on sketches and photographs, terrestrial surveys, aerial photographs, and satellite images. For Lewis Glacier in particular, various studies have examined parameters such as mass balance and ice thickness, which was mapped in the late nineteenth century. The mass balance was calculated from stake measurements for the period 1978–1996 (Hastenrath 1983, 2010), and from topographic maps and satellite data for the period 1934–2016 (Prinz et al. 2011, 2018). Based on measurements of ice thickness and surface elevation in Lewis Glacier by ground-penetrating radar (GPR) and differential global positioning system (DGPS) in 2010 (Prinz et al. 2012), it has been reported that the volume and area of the glacier has decreased by 90% and 79%, respectively, from 1934 to 2010 (Prinz et al. 2011).

For other glaciers here, although their number and area are typically identified from local sketches and photographs, terrestrial surveys, aerial photographs, and satellite images (Hastenrath 1983, 2005; Prinz et al. 2018), these estimates can be imprecise owing to the presence of snow cover. In addition, field surveys carried out for the certification of glaciers do not often distinguish between glaciers and snow patches. Furthermore, the steepness of rock walls on Mount Kenya make it difficult to measure the mass balance of its glaciers in the field, and therefore the mass balance has remained unclear for these glaciers. The creation of an accurate digital surface model (DSM) using satellite images is also difficult due to steep slopes of their rocky walls.

In this study, we identify the number of glaciers on Mount Kenya and determine their mass balances using DSMs created from the Pleiades satellite images from February 17, 2016, and digital images acquired from a Cessna aircraft on August 19, 2018.

2 Study Area

Our study area is Mount Kenya, which lies on the equator in the Republic of Kenya. Mount Kenya is the second highest peak (5,199 m a.s.l.) in Africa; it represents a basaltic stratovolcano that was active from the Pliocene to the Pleistocene (Shiraiwa 1995). Its mountain is heavily scraped and eroded near the crater, and forming radial valleys.

Mount Kenya, located in the humid tropics, has a climate consisting of two dry seasons (January to February and June to August) and two rainy seasons (September to December and March to May). The area is influenced by the intertropical convergence zone (ITCZ) and trade winds. The ITCZ is responsible for the humid climate, and the trade winds cause dry conditions (Kaser 2001). According to Kaser and Osmaston (2002) and Iwata (2010), Mount Kenya experiences its first dry season during January and February. As the ITCZ is located to the south, Mount Kenya gets covered by a dry air mass from North Africa. From March to May, Mount Kenya experiences a rainy season, and the highest precipitation occurs when the ITCZ passes over it. While moving northward, the ITCZ brings a wet air mass from the Indian Ocean and south-easterly winds from the Congo Basin. From June to August, Mount Kenya

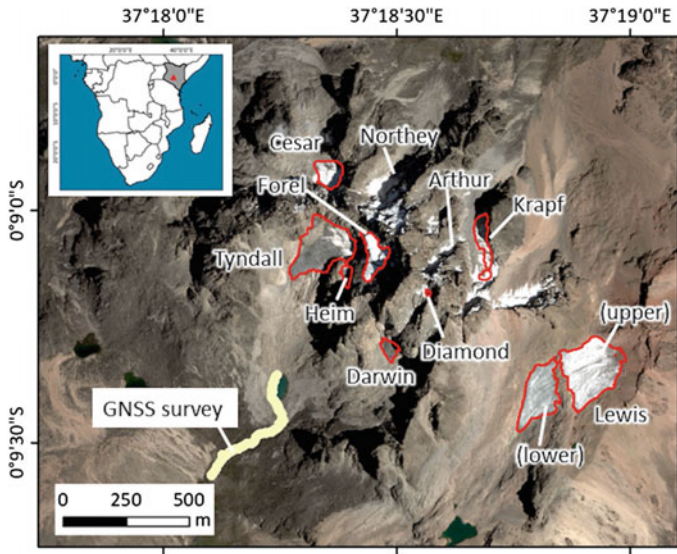


Fig. 1 Glacier distribution map of Mount Kenya. Satellite images were captured by the Pleiades satellite on February 17, 2016. Glacier areas (outlined in red) are derived by comparing the Pleiades digital surface model (DSM) of 2016 with Cessna DSM of 2018

experiences its second dry season, which is dominated by dry south-easterly winds as the ITCZ leaves Mount Kenya and moves further north. The second rainy season occurs from September to December, when the ITCZ covers Mount Kenya with a wet air mass as it passes southward. This moist air mass consists of south-easterly winds from Congo Basin and north-easterly winds from the Indian Ocean.

Currently, there are nine glaciers on the northern and southern sides of Mount Kenya (Prinz et al. 2018; Fig. 1). According to the revised glacier inventory of 2016, Lewis Glacier (73,300 m²) is the largest glacier in the region, with Tyndall Glacier (38,000 m²) the second largest. The residents of the towns and villages on the foothills of Mount Kenya depend on river water and groundwater supplied by precipitation and glacier meltwater. The $\delta^{18}\text{O}$ and δD values of groundwater in the foothills is closer to that of glaciers than to rainwater; therefore, the recent shrinkage of glaciers is expected to cause decreasing of water volume in the foothills of the mountain (Otani 2018).

3 Methods

3.1 *Generation of DSMs and Orthorectified Images from Pleiades Satellite and Cessna Aerial Images*

To investigate the changes in the surface elevation of Mount Kenya glaciers, we used DSMs generated from three stereo images acquired by the Pleiades satellite (Centre National d'Etudes Spatiales) on February 17, 2016, and from aerial images acquired from a Cessna aircraft on August 19, 2018. The three stereo images with rational polynomial coefficient (RPC) model from the satellite were converted into an orthorectified image and DSM (0.5 m resolution) without ground control points (GCPs) using PCI Geomatica software. For the Cessna digital aerial images, we captured vertical digital images from a Cessna C208 Grand Caravan aircraft of Tropic Air Kenya on September 21, 2017, based at the Nanyuki Airfield. A digital camera (Ricoh GR) was used for photography. On August 19, 2018, we acquired vertical digital images from the Cessna aircraft using a digital camera (Sony $\alpha 7ii$) at intervals of 1 s. Each flight lasted for 1 h, from 7:00 AM to 8:00 AM local time.

We created an orthorectified image and a DSM (0.2 m resolution) of the entire glacier area of Mount Kenya in 2018 using Pix4Dmapper (Pix4D S.A.), which is based on structure from motion multi-view stereo (SfM-MVS) photogrammetry techniques that identifies three-dimensional (3D) topography from Cessna aerial images. However, an orthorectified image and a DSM were created only for Lewis Glacier during 2017 because few aerial images from 2017 were available. We used GCPs from an orthorectified image and a DSM created based on the Pleiades satellite images on February 17, 2016.

We also obtained digital images of the frontal section of Tyndall Glacier from September 19, 2017 to March 1, 2018 using a time-lapse camera (images acquired once daily using Brinno Garden WatchCam) to investigate changes in glacier terminus and snow conditions.

3.2 *Accuracy of the Cessna DSM in 2018*

We confirmed the accuracy of the Cessna DSM (0.2 m resolution) of August 19, 2018, using Global Navigation Satellite System (GNSS) data that were acquired with Trimble GeoExplorer 6000 on September 19, 2017. Figure 2a shows the positions of the GNSS measurements. The studied locations represented a stable area in the downstream region of Tyndall Glacier. Figure 2b shows the results of the accuracy check between GNSS data of 2017 and the Cessna DSM of 2018; the DSM is highly accurate, to within 2.34 ± 0.85 m ($n = 2,018$) on average. Although the offset of 2.34 m may seem large, the standard deviation is within 0.85 m. The accuracy of the Cessna DSM in 2018 was also checked by comparing it with the Pleiades DSM on February 17, 2016. The average difference between these DSMs in 2016 and 2018

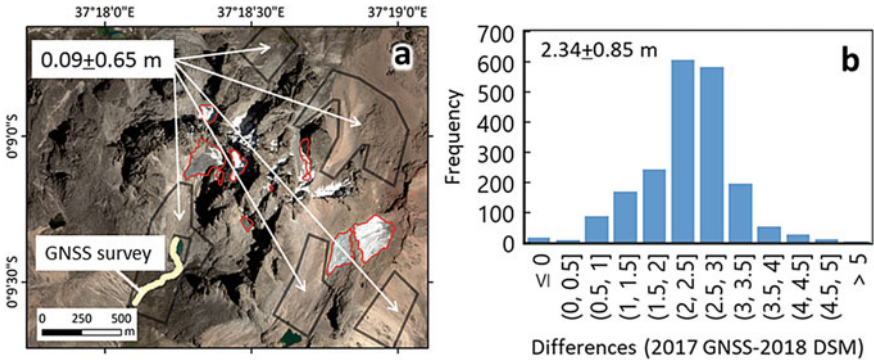


Fig. 2 Accuracy of the Cessna digital surface model (DSM) (0.2 m resolution) of August 19, 2018, estimated based on Global Navigation Satellite System (GNSS) data of September 19, 2017, and Pleiades DSM of February 17, 2016. **a** Position of the GNSS survey and accuracy verification areas (black polygons) of the differences between the Pleiades DSM of 2016 and Cessna DSM of 2018. **b** Histogram highlighting the differences between the GNSS data of 2017 and Cessna DSM of 2018. The GNSS survey was done in the downstream region of Tyndall Glacier

without any glaciated area (Fig. 2a) is 0.09 ± 0.65 m ($n = 3,122,942$). The Cessna DSM created using GCPs from the Pleiades DSM was directly compared with the Pleiades DSM.

4 Extraction of Glaciers on Mount Kenya

Figure 3 shows two orthorectified images, one acquired from the Pleiades satellite

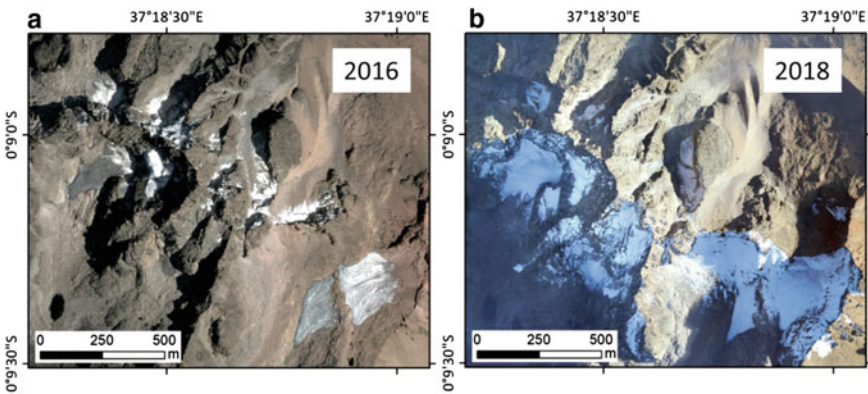


Fig. 3 Orthorectified images. **a**) From the Pleiades satellite on February 17, 2016. **b**) From the Cessna aircraft on August 19, 2018

on February 17, 2016, and the other from the Cessna on August 19, 2018. The images demonstrate the presence of residual snow around the northern glaciers in 2016, and around the southern glaciers in 2018. It was difficult to visually determine the glacier’s outline, particularly in the 2018 orthorectified image acquired after fresh snow. Even in aerial photographs, it was difficult to distinguish glaciers from fresh snow (Hastenrath 1983). Throughout the entire mapping history of the glaciers on Mount Kenya, the glaciated area was defined as the clean ice surface, with the potential debris-covered regions never being mapped (Prinz et al. 2018). Prinz et al. (2018) found it difficult to obtain accurate outlines of the small glaciers such as Krapf, Cesar, Forel, and Heim glaciers in the 2016 glacier inventory due to their locations in narrow cirques, surrounded by steep walls that cast persistent shadows. It is also difficult to distinguish Northey Glacier from seasonal snow cover.

Figure 4 compares the DSMs generated from images acquired by the Pleiades satellite (0.5 m resolution) and Cessna (0.2 m resolution). In this study, we confirmed the changes in surface elevation of eight glaciers. Although Prinz et al. (2018) describes Northey Glacier in the revised glacier inventory of 2016 (Fig. 4), they do not identify distinct surficial changes. In contrast, we show here (Fig. 4) slight changes in the surface elevation of Arthur Glacier (Fig. 4). Although this glacier was described in the sketch map by Arthur (1921) and the map prepared by Dutton (1929) based on observations in 1926, Benuzzi (1952) considered it as a snowfield. Based on these descriptions, the glacier was considered as having “disappeared” in an inventory compiled in the late 1960s (Hastenrath 1983). Moreover, the image of 2018 also showed the disappearance of snow from Arthur Glacier.

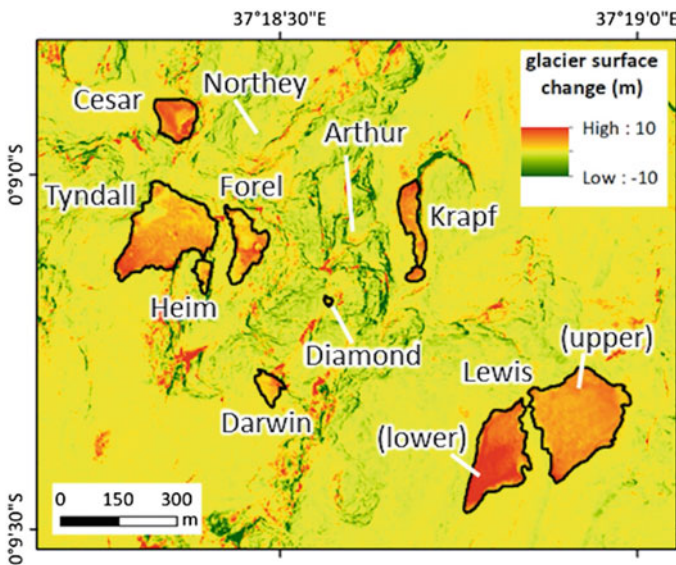


Fig. 4 Differences in surface elevation between the Pleiades digital surface model (DSM) and Cessna DSM

In this study, we identify the outlines of eight glaciers and their areas based on changes in their surface elevation. In the cases of the Lewis and Tyndall glaciers we include areas covered by debris. The total glaciated area reported in the glacier inventory of 2004 was 0.27 km² (Hastenrath 2005); the revised glacier inventory of 2016 reported the total glaciated area as 0.154 km² (Prinz et al. 2018). We instead found that the total glacier area in 2016 was 0.148 km² (Table 1).

Although Lewis Glacier separated into upper and lower parts in 2015, we count it here as a single glacier. Figure 5 shows the changes in its area during 2016 and 2017. The outline of the glacier in 2016 (marked by red line) is determined by differences between the DSMs of 2016 and 2018. This glacier had shrunk not only from the terminus but also from its sides. Prinz et al. (2012) also reports shrinkage of the entire glacier's outline. The images in Fig. 6 show time series of the terminus region of Tyndall Glacier acquired using a time-lapse camera from September 19, 2017 to March 1, 2018. The time-lapse camera was set up before the start of the

Table 1 Glacier areas on Mount Kenya from 1899 to 2016

| No | Glacier | Disappeared after | Area ($\times 10^3$ m ²) | | | | | | | |
|----------------------|-----------|-------------------|---------------------------------------|------|------|------|------|------|---------------------|------------|
| | | | 1899 | 1947 | 1963 | 1987 | 1993 | 2004 | 2016 | 2016 |
| | | | Hastenrath (2005) | | | | | | Prinz et al. (2018) | This study |
| <i>Northern side</i> | | | | | | | | | | |
| 1 | Krapf | | 85 | 43 | 43 | 23 | 21 | 14 | 12.4 | 9.6 |
| 2 | Gregory | | 290 | 94 | 91 | 45 | 35 | 12 | – | – |
| 3 | Cesar | | 100 | 49 | 40 | 24 | 18 | 16 | 9.6 | 9.5 |
| 4 | Joseph | | 63 | 34 | 25 | 10 | 6 | – | – | – |
| 5 | Peter | 1926 | 2 | – | – | – | – | – | – | – |
| 6 | Northey | | 50 | 39 | 30 | 11 | 9 | 3 | 1.1 | – |
| 7 | Mackinder | 1899 | 2 | – | – | – | – | – | – | – |
| 8 | Arthur | 1926 | 2 | – | – | – | – | – | – | – |
| <i>Southern side</i> | | | | | | | | | | |
| 9 | Kolbe | 1926 | 100 | – | – | – | – | – | – | – |
| 10 | Lewis | | 603 | 400 | 351 | 243 | 203 | 139 | 73.3 | 73.3 |
| 11 | Melhuish | Feb 1978 | 5 | 5 | 5 | – | – | – | – | – |
| 12 | Darwin | | 90 | 40 | 42 | 26 | 23 | 12 | 4.2 | 3.9 |
| 13 | Diamond | | 7 | 7 | 6 | 3 | 3 | 3 | 1.0 | 0.3 |
| 14 | Forel | | 37 | 37 | 25 | 16 | 15 | 12 | 11.0 | 11.7 |
| 15 | Heim | | 25 | 25 | 18 | 16 | 15 | 5 | 3.0 | 2.5 |
| 16 | Tyndall | | 165 | 101 | 90 | 78 | 65 | 51 | 38.0 | 37.4 |
| 17 | Barlow | 1926 | 6 | – | – | – | – | – | – | – |
| 18 | NW Pigott | 1926 | 5 | – | – | – | – | – | – | – |

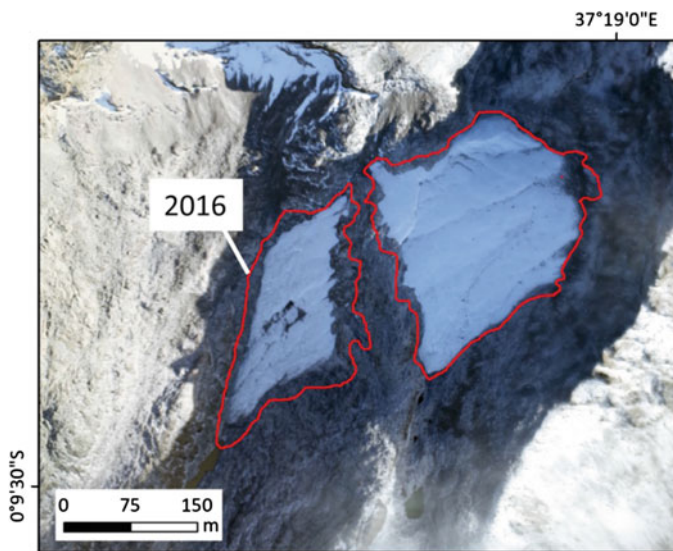


Fig. 5 Changes in the area of Lewis Glacier from 2016 to 2017. Red line represents the glacier area in 2016. Image is the Cessna orthorectified image captured on September 21, 2017

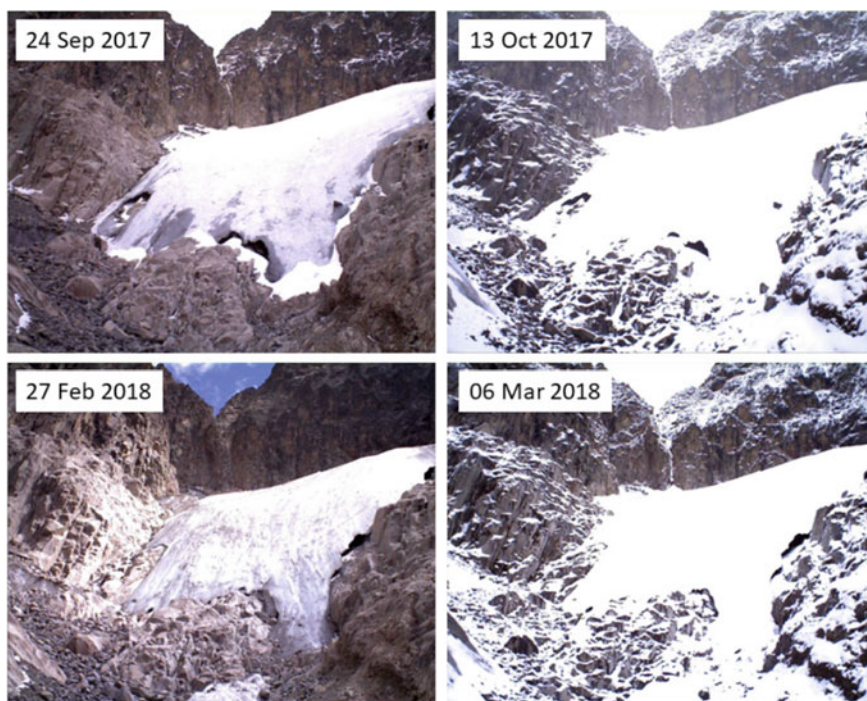


Fig. 6 Time series of the terminus region of Tyndall Glacier

snow season. The images show that the first snow season started from October 2 to November 26, 2017; the dry season with no snow was from November 27, 2017 to February 27, 2018; and the second snow season was from February 28 to May 2018. Although intermittent snowfall was confirmed during the dry season, the snow had disappeared from the ground within a few days. The images of October 13, 2017 and March 6, 2018 show the maximum snow cover during each snow season (images were acquired until May 1, 2018). Snow cover and snowfall were marginal around the glacier area on Mount Kenya. Images (end of two dry seasons) from earlier in these years (September 24, 2017 and February 27, 2018) were used to determine a decrease in the glacier's surface area and a retreat in its terminus over a period of five months.

5 Mass Balance of Glaciers on Mount Kenya

The differences between the DSMs of 2016 and 2018 (Fig. 4) show that the surfaces of the eight glaciers studied had declined. However, we could not obtain an accurate DSM for Forel and Cesar glaciers from the Pleiades images because of the shadows, even though the Pleiades satellite acquired images at 11:00 AM local time to avoid large shadows (Prinz et al. 2018). The peak of Mount Kenya is flanked by steep rocky slopes, and the two glaciers are located at the shadow borders. In contrast, the DSM produced from the Cessna images from 7:00 AM to 8:00 AM local time was smooth. The mass balance of the six glaciers was calculated based on a comparison between the two DSMs (Table 2). To convert volume into mass, we assume a constant ice density of 900 kg/m^3 (Prinz et al. 2018). Over the 30 months, the average mass balance of the six glaciers is -3.6 m w.e. (average annual mass balance: -1.4 m

Table 2 Mass balance of the glaciers on Mount Kenya between February 17, 2016 and August 19, 2018

| ID | Glacier | Area (m^2) | Change in avg. surface elevation (m) | Avg. mass balance (m w.e.) | Volume change (m^3) |
|----|---------------|-----------------------|--------------------------------------|----------------------------|--------------------------------|
| 1 | Lewis (upper) | 45,971.5 | -4.76 | -4.3 | -218,824.3 |
| | Lewis (lower) | 27,369.2 | -7.55 | -6.8 | -206,637.5 |
| | Lewis (total) | 73,340.7 | -6.16 | -5.5 | -451,778.7 |
| 2 | Tyndall | 37,438.4 | -4.21 | -3.8 | -157,615.7 |
| 3 | Forel | 11,712.0 | | | |
| 4 | Krapf | 9595.9 | -3.32 | -3.0 | -31,858.4 |
| 5 | Cesar | 9471.2 | | | |
| 6 | Darwin | 3918.2 | -3.82 | -3.4 | -14,967.5 |
| 7 | Heim | 2496.3 | -2.42 | -2.2 | -6,041.0 |
| 8 | Diamond | 342.4 | -1.51 | -1.4 | -517.0 |

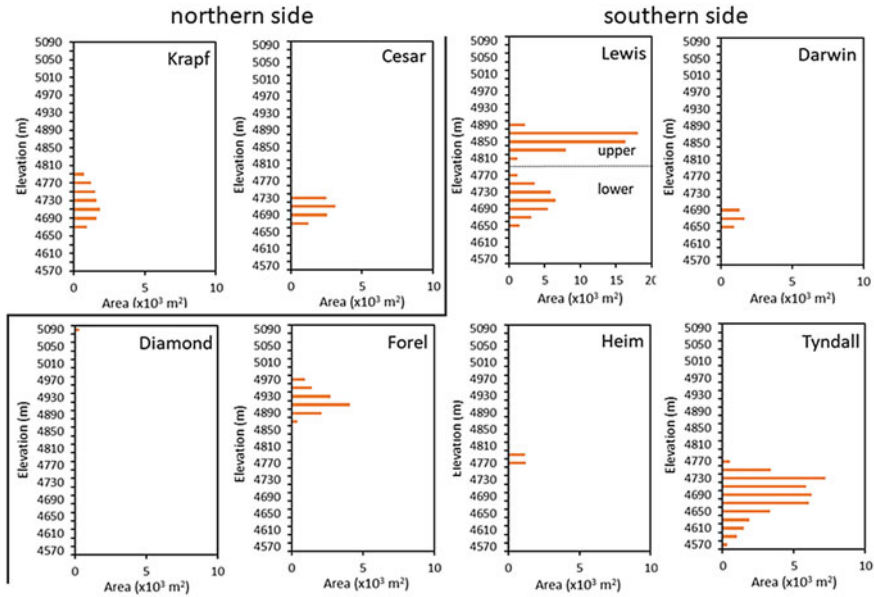


Fig. 7 Area–elevation distribution of the eight glaciers on the northern and southern sides. The scale for Lewis Glacier is twice as large as the other glaciers

w.e./a). All six glaciers have negative mass balances, with the largest being Lewis (−5.5 m w.e./30 months), Tyndall (−3.8 m w.e./30 months), and Krapf (−3.6 m w.e./30 months) glaciers. Using data from topographic maps and satellite data, the rate of mass balances of Lewis Glacier has changed from −0.99 m w.e./a in 1974–1983, to −0.70 m w.e./a in 1983–1993, to −2.22 m w.e./a in 1993–2004, to −0.63 m w.e./a in 2004–2010, and finally to −1.47 m w.e./a in 2010–2016 (Prinz et al. 2011, 2018). We find here a mass balance of about −2.2 m w.e./a (= −5.5 m w.e./30 months × 12 months). The result suggests that the negative mass balance has increased in recent years.

Figure 7 shows the distribution of the glaciated areas according to their elevation class. The eight glaciers are distributed at an altitude between 4,570 and 5,110 m. The lower parts of Lewis, Darwin, Heim, Tyndall, Krapf, and Cesar glaciers lie at 4,570–4,830 m, whereas Diamond and Forel glaciers are at higher elevations. The mass balances of these glaciers are not related to their distribution within each elevation class (Table 2). Since 1899, the northern side of Mount Kenya has had 6 of its 8 glaciers disappear, the southern side has had 4 of its 10 glaciers disappear (Table 1). Between 1947 and 2016, the glacier areas shrank by the following percentages: Cesar (81%) and Krapf (78%) on the northern side, and Darwin (90%), Heim (90%), Lewis (82%), Forel (68%), and Tyndall (63%) on the southern side. The areas of shrinkage did not significantly differ between the northern and southern sides.

The mass loss of glaciers from 2004 to 2010 on Mount Kenya was due to very dry conditions (Prinz et al. 2018). According to Prinz et al. (2018), the increasingly

negative mass balance rates since 2010 were caused by decreasing albedo due to sediment accumulation, and increased longwave heating from the surroundings and the recently developed rock outcrops. The glacier shrinkage was also affected by the energy balance of solar radiation, with the shrinkage in area being larger on the southern and eastern sides, which is exposed to stronger solar radiation (Kruss and Hastenrath 1987). We investigated the differences in average daily solar radiation in the absence of clouds using the Pleiades DSM on ArcGIS. The average daily solar radiation levels (kWh/m²/day) differed among the eight glaciers, being relatively small for Tyndall, Cesar, Diamond, Krapf, and Darwin glaciers, but we could not find a correlation with the mass balances.

6 Disappearing Glaciers

We have confirmed the existence of the eight glaciers by comparing the changes in the surface elevation of two DSMs generated from images acquired on February 17, 2016 and August 19, 2018. However, it remains uncertain whether some of the observed glaciers are in fact disappearing glaciers with stagnant ice. Only Lewis Glacier was directly investigated to determine its mean ice thickness (18 m; maximum 45 m) using a GPR survey in 2010 (Prinz et al. 2012). However, after this survey, the glacier separated into upper and lower parts in 2015. Ice thickness was not confirmed for other glaciers. The average surface gradients were very steep, between 30 and 45 degrees (with the exception of the 18 degrees for the upper part of Lewis Glacier). In particular, Darwin (0.0039 km²), Heim (0.0025 km²), and Diamond (0.00034 km²) glaciers were very small, and they might lack sufficient ice thickness to cause internal flow deformation. These extremely small glaciers can be considered as disappearing glaciers with stagnant ice bodies that had transitioned from active glaciers. Northey Glacier, described in the 2016 revised glacier inventory (Prinz et al. 2018), did not show any clear surficial changes. Therefore, it is likely that this glacier had already changed into a seasonal snow patch without an ice body.

The changes in surface elevation of the eight glaciers described in this study indicate that each glacier lies entirely within an ablation zone. That is, the climatic glacier equilibrium line altitude (ELA) is located above the glacier distributions. Although glaciers and perennial snow patches can persist in areas where the climatic ELA exceeds the mountain ridge line, their persistence would depend upon a large accumulation of snow from topographical effects such as snow drifts and avalanches. Such a situation occurs for perennial snow patches of mountains of Japan (Higuchi, 1968), but in contrast to the heavy snowfall areas of the Japanese mountains, Mount Kenya receives little snowfall and has a small mass exchange. Although an increase in the ice mass of Mount Kenya requires snow accumulation, the recent trend suggests a decrease in snow accumulation. As shown by the time series in Fig. 6, the snow cover and snowfall were marginal around the glacier throughout these two rainy seasons. The snowfall period during the two rainy seasons might also have decreased due

to climate warming. Therefore, glacier shrinkage is expected to continue on Mount Kenya owing to increased ablation during the recent global warming period.

Small glaciers and perennial snow patches exist in British Columbia, Canada and Japan (Schiefer et al. 2008; Christopher and Martin 2009; Arie et al., 2022). Small glaciers can be distinguished from snow patches by confirming the presence of visible crevasses and exposed ice (Christopher and Martin 2009). Climate warming in the future will likely cause many mountain glaciers to undergo significant shrinkage, which might increase the number that transition from an active glacier into a disappearing glacier with stagnant ice. When making a glacier inventory, it is important to distinguish between snow patches (or fresh snow) and very small glaciers. One method is to monitor such glaciers using a very high resolution data (Christopher and Martin 2009; Fischer et al. 2014). The results of this study suggest that detecting changes in the surface elevation of glacier is also very useful for distinguishing fresh snow from the actual glaciers, particularly for mapping very small glaciers.

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