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Kazuharu Mizuno
Yuya Otani *Editors*

Glaciers, Nature, Water, and Local Community in Mount Kenya

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Preface

Among the high mountains of Africa, only Kilimanjaro, Mount Kenya, and Rwenzori Mountains are still capped by glaciers. The rate of retreat of these glaciers has accelerated, and they are expected to disappear in the near future.

In the area around Mount Kenya, precipitation is decreasing in quantity and increasing in variation, such that rainfall cannot stably supply water for farmlands and daily life. It is expected that springs have appeared at the foot of the mountain due to glacier melt water. It is therefore important to characterize the condition of water sources near Mount Kenya for use by local people.

This book will present the results of two research projects that have addressed the quality of water sources related to glacier melt:

1. *The impact of glacial reduction and change of water environment on local communities near Mount Kenya, Kenya.* (2016–2019, Project No. 16H02714, headed by Dr. Kazuharu Mizuno, Kyoto University), funded by the Ministry of Education, Science, Sports, Culture, and Technology of Japan.
2. *The impact of glacial reduction on ecosystems and local communities near tropical high mountains.* (2012–2015, Project No. 24251001, headed by Dr. Kazuharu Mizuno, Kyoto University), funded by the Ministry of Education, Science, Sports, Culture, and Technology of Japan.

These research projects had two objectives: (1) to characterize the natural environments surrounding Mount Kenya, including factors such as topography, climate, water environments, glaciers and vegetation, and the interactions between these factors, and (2) to examine relationships between the natural environment and different types of human activity in this region.

We received assistance from many people during the production of this book. We sincerely thank Dr. Francis Mwaura, Nairobi University and Dr. Charles Musyoki, Director General, Kenya Wildlife Service for their assistance with our glacial research projects. We also thank Mr. Steve Wahome and Mr. Alfred Wanjohi, mountain guides of Naro Moru, and local residents of Naro Moru who have helped carry out interviews and fieldworks.

The authors hope that this book will provide new and useful information about the environment and people of Mount Kenya and will inspire future research in this region.

Kyoto, Japan Kazuharu Mizuno

The glacier around the summit of Mount Kenya. Lewis Glacier (right) and Tyndall Glacier (left) are visible in the distance.


Africa
South Sudan
Ethiopia
N
Kenya
Rwenzori Mountains (5,109m)
Uganda
Nanyuki
Naro moru
Chogoria
0 °
Lake Victoria
Mt. Kenya (5,199m)
Nairobi
Rwanda
Burundi
Congo
Kilimanjaro (5,895m)
Tanzania
Dar es Salaam
Lake Tanganyika
Matengo Highlands

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Editors and Contributors

About the Editors

Kazuharu Mizuno is physical geographer and a professor in the Department of Geography, Graduate School of Letters, Kyoto University, following nearly 20 years as an associate professor of the Graduate School of Asian and African Area Studies, Kyoto University, Japan. He graduated from Department of Geography at Nagoya University, and earned his master's degree in the Graduate School of Environmental Science at Hokkaido University, and obtained his doctoral degree in the Department of Geography, the Graduate School of Science at Tokyo Metropolitan University.

He has researched vegetation and environments of the Japan Alps and the Daisetsuzan Mountains of Japan; glacial fluctuation and vegetational changes in tropical high mountains (Mount Kenya, Kilimanjaro, and Andean Cordilleras); natural environments and human activities in the Namib Desert of Namibia; and nature, culture, and society of the Arunachal Pradesh of India. He is co-author of *Himalayan Nature and Tibetan Buddhist Culture in Arunachal Pradesh, India* (2015, Springer).

Yuya Otani is a project assistant professor in the Graduate School of Agricultural and Life Sciences, The University of Tokyo, Ecohydrology Research Institute. His research interests are watershed hydrogeology, stable isotope hydrology, and regional studies.

At Tokyo University of Agriculture, he investigated the effects of chemical fertilizer substances on the sea area using stable isotope in coral skeletal annual rings at Yoron Island, Kagoshima Prefecture.

As doctoral research at the Graduate School of Letters, Kyoto University, he worked on the effects of glacier shrinkage on the surrounding water environment at Mount Kenya and Kilimanjaro using oxygen and hydrogen stable isotopes and regional surveys. He has been a member of the Association of Japanese Geographers and Japan Association for African Studies.

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

Chiyuki Narama and Kenshiro Arie

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 km^2), Heim (0.0025 km^2), and Diamond (0.00034 km^2) 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 km^2 on Mount Kenya, 4.9 km^2 on Mount Kilimanjaro, and 1.7 km^2 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

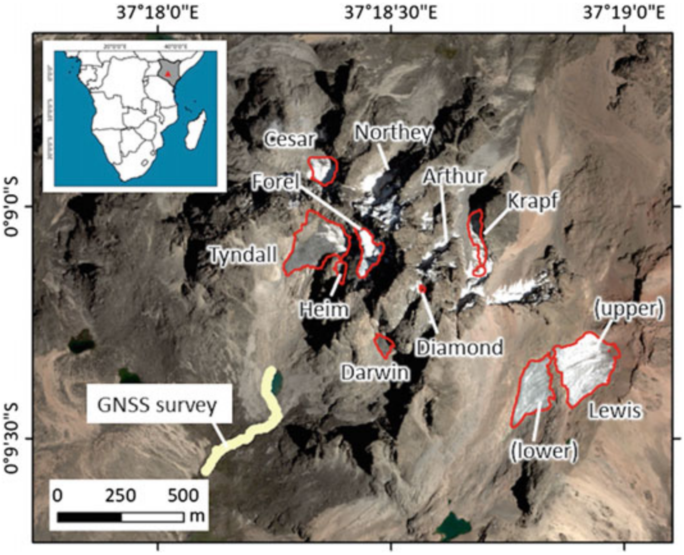

Fig. 1 Glacier distribution map of Mount Kenya. Satellite images were captured by the Pleiades satellite on February 17, 2016. Glacier areas (outlined in red) are derived by comparing the Pleiades digital surface model (DSM) of 2016 with Cessna DSM of 2018

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 m^2) is the largest glacier in the region, with Tyndall Glacier (38,000 m^2) 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 $\delta^{18}O$ 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 α7ii) 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

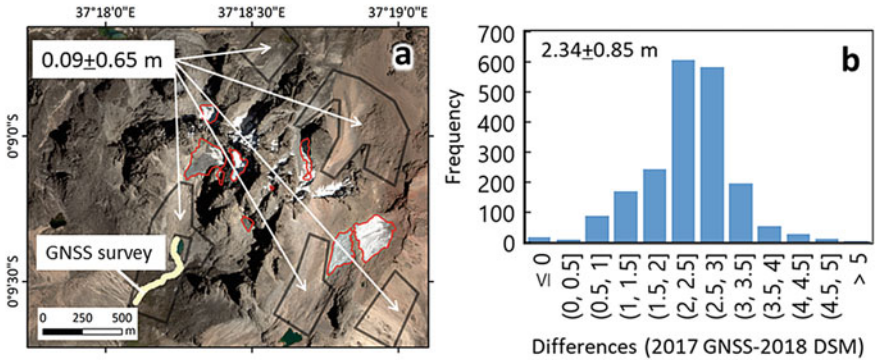

Fig. 2 Accuracy of the Cessna digital surface model (DSM) (0.2 m resolution) of August 19, 2018, estimated based on Global Navigation Satellite System (GNSS) data of September 19, 2017, and Pleiades DSM of February 17, 2016. **a** Position of the GNSS survey and accuracy verification areas (black polygons) 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

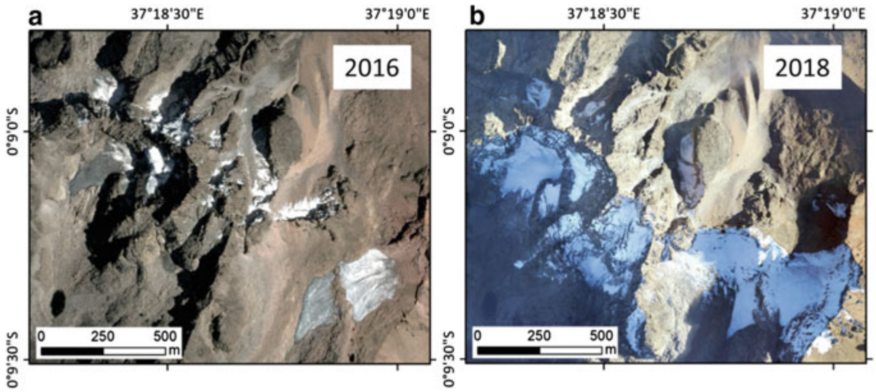

Fig. 3 Orthorectified images. **a)** From the Pleiades satellite on February 17, 2016. **b)** From the Cessna aircraft on August 19, 2018

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.

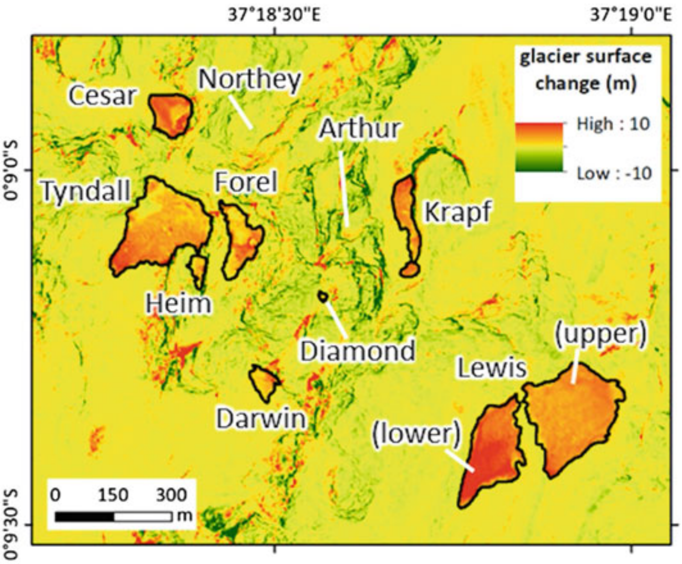

Fig. 4 Differences in surface elevation between the Pleiades digital surface model (DSM) and Cessna DSM

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 km^2 (Hastenrath 2005); the revised glacier inventory of 2016 reported the total glaciated area as 0.154 km^2 (Prinz et al. 2018). We instead found that the total glacier area in 2016 was 0.148 km^2 (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 repots 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
Northern side										
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	–	–	–	–	–	–	–
Southern side										
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	–	–	–	–	–	–	–

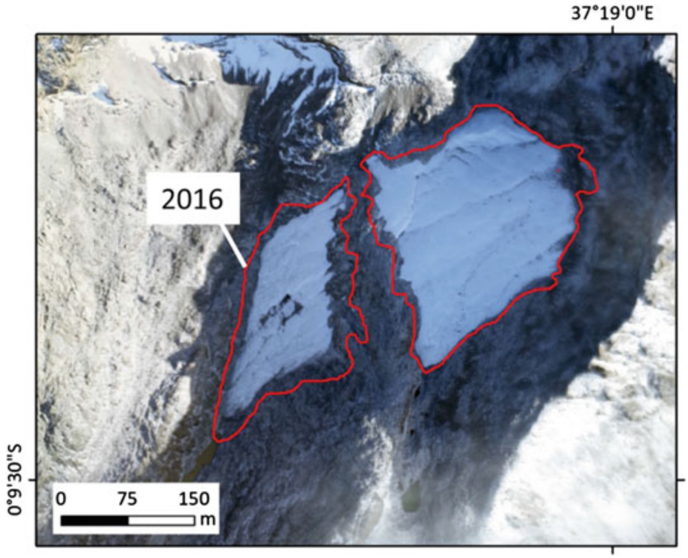

Fig. 5 Changes in the area of Lewis Glacier from 2016 to 2017. Red line represents the glacier area in 2016. Image is the Cessna orthorectified image captured on September 21, 2017

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

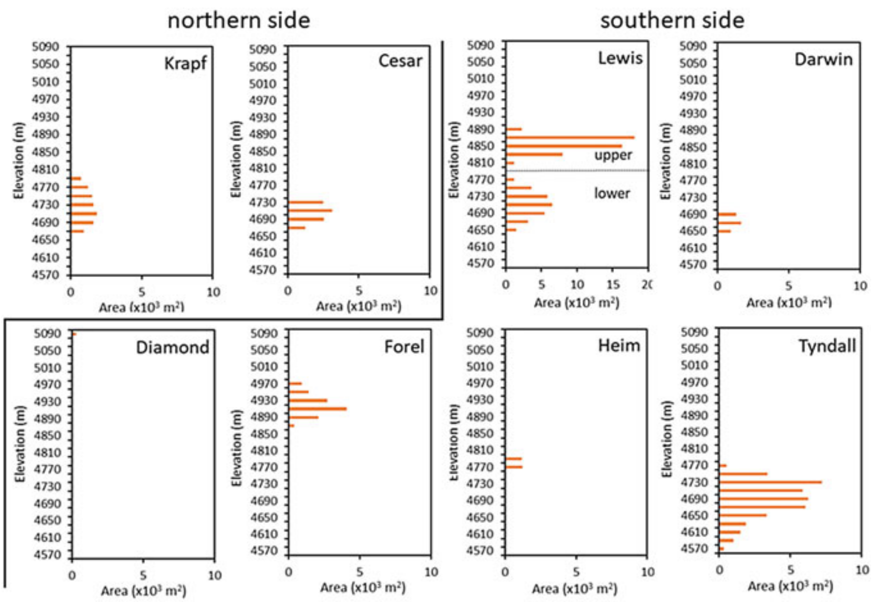

Fig. 7 Area–elevation distribution of the eight glaciers on the northern and southern sides. The scale for Lewis Glacier is twice as large as the other glaciers

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/m^2/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 km^2), Heim (0.0025 km^2), and Diamond (0.00034 km^2) 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 persistance 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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Climatology: Seasonal Changes of Rainfall Around Mount Kenya and Its Relation to Atmospheric Circulation

Wataru Morishima

Date: 2016/8/14Cloud cover over the western slope of Mount Kenya during the dry season. Precipitation is predominant mostly in the afternoon

Abstract The regions surrounding Mount Kenya have both long and short rainy seasons, and the corresponding peak rainfalls occur during April and November, respectively. Rainfall in these two seasons reach their maximum potential in areas centered on the southeastern part of the foothills of Mount Kenya and in the Aberdare Range. The relationships between the onset of these rainy seasons and the inland penetrations of the easterly winds at 700 hPa demonstrated that during the long rainy season, wind penetration from the Indian Ocean occurs along the ridge, extending northwards from the southern hemisphere along the eastern coast. During the short rainy season, wind penetration occurs with the strengthening of easterly winds associated with deepening low pressure in the Congo Basin. The relationship between the location of the convergence and divergence of wind field at 700 hPa and the seasonal march of rainfall around Mount Kenya suggest that the seasonal changes in rainfall are not only a result of north–south movement of the convergence zone with the meridional component of wind, but also a result of east–west movement of the divergence zone with the zonal component of wind.

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Keywords Rainy season · Dry season · Convergence zone · Equatorial trough · Subtropical ridge · Zonal wind

1 Introduction

Rainfall in the equatorial regions of East Africa, where Mount Kenya is located, is characterized by bimodal seasonal variations. The long rainy season occurs between March and May, and the short rainy season occurs between October and November. The spatial distribution of rainfall strongly depends on regional topography (Oettli and Camberlin 2005). As rainfed cultivation depends on these seasons, any changes in the amount and duration of rainfall during these seasons have a significant impact on agricultural production. Based on precipitation data at observation stations, several previous studies have elucidated the long-term variability of precipitation in different areas, including the equatorial region of East Africa. According to Nicholson et al. (2018), the annual rainfall in this region has remained highly variable since the late nineteenth century, although there is no significant trend of it. Seasonal rainfall in the long rainy season displays a distinct trend of dryness since the early 1970s, while the short rainy season exhibits a wetting trend since the 1960s, indicating a major change in regime (Funk et al. 2005, 2008; Williams and Funk 2011).

Nicholson (2017) provided a comprehensive review on the variability of rainfall in East Africa. In equatorial East Africa, the interannual variabilities of rainfall appear relatively coherent; however, if more detailed information is desired for the long rainy season, we should consider the coastal, the western highlands, and the regions around Lake Victoria separately. Yang et al. (2015) have also mentioned the need to fully understand the seasonal changes of climatological rainfall, because the results of recent coupled models overestimate rainfall in the short rainy season and misrepresent the seasonal changes in East Africa. In this study, the authors have shown that the atmosphere over a region with bimodal seasonal change of rainfall remains convectively stable throughout the year, and the divergence in the lower troposphere contributes to dryness in the region. It has also been demonstrated that enhanced rainfall during the two rainy seasons occurs due to increase in the static energy of surface moisture and vertically integrated moisture flux (Yang et al. 2015). On the other hand, several studies have shown that seasonal and interannual variations of zonal winds in the middle troposphere are related to variations in rainfall during the wet and dry seasons (e.g. Nakamura 1968). It is suggested that at a pressure of 700 hPa in western Kenya, an increase and decrease of rainfall over the highlands during boreal summer are associated with westerly and easterly wind anomalies, respectively, and a reverse relationship exists in coastal areas (Camberlin 1996). Furthermore, Camberlin and Wairoto (1997) demonstrated that rainfall in the central highlands near Nairobi tends to decrease during the long rainy season, and increase during the short rainy season. Similar trend can be observed in easterly wind anomalies.

The objective of this study is to understand the characteristics of mean seasonal changes and the spatial distribution of rainfall around Mount Kenya. Using data with high temporal and spatial resolution, we attempted to demonstrate the linkage of these seasonal characteristics with large-scale atmospheric circulation. Data from the Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) were used in this study. CHIRPS provides an estimated dataset for precipitation based on satellite infrared data and ground precipitation (Funk et al. 2015). These data, with a spatial resolution of 0.05°, spatially cover the land area between the northern and southern latitudes of 50°, and temporally, from 1981 to the present. In this analysis, the total data of pentadal precipitation (i.e., five-day rainfall with six pentads per month) were used for a period of 38 years from 1981 to 2018; an area of approximately 200 km^2, with 40 east–west (36.375°E–38.375°E) and 40 north–south (1.175°S–0.775°N) grids centered on Mount Kenya, was covered, as shown in Fig. 1. The JRA-55 Product, provided from the Japanese 55-year Reanalysis project carried out by the Japan Meteorological Agency, was used to investigate the relationship between seasonal changes in rainfall and atmospheric circulation. The analyzed data has a spatial resolution of 1.25° latitude/longitude. The pentad datasets were also created for the geopotential height and wind data at 850 and 700 hPa from 1981 to 2018 to match the precipitation dataset. Data from NASA's Shuttle Radar Topography Mission (SRTM) and United States Geological Survey (USGS)'s Global 30 Arc-Second Elevation (GTOPO30) were used for generating large- and small-scale maps to show the topography.

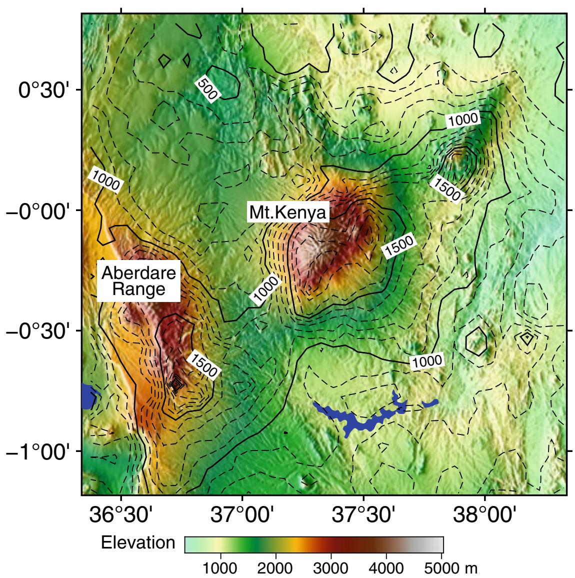

Fig. 1 Mean annual rainfall in the study area. Contour interval for rainfall is 100 mm. Shuttle Radar Topography Mission (SRTM) data are used for terrain representation

2 Rainfall Distribution and Its Seasonal Changes Around Mount Kenya

Figure 1 shows the distribution of the mean annual rainfall during the period 1981–2018. The calculations were made using CHIRPS data. It was found that the rainfall over Mount Kenya and the Aberdare range exceeds 1000 mm, and that over the southern to southeastern foothills of these mountains exceeds 1500 mm. The spatial characteristics of rainfall around Mount Kenya was in good agreement with that obtained from ground-based observations by Thompson (1966). However, the spatial resolution of the CHIRPS data was not high enough to represent the decrease in rainfall near the summit.

To reveal the average seasonal changes in rainfall distribution, the empirical orthogonal function (EOF) analysis was applied to the correlation matrix derived from 72 mean pentad rainfalls from 1981 to 2018 for a total of 1600 grids, with 40 east–west and 40 north–south grids, as shown in Fig. 1. The results indicate that the first and second EOFs can explain 81.4% and 10.4% of the seasonal variations, respectively. Their total contribution of more than 90% suggest that these two components were the most representative characteristics of the seasonal variations in rainfall.

Figure 2 shows the time coefficient of the first EOF (EOF1) and the spatial pattern of the corresponding regression coefficients for the pentad rainfall. The regression coefficients were found to have positive signs in all areas, and their relationship with time coefficients indicate that EOF1 was extracted as the seasonal mode of rainfall with wet and dry conditions in the entire area. The factor loadings values of higher than 0.8 (not shown in the figure) indicate a statistically significant relationship ($p < 0.01$) across the region, except for the western side of the northern hemisphere at 36.5°E. In fact, a correlation coefficient of 0.95 was obtained between the time coefficients of EOF1 and the total pentad rainfall over the entire region. It was also found that the eastern foothills of Mount Kenya and the southern Aberdare Range are situated in areas of greater rainfall variations with values above 20 mm, while the western foothills of these mountains experience lesser variations. These distributions, which are similar to those of the annual rainfall given in Fig. 1, can be considered as an effect of the mountain on wind flowing along southeast-to-east direction. This explains why rainfall is higher on the windward side and lower on the leeward side. This spatial pattern of rainfall is reflected by changes in the time coefficients. Upon comparing the rainfall distribution in individual pentads with time coefficient, the spatial pattern of EOF1 was clearly observed during the period of "long rains" that occurred from late March to mid-May. On the other hand, periods of "short rains" occurred from middle October to middle December. The time coefficients indicated that the peak rainy seasons occurred during mid to late April and early to mid-November; thereafter, they decreased from the beginning of May and from mid-November, respectively. On the other hand, the spatial distribution of regression coefficients for the second EOF (EOF2) demonstrated that the positive values tend to appear at relatively high elevations, and negative values at low elevations (Fig. 3).

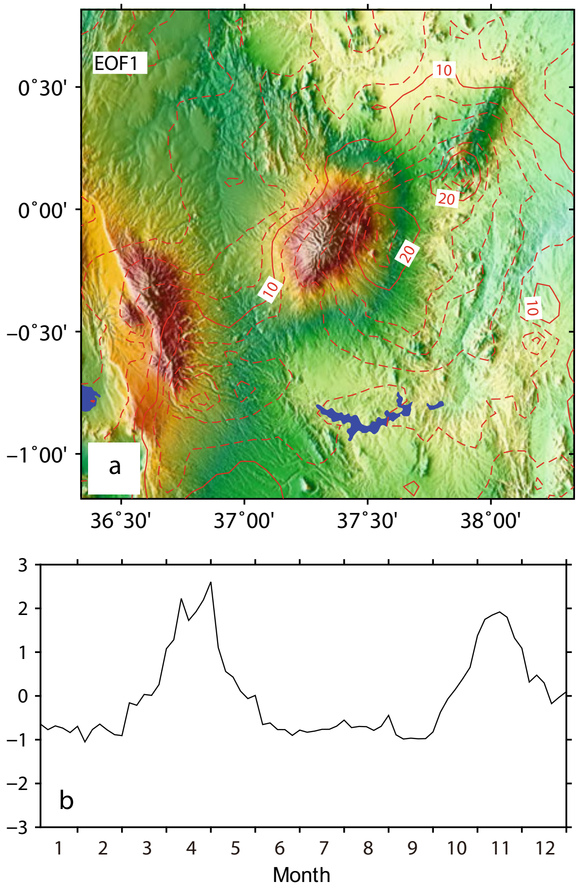

Fig. 2 **a** The spatial pattern, and **b** the time coefficients for the first empirical orthogonal function (EOF; EOF1) detected from 72 pentad rainfalls. (**a**) Distribution of regression coefficient for the pentad rainfall in relation to time coefficient. The contour interval is 2 mm per unit. Shuttle Radar Topography Mission (SRTM) data are used for terrain representation

However, significant factor loadings ($p < 0.01$) were found only in the positive areas, which extend northwestward from the southern foot of Mount Kenya and northward from the southern part of the Aberdare Range. Overall, we can consider EOF2 as an expression of rainfall variation at high elevations. As the time coefficients increase from the end of the rainy season (May) to August, the high elevation areas and their northward regions display an increasing trend of rainfall during this period.

Classifying the seasonal changes in rainfall distribution pattern based on temporal changes of the time coefficient for two EOFs, the seasonal progress of rainfall can be recognized not only from the two rainy and dry seasons but also from those seasons occurring during the transitional periods between the rainy and dry seasons. The pentad rainfall distributions are shown as typical instances of seasonal rainfall in Fig. 4. From middle December (70th pentad) to middle March (14th pentad), the time coefficients of both the first and second EOF components displayed negative values, indicating low rainfall over the entire region (Fig. 4a). After this dry season, the time coefficients for EOF1 started to have positive values from middle March

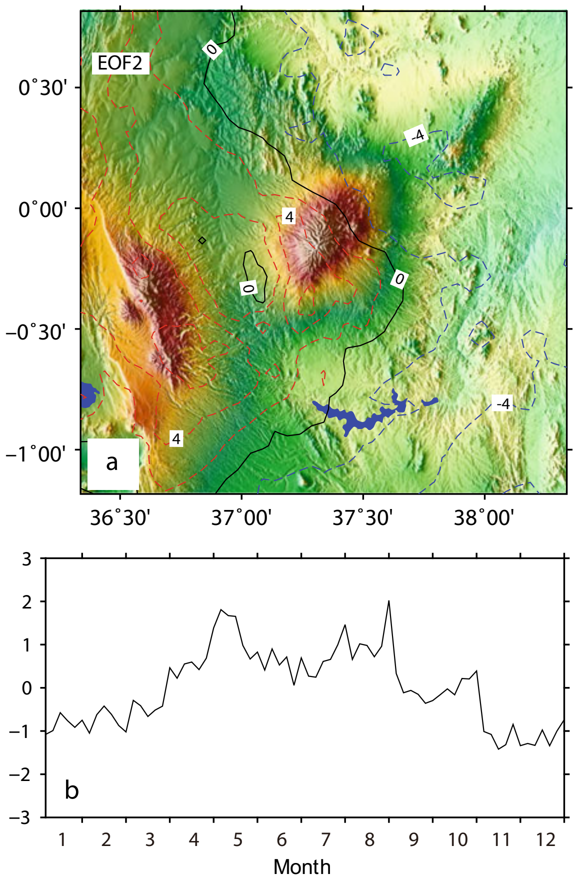

Fig. 3 Same as Fig. 2, but for the second empirical orthogonal function (EOF; EOF2)

to late March (15th–17th pentad), while those for EOF2 remained negative. This combination of time coefficients reflects a situation in which rainfall increases over the entire region, although it is less pronounced in the southern foothills of the mountains and in higher elevation areas (Fig. 4b). After this transitional period, precipitation during "long rains" season occurred in full swing over the entire region with positive time coefficients of EOF1 and EOF2, and it lasted from the end of March (18th pentad) to the end of May (30th pentad). In particular, the rainfall pattern of EOF2 was remarkable during early to middle May, with increased rainfall in high-altitude areas such as the southern skirts of Mount Kenya (Fig. 4c). The rainfall distribution characterized by the spatial pattern of EOF2 occurred during the dry season from early June (Fig. 4d) and continued until early October. The time coefficient of EOF1 began to increase during middle October, which increased the rainfall in the low-altitude areas (Fig. 4e). In comparison with the prior dry season from January to February, this dry season can be distinguished by the amount of rainfall in high altitudes. During the short rainy season from middle October to

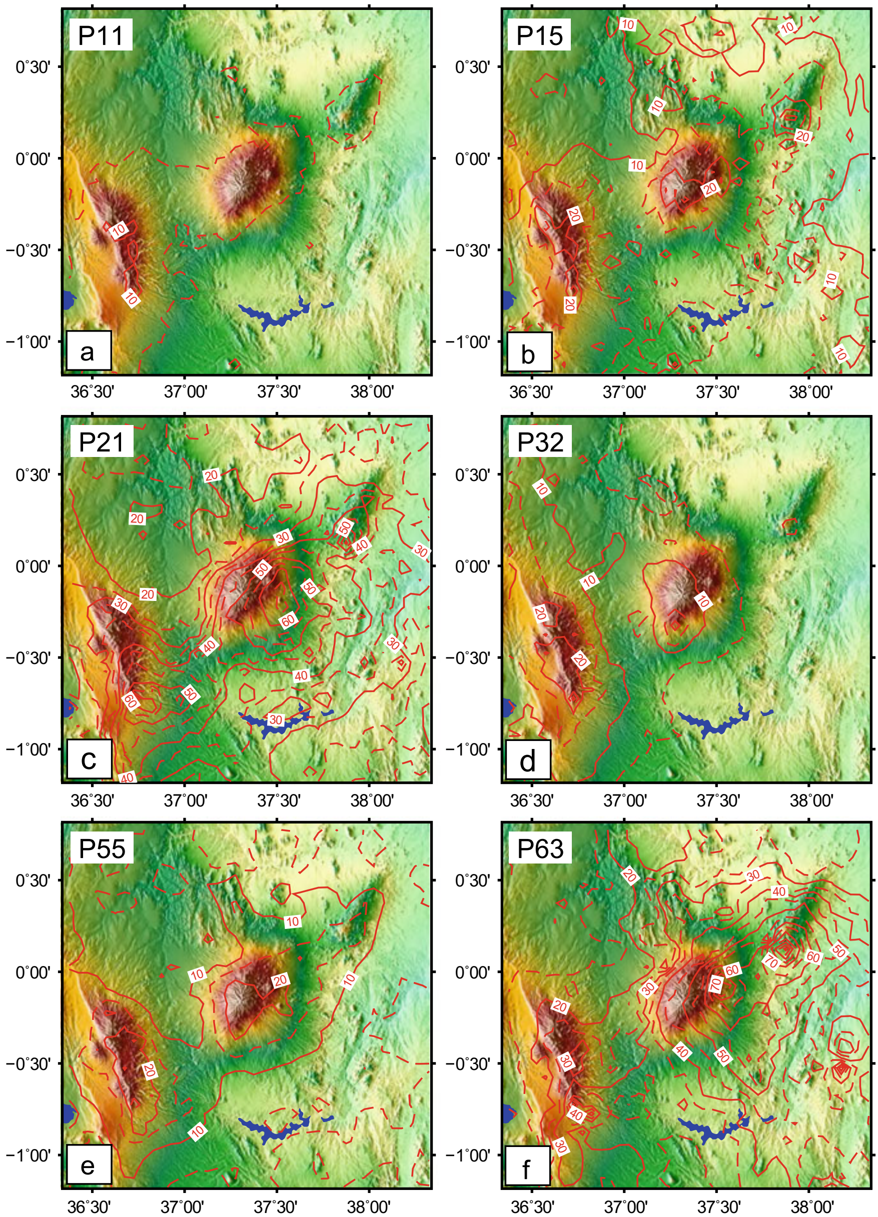

Fig. 4 Seasonal changes in rainfall distribution. Contour interval for rainfall is 5 mm. The alphabets from **a** to **f** in each figure denote the 11th, 15th, 21st, 32nd, 55th, and 63rd pentads, respectively. Shuttle Radar Topography Mission (SRTM) data are used for terrain representation

middle December (Fig. 4f), the time coefficient of the EOF2 became negative, and that of EOF1 was positive. Comparing the rainfall distributions of long and short rainy seasons (Fig. 4c, f), it is observed that the only difference in distribution of rainfall during these rainy seasons is that there is no significant increase of rainfall at the southern foot of the mountains during the short rainy season.

3 Relationship Between Seasonal Changes in Rainfall and the Atmospheric Circulation Field

As seen in the previous section, the seasonal changes in the distribution of rainfall around Mount Kenya are indicated by two EOF modes of seasonal changes, one of which is almost similar in all areas from low to high-altitude areas, and the other is limited to high-altitude areas. To consider the relationship between the characteristics of these seasonal changes and the large-scale atmospheric circulation, a correlation analysis was conducted between the time coefficients of each EOF and the geopotential height. Considering that the elevation above 1500 m covers a wide are, including the study area, the relationships at 700 hPa were plotted (Fig. 5). EOF1 had a significant negative correlation ($p < 0.01$) in the equatorial interior of the African continent, and a significant positive correlation in regions extending from the Indian subcontinent to the northern part of the Horn of Africa and at approximately 20°S over the southern Indian Ocean (Fig. 5a). This suggests that the increase in rainfall

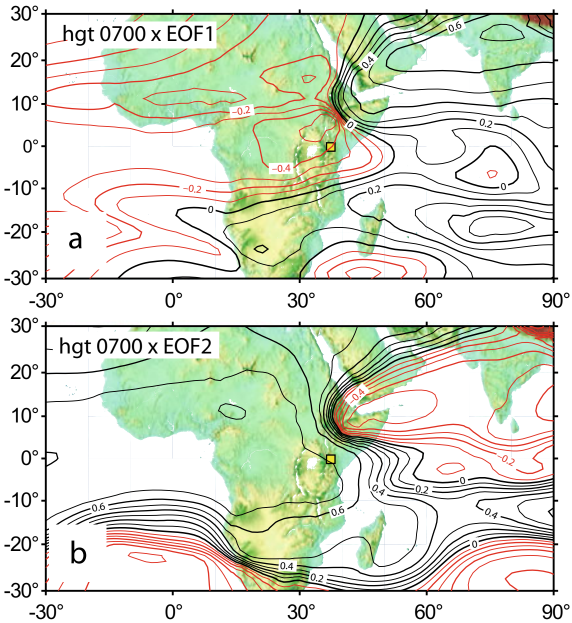

Fig. 5 Spatial patterns of correlation coefficients between the geopotential heights at 700 hPa and the time coefficients detected from the empirical orthogonal function (EOF) analysis for rainfall. **a** and **b** show the relations to time coefficients for EOF1 and EOF2, respectively. The yellow box corresponds to the area in Fig. 1. Global 30 Arc-Second Elevation (GTOPO30) data are used for terrain representation

for EOF1 occurred concurrently with i) a decrease in atmospheric pressure at the northern side of the study area, and ii) an increase in atmospheric pressure over the Indian subcontinent and the southern Indian Ocean. Corresponding to these changes, a zonal low-pressure area appeared in the equatorial region of the African continent, while high-pressure areas were clearly visible in the Indian subcontinent and in the South Indian Ocean. On the other hand, for EOF2, the negatively correlated area was distributed in east–west direction from the Indian subcontinent to the northern Horn of Africa, while the positively correlated area appeared over the equatorial region of Africa, and extended to Madagascar (Fig. 5b). The positive and negative time coefficients of EOF2 corresponded to the periods when low pressure, associated with the Indian monsoon, extended from the Indian subcontinent to the northern Horn of Africa, and when the same area was covered by the subtropical anticyclone, respectively. In addition, we considered that the positively correlated region over Africa corresponds to the development of a subtropical anticyclone in boreal summer and the expansion of the low-pressure area from the equator during winter.

To understand these relationships between rainfall distribution and geopotential heights from the standpoint of seasonal changes in pressure fields and the associated wind flows, the geopotential height and wind flow at 700 hPa for the same pentads of Fig. 4 were plotted (Fig. 6). The same analysis was also performed at 850 hPa field; however, the results are not shown in the figure.

It was found that during dry season, mainly in January and February, the ridge extended from the northern hemisphere along the eastern shore of Africa to the southern hemisphere, and the northeasterly airflow extended to the southern hemisphere (Fig. 6a). On the other hand, at 850 hPa and at the same time, a low-pressure zone developed at the north of Lake Victoria and a ridge formed from the northern hemisphere, which extended along the eastern coast of Africa. Due to this pressure pattern, northeasterly winds near the Horn of Africa changed to easterly winds towards Lake Victoria near the equator. The easterly winds tended to diverge to the north and to the south around the equatorial area of research interest.

From the 13th pentad (early March), the ridge extending from the northern to southern hemisphere began to retreat to the northern hemisphere. On the 15th pentad, the study area became an obscure high-pressure area that formed between the low-pressure areas over the West African and Indian Ocean equatorial regions (Fig. 6b). In the southern hemisphere, another ridge began to form along the eastern coast of the African continent from the south to the equator. Corresponding with this ridge expansion, the weak convergence of northerly and southerly wind components appeared along 10°S near the coast of Africa. Furthermore, over the ocean near the east coast of Africa (7.5°S, 40°E), the wind diverged to the east and west directions. This area, where such convergence of the north–south components and divergence of the east–west components of the wind occurred was referred as the EWdNSc area (denoted as a circle in Fig. 6). The seasonal changes in wind direction around Mount Kenya appeared to change with the movement of this area, which was related to seasonal pressure distribution. In the 15th pentad, when this area was in the southern hemisphere, the wind direction around Mount Kenya continued to be northeasterly. At 850 hPa, easterly winds toward Lake Victoria still prevailed around the research

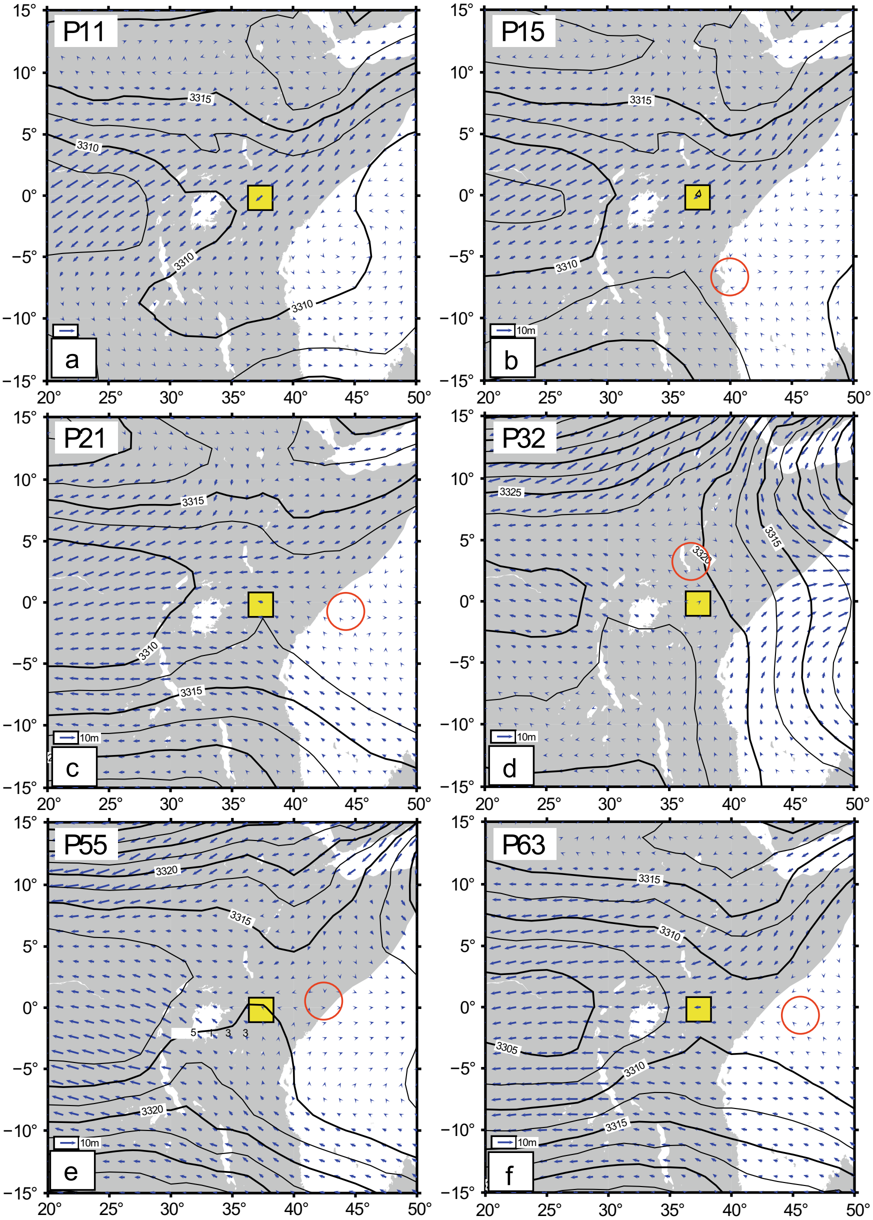

Fig. 6 Seasonal characteristics of geopotential heights and wind fields at 700 hPa. The letters from "a" to "f" in each figure denote the 11th, 15th, 21st, 32nd, 55th, and 63rd pentads, respectively. The red circle and yellow box show the location of EWdNSc area and the study area for rainfall, respectively

area; however, similar to conditions at 700 hPa, a ridge extension occurred over the eastern coast of the continent from the southern hemisphere, and a southerly wind component began to appear over the southern hemisphere. With the strengthening of the southerly component, the divergence of north and south wind components around Mount Kenya were weakened. This might have contributed to the onset of the rainy season around Mount Kenya.

After mid-March, the low-pressure area around Lake Victoria became gradually obscured at 850 hPa, and was replaced by a low-pressure area over the western part of the Ethiopian Plateau. Along with this replacement, the ridge extended northwards from the southern hemisphere along the east coast of the continent and reached the equator. In the middle of April, it crossed the equator and expanded to the northern hemisphere. The changes in the pressure field at 700 hPa were synchronized with those at 850 hPa. This involved ridge extension from the southern hemisphere to the north, and northeastward trough extension from the vicinity of Lake Victoria to the western Ethiopian Plateau was clearly visible (Fig. 6c). As the wind direction around Mount Kenya shifted from northeasterly to southeasterly direction at 700 hPa, the formations of the ridge in the southern hemisphere and of the trough in the northern hemisphere facilitated the entry of southeasterly winds from the South Indian Ocean to the equatorial interior. These southeasterly and northeasterly winds from the ridge were maintained at the south of the Horn of Africa and converged near the equator. Moreover, the extension of the ridge from the southern hemisphere also contributed to the formation of the EWdNSc area near the east coast of the continent at the equator, which brought easterly winds from the ocean.

The EWdNSc area moved to Lake Turkana in early June (Fig. 6d), and the winds around Mount Kenya shifted from southeastern to southwestern direction. In other words, the movement of the EWdNSc area appeared both with the northward shift of convergence line by northerly and southerly wind components, and with the westward shift of divergence area with easterly and westerly wind components. This movement of the EWdNSc area might be considered a result of the westward movement of the relative ridge, formed between the troughs extending from the Congo Basin, and from the Horn of Africa. Such trough expansion from the Horn of Africa could be related to the deepening and westward expansion of the low-pressure system in the North Indian Ocean. In a follow-up confirmation of the seasonal changes in rainfall around Mount Kenya associated with the movement of the EWdNSc area, the area moved to the north of Mount Kenya in early June, which corresponds to the beginning of the dry season around Mount Kenya. It continued to be located at the northwestern side of Mount Kenya for the period characterized by low rainfall and the prevalence of southwesterly winds until the middle of September. This period of prevailing southwesterly winds also corresponded with the positive phase of EOF2, which predominates the mountain-centered rainfall, although the amount is relatively small.

The trough in the North Indian Ocean side receded rapidly in middle September, while the ridge distinctively appeared along the eastern coast from the northern hemisphere side. The EWdNSc area, which was located on the western side of the Ethiopian Plateau in early September, moved southwards to the north side of

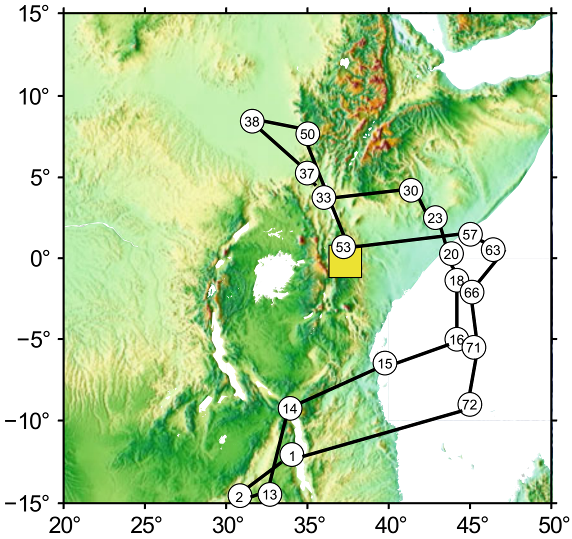

Fig. 7 Seasonal migration of the EWdNSc area. The numbers inside the circles denote the pentad number. The yellow box shows the study area considered for rainfall estimation. Global 30 Arc-Second Elevation (GTOPO30) data are used for terrain representation

Mount Kenya in middle September, and thereafter moved eastward along the equator (Figs. 6e and 7). This can be also referred to as the beginning of the short rainy season, when the easterly winds became dominant around Mount Kenya. Subsequently, as the low pressure deepened on the Congo Basin side, the easterly winds became even stronger, which resulted in the maximal period of short rainy season (Fig. 6f). The wind direction changed from the east to northeast as the ridge moved from the northern to the southern hemisphere, and the rainy season terminated in late December (Fig. 6).

4 Seasonal Changes in Rainfall in the Context of the EWdNSc Area Movement

As shown in Sect. 3, the seasonal changes in rainfall pattern around Mount Kenya coincide with the seasonal expansion and contraction of the ridges from the two hemispheres along the east coast, and with the expansion and contraction of the troughs over the Congo Basin and over the North Indian Ocean at 700 hPa. The easterly wind component around Mount Kenya at 850 hPa remained active throughout the year, although the northerly and southerly components changed seasonally. With the seasonal changes of these ridges and troughs, the convergence zone associated with the meridional components of winds moved in north–south direction. This convergence zone also had divergence zones of zonal wind components, which formed the boundary of troughs distributed over the Congo Basin and the Indian Ocean. In this study, the divergence area of zonal wind components, formed in the convergence zone of meridional wind components, has been referred to as the EWdNSc area. It was observed that the location of the EWdNSc area is related to the changes in the zonal wind components around Mount Kenya. Its location in the equatorial Indian Ocean is considered to be important in promoting the inland penetration of easterly winds from the Indian Ocean, especially during the rainy season. In addition, the inland movement of the EWdNSc area during dry season in boreal summer was consistent with the changes in the wind components from easterly to westerly around Mount Kenya. This movement might explain the mechanism behind the dominance of the westerly winds, as pointed out in previous studies (Nakamura 1968).

The relationship between the seasonal march of the EWdNSc area and rainfall around Mount Kenya is explained and summarized in Fig. 7, where the pentad numbers required to trace the position of the EWdNSc area are shown. Around the middle of March (14th pentad), the expansion of the South African anticyclone to the equator became more pronounced, and the south wind flowing from Madagascar to the east coast of Africa invaded the northern part of Lake Malawi. The EWdNSc area situated in the southwest of the lake moved to its northern side. Concurrent with this movement, the time coefficient of rainfall for EOF1 increased. The EWdNSc area moved rapidly into the Indian Ocean towards the end of March due to the strengthening of the southeasterly winds from the South African High to the equator, and due to the eastward movement of the relative ridge between the equatorial troughs. This migration of the EWdNSc area caused the northeast and southeast winds to converge around Mount Kenya, which corresponded with a full-fledged rainy season. The EWdNSc area continued to remain in the east of Mount Kenya until late May (30th pentad), which brought easterly winds from the Indian Ocean. Subsequently, it gradually moved to the northwest. From early to mid-June (32nd pentad), when the South African High expanded further north and got associated with the Arabian High or the Sahara High, a north–south ridge was formed at approximately 30°E. Subsequently, the EWdNSc area migrated rapidly westwards to the northwestern side of Mount Kenya, and the long rainy season terminated. As the EWdNSc area was located to the west of Mount Kenya until late September (53rd pentad), the southwesterly wind blowing from the inland prevailed around Mount Kenya at 700 hPa. During this period, rainfall became more pronounced on the high-altitude side, which was reflected in the spatial distribution of EOF2. In relation to the geopotential height at 700 hPa (Fig. 5b), this southwesterly wind could be also a result of widespread increase in pressure over the equatorial region and a drop in pressure over the northern Horn of Africa. After late September, the time coefficient of EOF1 began to increase again; however at this time, the EWdNSc area shifted to the southeast and stayed to the east of Mount Kenya attracting the easterly wind from the ocean. Subsequently, the EWdNSc area migrated eastwards along the equator until the middle of November (63rd pentad), when the short rainy season reached its peak. The equatorial trough on the Congo Basin side also deepened, and easterly winds became stronger. From late November, the EWdNSc area migrated southwards along the meridian at 45°E to approximately at 10°S by the end of December. As the location of the north–south convergence zone moved southward, the short rainy season was gradually terminated. In the beginning of January, the EWdNSc area moved from the Indian Ocean to Lake

Malawi, and subsequently, it migrated southwards to stay in the southwestern side of Lake Malawi until late February.

5 Summary

In this chapter, the characteristics of seasonal changes in rainfall around Mount Kenya were studied, and the relationship between the changes in the atmospheric circulation field and the rainy and dry seasons were evaluated. Most of the seasonal changes in rainfall distributions in the area appeared to be related to the overall rainfall, and in the mountainous areas, the changes corresponded to rainy and dry seasons. The investigation of the characteristics of wind directions around Mount Kenya at the onset, peak, and withdrawal stages of the rainy and dry seasons confirmed that the wind direction at 850 hPa remained easterly throughout the year, while the wind direction at 700 hPa showed a characteristic change. The easterly winds at 700 hPa were predominant in both rainy seasons, while the northeasterly winds were predominant in the dry season, followed by the short rainy season. The southwesterly winds were dominant in the dry season followed by the long dry season. Both the dominant wind directions in the dry season originated from the land. On the other hand, during the dry season corresponding to boreal summer, an additional seasonal component was detected as EOF2 for rainfall, suggesting that the increase in rainfall was mostly associated with southwesterly winds. In the rainy season, the easterly winds brought the oceanic air from the Indian Ocean to inland. It is evinced that the north–south movement of the convergence zone, formed by northerly and southerly wind at 700 hPa, is an important parameter for the seasonal changes of rainfall in this region. However, the ridge between the continental and oceanic equatorial troughs determines the flow of oceanic and continental winds and the amount of water vapor produced, whereby the location of the ridge to the east of the target area strengthens the flow of oceanic winds.

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Hydrology I: Impact of Glacier Shrinkage on the Water Cycle of Mount Kenya

Yuya Otani

U-shaped valley in the western foothills of Mount Kenya. The Teleki River flows along the valley, and the river water is used by the inhabitants at the base of the mountain for agriculture and domestic use

Abstract This study focuses on the shrinkage of glaciers on Mount Kenya (5199 m), which is located in central East Africa. Based on field observations, isotope ratio analyses, groundwater age measurements, and interview surveys, here we have discussed the impact of Mount Kenya's glacial shrinkage on the water environment and the

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availability of water resources in the surrounding areas. In the study area, which is located at approximately 2000 m elevation, the level of precipitation is generally low, and therefore, the usage of water for agricultural and household activities depends on river water and spring water from Mount Kenya. The average elevation of the recharge zones of river water used by the residents of this mountainous basin is 4650 m, and that of spring water is 4718 m. It is evinced that water from the glacial zone contributes significantly to river water at the base of the mountain. Furthermore, it takes 40–60 years for glacial meltwater to be discharged at the base of the mountain. The glaciers of Mount Kenya are expected to disappear by 2030, which might have a considerable impact on water resources at the foot of the mountain.

Keywords Mount Kenya · Glacier shrinkage · Water environment · Stable isotope · Groundwater age

1 Introduction

The rapid increase of global warming in recent years has significantly impacted the glaciers. Mountain glaciers around the world are shrinking rapidly, and the most prominent ones include the high-mountain glaciers of tropical Africa. In this region, glaciers are present on Kilimanjaro, Mount Kenya, and Mount Rwenzori, and all of them are shrinking (Hastenrath 1984, 2005, 2008). It has been predicted that these glaciers would disappear by 2030 (Thompson et al. 2009). Most notably, the glaciers of Mount Kenya, which has been designated a World Heritage Site, are shrinking at rates of 7–10 m/year (Mizuno and Fujita 2014). Therefore, monitoring programs are urgently required to record the relationship between glacier contraction, and the surrounding water environment and ecosystem.

Kenya generally has low rainfall with significant annual fluctuations. Therefore, relying solely on rainfall to provide a stable water supply for agricultural and domestic use is difficult in this region. On the other hand, Mount Kenya brings significant water resources to such dry lowlands, which makes it a "water tower" in the East African region (Njeru and Liniger 1994; Liniger and Weingartner 2000). The water from Mount Kenya makes it possible to grow coffee, tea, roses, and other crops in areas surrounding the mountain (Enjebo and Öborn 2012). However, the extent to which glacier meltwater contributes to this water supply is not yet known.

Melted water from the mountainous glaciers is considered an important resource for downstream residents in the Andes region. Vergara et al. (2007) showed that the abundance of glaciers in Bolivia, Venezuela, and several other tropical glaciers located near the equator is declining. For example, a glacier that was 2,940 km^2 in size in 1970 was reduced to 2,493 km^2 in 2002. By analyzing selected areas that are likely to be affected by the reduction of water resources due to glacial contraction, Vergara et al. (2007) demonstrated the contribution of glacial meltwater to river water. The authors found that approximately 50% of the river water in the area was derived from glacial meltwater. This indicates that glacial contraction has the potential to severely impact the agricultural productivities in the area.

Similar to the Andes, a decrease in water resources has been recently observed in Mount Kenya and its surrounding regions (Liniger et al. 2005). Although river water and groundwater derived from Mount Kenya are widely used for agricultural and domestic purposes (Enjebo and Öborn 2012), its source and water cycle have not been yet determined.

A study conducted at Kilimanjaro using tritium dating of water showed that groundwater was recharged approximately 50 years ago (McKenzie et al. 2010). However, such studies are yet to be conducted for Mount Kenya.

There is ample evidence of glacial melting on Mount Kenya. However, the timescale for groundwater recharge from glacial melt and mountain precipitation is unknown. Therefore, the extent to which the recent glacial contraction has affected the aquatic environment at the base of the mountain has not yet been determined. The present study is the first to investigate the influence of glacial meltwater on the water circulation of Mount Kenya and its surrounding regions. The results have the potential to predict and mitigate changes in the water environment around Mount Kenya, which is of great significance for the local community.

2 Overview of the Survey Area

2.1 Alpine Zone (Elevation >4000 m)

Most of the surface of the alpine zone of Mount Kenya is covered with snow, glaciers, debris separated from columnar basalt joints, and alpine plants (Fig. 1a). The average annual precipitation above 4200 m is 790 mm, and most of it falls as snow (Hastenrath 2005). The average annual temperature at 4800 m is 4 °C. Liniger et al. (1998) classified the dominant type of soil in this zone as Regosol (immature soil composed of freshly deposited alluvial stratification or sand). Soils of this type are often found in landslide areas and are poor in O layers.

Studies conducted at elevations of 4000 m and above in Mount Kenya have focused on glacier facies (Hastenrath 1984; Mahaney 1990) and the appearance of new plant species with glacial retreat (Coe 1967; Mizuno 1998, 2005; Mizuno and Fujita 2014). The glaciers of Mount Kenya are shrinking rapidly owing to climate change, and plant species are expanding their range as the receding glaciers expose more land surfaces.

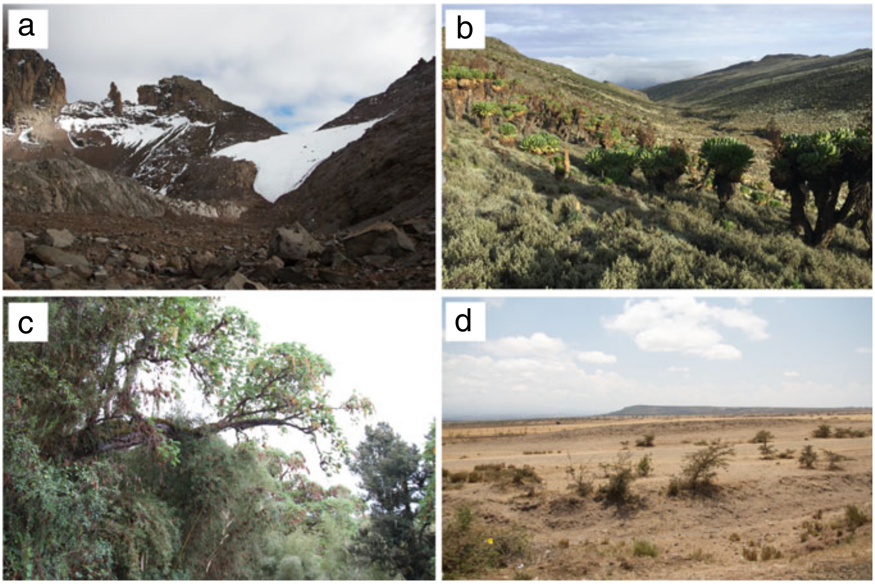


Fig. 1 Regional landscape of Mount Kenya sorted according to their elevation. **a** Alpine Zone (>4000 m), **b** Moorland Zone (3200–4000 m), **c** Forest Zone (2,300–3,200 m), and **d** Mountain Foot Zone (<2300 m)

2.2 Moorland Zone (3200–4000 m)

This represents a rough area, where the Teleki River flows through the bottom of a large U-shaped valley (Fig. 1b). The Teleki River is a valuable source of water for irrigation and human consumption in Naromoru village, which is located downstream at an altitude of 2000 m. The soil in the upper parts of the Moorland zone has good permeability, and therefore, groundwater veins are easily formed in this region. On the other hand, the lower part of the zone consists of poorly permeable soil, called Histosol (Liniger et al. 1998). The vegetation in the upper Moorland zone is similar to that found in the alpine zone; however, the lower part of the zone is dominated by wetland and heathland with *Erica* and *Philippia* shrubs being the dominant species (Decurtins 1992).

2.3 Forest Zone (2300–3200 m)

The annual average precipitation at an altitude of 3000 m is approximately 1500 mm, and the average annual temperature is 11.5 °C, which permits the growth of forests in the region (Fig. 1c). The soil above 3000 m consists of Andosol (black and white soil) with good drainage and humus. The surface soil is black or gray with thick organic matter-rich O layers. The soil undergoes transition from Andosol to Acrisol (a red-yellow podzolic soil) below 2500 m (Liniger et al. 1998).

Most parts of this elevation zone are located within the Mt. Kenya national park; however, most natural forests below 2400 m were cleared before the establishment of the national park, and subsequently the forests were harvested. Since several harvested areas are used as farmland, the demand for irrigation water in this area is increasing, and appropriate quantitative management of river water and groundwater derived from Mount Kenya is necessary.

2.4 Mountain Foot Zone (<2300 m)

Several areas such as Nanyuki and Naromoru are situated around Mount Kenya outside the boundaries of the national park. Nanyuki is a busy relay point for transportation, and the route leads to the northern part of Kenya. Nanyuki is also considered the initial base point for mountain climbing in Kenya. The average annual rainfall in the Naromoru region (altitude of ~2,000 m), which is located at the western base of Mount Kenya, is approximately 640 mm, and the average annual temperature is 16 °C.

Steep terrain and steep cliffs are found at approximately 2300 m above sea level, and the regions are sparsely populared. However, the land is extremely flat and dry below 2200 m (Fig. 1d). This area contains many villages and residents. Five villages in the Naromoru region are located alongside the river flowing from Mount Kenya.

The primary soils in this elevation zone are iron-rich Luvisol and Acrisol (Liniger et al. 1998). Luvisol are reddish brown fertile soils. Due to their physical properties, they are well-drained and extremely favorable for cultivation. Luvisol are often formed in semi-humid and semi-arid climate zones if the host rock is limestone.

Kenya experiences both rainy and dry seasons. Precipitation during the rainy season (March–May, October–December) is caused by the absorption of water vapor evaporated from the Indian Ocean, and its subsequent transportation by winds flowing from the southeast direction. On the other hand, the dry season is associated with winds from the northeastern regions of the Indian Ocean during January–June and June–September (Levin et al. 2009). At an altitude of approximately 2000 m at the foot of Mount Kenya, rainfall of 50–140 mm/month is recorded during the rainy season (Apr–Dec, Oct–Dec), and 30–60 mm/month in the dry season (WRMA 2016).

3 Application of Isotope Analysis

The total amount of groundwater cannot be determined by visual observations, which complicates the efforts pertaining to water resource management. Therefore, stable isotope ratios of hydrogen (δD) and oxygen ($\delta^{18}O$) have been used to characterize groundwater (Criss and Davisson 1996; Rowland et al. 2011). Isotope analyses have been also used to map the origin of the mountainous spring water. The variations in δD and $\delta^{18}O$ values in precipitation can aid in determining the altitude effects; for example, δD and $\delta^{18}O$ generally decrease with an increase in altitude. When clouds move from the ocean to the foot of the mountain, the precipitation at low altitudes possesses preferentially heavier δD and $\delta^{18}O$ due to gravity. Consequently, δD and $\delta^{18}O$ decrease with snowfall at higher altitudes and in glacial meltwater originating at higher altitudes of the mountainous body. In the present study, the contribution of melt water from glaciers and snow to the spring water at the foot of the mountain was estimated based on the differences in δD and $\delta^{18}O$ values between water found in the glaciers and snow versus the precipitation samples collected from the bottom of the mountain. δD and $\delta^{18}O$ in spring water at the base of the mountain were found to be lesser than in precipitation falling in the same elevation zone, thereby evincing that the spring water is fed by melting glaciers and snow.

In mountains whose upper regions are composed of volcanic basalt (Baker 1967), such as Mount Fuji (Tsuchi 2017), both precipitation and meltwater can easily permeate the ground in the upper parts of the mountain. However, dense lava flows in the lower regions of such mountains prevent the precipitates to deeply permeate the ground. Thus, surface water and shallow groundwater flow down to the foot of the mountain, while water at the upper elevations flows deep underground, and emerges at the base of the mountain as confined groundwater. It is possible that the base of Mount Kenya, which is composed of basalt (similar to that of Mount Fuji), is recharged by meltwater from the upper regions of the mountain, and not by precipitation at middle and lower regions.

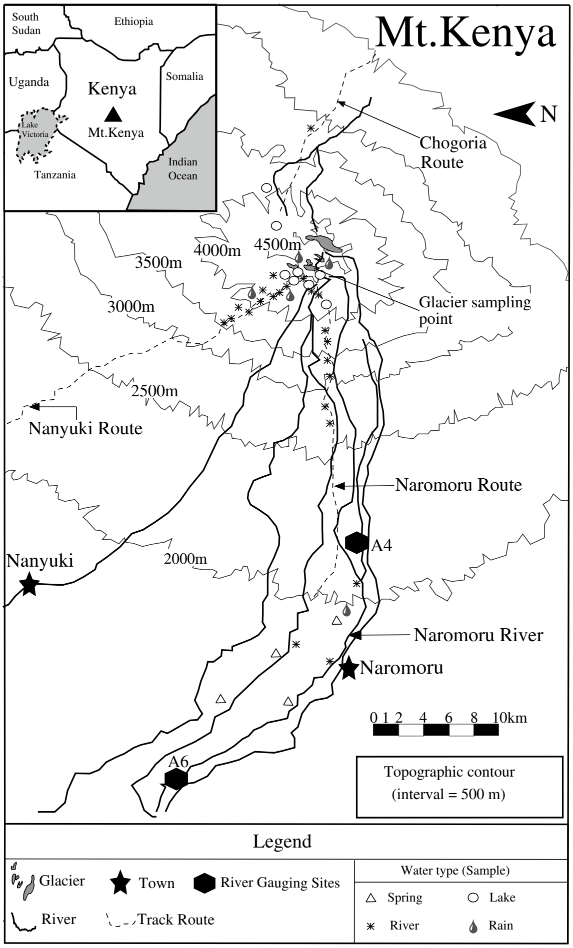
To understand the contribution of glacial meltwater to spring and river water at the western base of Mount Kenya, we carried out δD and $\delta^{18}O$ analyses as well as trace element analyses of glaciers, river water, spring water, lake water and precipitation. The investigation was conducted during 2015–2016 dominantly on the western parts of Mount Kenya, which includes Tyndall glacier.

3.1 Sampling Method and Sampling Locations

Spring water, river water, glacial meltwater, lake water, and precipitation were sampled from August 2015 to October 2016, and from July to September 2016. The objective was to assess the hydrological characteristics of the Naromoru region at the western foot of Mount Kenya (Fig. 2). All sampling activities were performed during the dry season. Samples were collected in 100 mL plastic water bottles. Water temperature and electrical conductivity (EC) were measured by placing a portable conductivity meter (ES-71, HORIBA), attached to a 1.5 m long cord, directly in the water in an area where the water flow was relatively gentle. The sensor of the compact pH meter (B-712, HORIBA) was rinsed before each measurement to remove contaminants. GPS coordinates were recorded for all sampling and measuring points.

Spring water was sampled at four points located 2 km away from the urban area of Naromoru in Mount Kenya. A total of 23 river water samples were collected from

Fig. 2 Study area in Mount Kenya with marked water sampling sites (Otani 2018)



the rivers running from 4500 to 2000 m above sea level on the climbing routes of Nanyuki, Naromoru, and Chogoria mountains. Two glacial meltwater samples were collected from Tyndall glacier at 4600 m above sea level, and two more samples were collected from ice bodies buried in debris beneath the Tyndall glacier. A total of eight lake water samples were collected from glacial lakes located at an altitude of 4500 m. Rainwater was sampled by collecting rain in polyethylene vinyl sheets at seven points (7 samples) in the 5000–2000 m zone of the Nanyuki and Naromoru routes.

4 Results

4.1 Effects of High-Altitude on Precipitation and the Estimation of Recharge Altitude of Mountain Spring Water

Table 1 shows the statistical values of δD and $\delta^{18}O$ of spring water, river water, lake water, rain water, and glacier water. Figure 3 shows the relationship between δD and $\delta^{18}O$ for each sample. Glacial meltwater, spring water, river water, and precipitation were found to plot on the global meteoric water line (GMWL).

The pattern in the variation of lake water in Mount Kenya with altitude was different compared to that of rainwater. During evaporation, the light isotopes of water selectively evaporate from the lake water such that the residual lake water gets preferentially enriched in heavy isotopes (Weitz and Demlie 2014). Due to the presence of heavier isotopes in the lake water of Mount Kenya compared to that in the rainwater, the lake water samples plotted at an inclination lower than of the rainwater line in the δD versus $\delta^{18}O$ plot. In addition, it was found that d-excess ($= \delta D - 8\delta^{18}O$), an index of dynamic fractionation defined by δD and $\delta^{18}O$ of water, changes with relative humidity and water temperature mostly when water evaporates. For example, when water evaporated under dry conditions, water vapor was affected by large dynamic fractionation, and eventually the sample exhibited high d-excess (20‰ or higher).

Therefore, evaporative water is expected to show high d-excess in the dry mountain ranges of Mount Kenya. The mean δD value of water sampled from Mount Kenya was 0.5‰, which was lower than that of the water evaporated under dry conditions.

Table 1 Stable isotope data of water samples in Mount Kenya

	No. of Samples		$\delta^{18}O$ (‰)	δD (‰)
Spring water	4	Mean Minimum Maximum	–3.74 –4.12 –3.33	–17.77 –20.66 –15.91
River water	23	Mean Minimum Maximum	–4.24 –6.32 –1.63	–22.03 –40.72 1.92
Lake water	8	Mean Minimum Maximum	–1.78 –4.63 4.93	–13.75 –30.47 17.44
Rain water	6	Mean Minimum Maximum	–0.77 –2.23 3.17	7.28 1.80 18.94
Glacier water	4	Mean Minimum Maximum	–2.73 –4.35 –1.88	–15.74 –27.44 –9.83

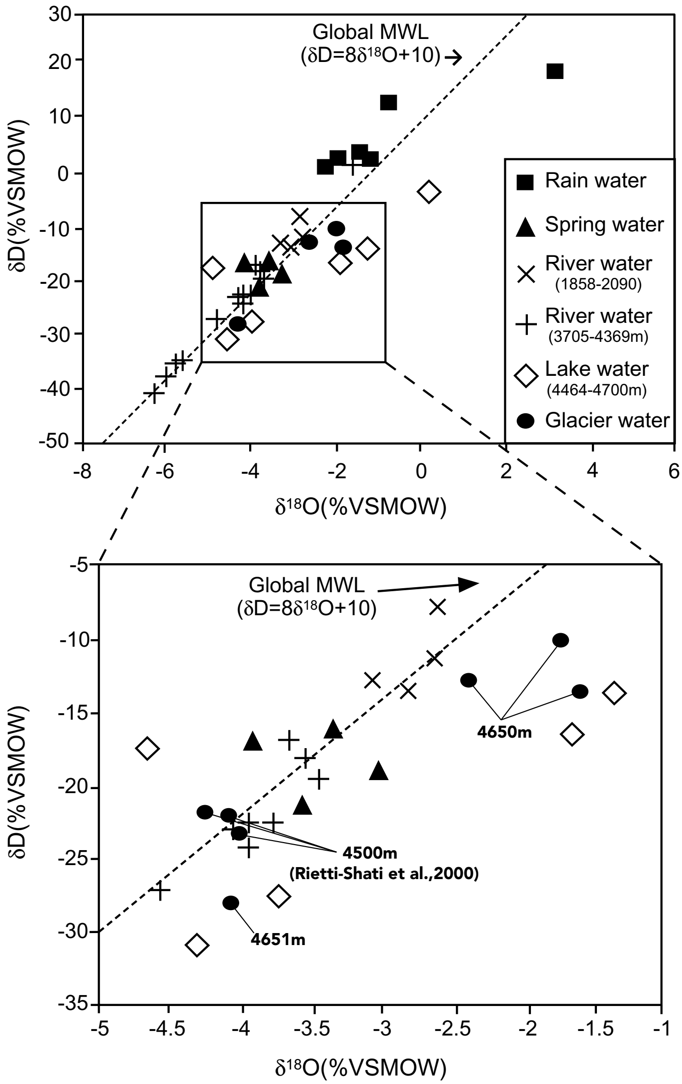


Fig. 3 Relationship between δD and δ18O in water samples collected along the Naromoru River watershed, Mount Kenya (Otani 2018). The dotted line indicates the global meteoric water line (GMWL)

This might be a result of the low d-excess of the residual lake water owing to the selective evaporation of water with high d-excess.

As shown in Fig. 3, the $\delta^{18}O$ of spring water at an elevation of 1943–2085 m ranged from −4.12‰ to −3.33‰, and δD ranged from −20.66‰ to −15.91‰. The $\delta^{18}O$ of river water at an elevation of 1858–2090 m ranged from −3.29‰ to −2.85‰, and δD ranged from −13.42‰ to −7.58‰. From Fig. 3, it is evident that

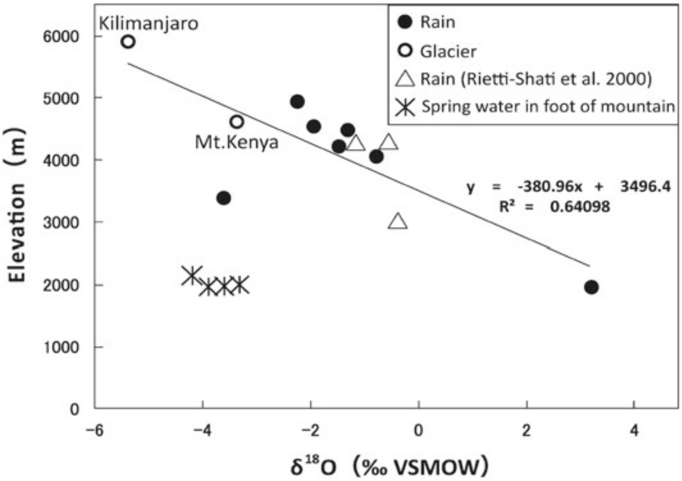


Fig. 4 Effect of altitude on the isotopic composition of precipitation on Mount Kenya (Otani 2018). The solid line indicates the approximated relationship between the $\delta^{18}O$ values of precipitation and elevation

these isotope values are close to those of the glacier meltwater originating at heights of 4500–4651 m (i.e., $\delta^{18}O = -4.35$‰ to -1.88‰, $\delta D = -27.44$‰ to -9.83‰) and river water from high elevation zone of 3,705–4,396 m ($\delta^{18}O = -4.82$‰ to -3.55‰, $\delta D = -26.81$‰ to -15.15‰). Therefore, it is likely that the primary sources of recharge in the foothill springs and rivers of Mount Kenya during dry season are glacial meltwater and river water originating in the high-altitude zone.

Figure 4 reflects that the $\delta^{18}O$ of the precipitation samples collected at each altitudinal zone exhibited a high altitudinal effect (i.e., δD and $\delta^{18}O$ values decreased with increasing altitude). The moisture mass that brings precipitation to Kilimanjaro and Mount Kenya originates from the Indian Ocean (Levin et al. 2009; McKenzie et al. 2010). The $\delta^{18}O$ of glacial meltwater and precipitation at 5895 m on Kilimanjaro is -3.7‰ (Moser and Stichler 1970), which is consistent with the altitude effect line shown by the approximated relationship between the $\delta^{18}O$ value of precipitation and elevation in Fig. 4. Therefore, we used samples collected from Kilimanjaro at 4600 m for comparison. The altitude effect line, expressed as $E\ (m) = -380.96 \times \delta^{18}O + 3496.4$, was calculated by combining the values of $\delta^{18}O$ at two points per altitude zone obtained in a previous study (Rietti-Shati et al. 2000) with the values for precipitation samples obtained in the current study (Fig. 4). Thus, we estimated the recharge altitude of the spring water at the foot of the mountain. The $\delta^{18}O$ values of spring water sampled at 1943 m, 1965 m, 1972 m, and 2085 m were -3.89‰, -3.60‰, -3.33‰ and -4.12‰, respectively. In the altitude effect line, the values corresponded to altitudes of 5065 m, 4978 m, 4867 m, and 4761 m, respectively. Considering the mean value of $\delta^{18}O$ (3.03‰) for river water at the base of the mountain, the average recharge elevation of river water was estimated to be 4650 m based on the sample's position in the altitude effect line. From these results, it is apparent that water in the glacier zone at high altitudes flows to the base the mountain as groundwater and river water.

4.2 High-Altitude Effects on Precipitation

The effect of high-altitude on precipitation, calculated in the present study, demonstrated that $\delta^{18}O$ decreased by approximately 0.18‰ with every 100 m increase in altitude. Rietti-Shati et al. (2000), who examined the altitude effect on Mount Kenya using stable isotopic composition of water, found that the $\delta^{18}O$ of precipitation samples was −0.44‰ and −1.44‰ at 3050 m and 4200 m, respectively. The results indicate that $\delta^{18}O$ decreases with an increase in altitude. However, the altitude effect was weaker in Mount Kenya compared to that in other African mountainous regions (Rietti-Shati et al. 2000). Previous studies on altitudinal effects (Clark and Fritz 1997) have shown that $\delta^{18}O$ decreases from −0.15‰ to −0.5‰ for every 100 m increase in elevation, whereas $\delta^{18}O$ values of precipitation samples collected by Rietti-Shati et al. (2000) from Mount Kenya decreased by only −0.09 to −0.02‰. The cause of this discrepancy is unknown, which could be revealed by further comparative research.

Studies by Levin et al. (2009) have shown that $\delta^{18}O$ values in the precipitation samples collected during the rainy season were lower than those collected during the dry season. The $\delta^{18}O$ values of precipitation in Addis Ababa region of Ethiopia were approximately −5‰ higher in the rainy season compared to the dry season. As all precipitation samples analyzed in the present study were collected during the dry season, and the $\delta^{18}O$ values were lower in the rainy season, it is expected that the mid-mountain precipitation made a greater contribution to river water at the base of the mountain. Therefore, future studies should analyze samples collected during the rainy season to better understand the effects of altitude on precipitation.

5 Groundwater Dating with Chlorofluorocarbons and Tritium

5.1 Chlorofluorocarbons

It is essential to determine the age of groundwater to evaluate groundwater resources, flow conditions, and safety of drinking water. Chlorofluorocarbons (CFCs) are organic compounds that were artificially produced in the 1930s, and are characterized by extremely stable properties. CFCs, which are mainly used in industrial applications such as coolants and detergents, are eventually released into the atmosphere. As a result, large quantities of CFCs have accumulated in the atmosphere with their increasing usage since the 1930s.

The concentration of CFCs increased at a high rate of 3% per year over a 50-year period from the 1940s to the 1990s, which has established the potential to apply CFC concentration for groundwater dating (Thompson et al. 1974). In the 1990s, the use of CFCs alongside tritium was initiated to measure the age of young groundwater. Since 2006, the concentration of CFC has been used to date volcanic mountain spring water and alluvial fan groundwater in Japan (Asai et al. 2006).

Groundwater dating using CFCs is based on the principle of solubility equilibrium between air and groundwater. Precipitation infiltrated into the ground reaches a state of concentration dissolution equilibrium with the gas in the soil when it descends and penetrates through the unsaturated zone (i.e., the range from the ground surface to the groundwater table), and is recharged as groundwater. As CFCs are not present in the crust, contamination from underground sources is not relevant. In other words, the concentration of CFCs in groundwater reflects the atmospheric concentration of CFCs during recharge. Therefore, the age at which the spring water was recharged can be deduced by comparing the CFC concentration of spring water with the historical atmospheric CFC concentrations (Asai and Tsujimura 2010).

5.2 Tritium

Tritium has also been used for estimating the recharge age of groundwater (Szabo 1996). Such estimates are based on the half-life of tritium (12.4 years) and on the variations in tritium concentrations resulting from hydrogen bomb experiments conducted during 1950s and 1960s. The baseline tritium concentration in precipitation during the first hydrogen bomb tests was 5.0 TU. The concentration of tritium in groundwater decreases over time given its 24-year half-life. It is reported that tritium concentration of groundwater decreased to 2.5 TU in 1964, 1.8 TU in 1976, 1.1 TU in 1988 TU, 0.6 TU in 2000, 0.3 TU in 2012, and 0.1 TU in 2016. Therefore, if the tritium concentration of groundwater sampled in 2016 is higher than 0.1 TU, we can consider that the groundwater was recharged after 1952 due to the large quantities of tritium released when hydrogen bomb tests were conducted. On the other hand, if the value is lower than 0.1 TU, it can be deduced that the water was recharged before 1952. The tritium concentration in African precipitation at the peak of hydrogen bomb testing (1952–1970) was 10–1,000 TU (IAEA 2016). As the concentration of tritium in the spring water sampled in the present study were lower than 10–1,000 TU, it is likely that the water recharge occurred prior to 1952.

6 Age of Spring Water at the Foot of Mount Kenya

Tritium concentration in the spring water of Mount Kenya was found to be 0.3 TU. After the peak nuclear testing period, the tritium concentration in the precipitation of Africa ranged from 10 to 1,000 TU, and in Kenya the concentration was 10–90

TU in 1968. If tritium concentration was 10 TU during this period, the half-life of tritium requires that its concentration should be 0.6 in 2016. As the concentration measured in the present study was 0.3 TU, the spring water at the base of Mount Kenya can be considered as groundwater that was recharged before 1950.

Three kinds of CFCs were detected in the spring water. The concentration of CFCs in spring water was converted to its atmospheric concentration during recharge, and compared with the historical atmospheric CFC concentrations in the Northern Hemisphere. The residence time was thereby estimated to be approximately 40 years. The difference in residence time, estimated by plotting tritium vs. CFCs concentrations, might be due to the fact that the analytical sensitivity of CFCs is higher than that of tritium. Thus, trace contamination of young groundwater during the runoff process might have decreased the estimated residence time. The results show that spring water at the base of Mount Kenya has a recharge age of at least 40 years.

7 Conclusion

The present study confirmed the existence of large ice bodies beneath the layers of debris at downstream of the glacier. We measured the contribution of such icy bodies to the processes of water cycle using isotope analyses. Previous studies on the aquatic environment in the African alpine region are remarkably scant compared to the other regions. The results of this research are expected to make a significant contribution to the understanding of the volcanic hydrology in Africa. Future research should investigate large-scale agricultural regions in the eastern and southern parts of Mount Kenya to comprehensively understand the processes involved in water cycle in the region, and its effect on the region's inhabitants.

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Hydrology II: Hydrology, Society of Regions Surrounding Mount Kenya

Francis Mwaura and Moses Ndarua Njoki

View of the leeward side of Mount Kenya from the Timau region. Mount Kenya is considered as a sacred mountain by the communities inhabiting the surrounding regions. The white snow-capped summit is regarded as the divine resting place of the Agikuyu God, "Ngai." The glaciers are the source of water and serve as the lifeline of the society

Abstract This study evaluated whether the local communities residing in the leeward side of Mount Kenya in East Africa are aware of the on-going glacier changes, and its implications on domestic water supply and livelihoods. The spatial analysis of the glacial changes in Mount Kenya was conducted using medium resolution

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(30 m × 30 m) Landsat imageries and ArcGIS and ENVI software. The local perception survey on glacial changes, river flow, and livelihood impacts was undertaken through face-to-face interviews with 90 riparian residents along the Naromoru and Likii rivers, which included farmers, pastoralists, and urban residents. The findings demonstrated that Mount Kenya has continuously experienced progressive glacial retreat in the last four decades (1976–2016). The level of public perception on the glacial retreat was similar to the actual trend documented through scientific research. Based on this study, we recommend that both the national and county governments should integrate glacial retreat and its hydrological implications in policy and relevant development and natural resources management plans.

Keywords Climate change · Glacial recession · Water resources · Local perceptions

1 Introduction

1.1 Mount Kenya

Mountains in Kenya, as those in other parts of the world, represent an important natural heritage because they ensure water supply for the development of society and the economy. Mount Kenya (~2000 km^2) is the largest and tallest (5199 m) mountain in Kenya, and the second highest summit in Africa. In terms of regional geography, the mountain is the source of the two largest rivers in Kenya, namely, River Tana that flows 1000 km southeastwards into the Indian Ocean (Omengo et al. 2016) and River Ewaso Ngiro that flows 700 km northeastwards toward the Kenya Somalia border (Fig. 1).

It is estimated that approximately 50% of Kenyans rely on the water resources which originate from Mount Kenya. In addition, the mountain also provides approximately 70% of the country's hydroelectric power. The mountain is surrounded by six different counties, namely Kirinyaga, Nyeri, Embu, Tharaka-Nithi, and Meru on the windward side and Laikipia on the leeward side (Fig. 2). These six counties are heavily dependent on the mountain, which sustains a wide range of economic sectors including agriculture, livestock husbandry, fisheries, forestry, tourism, and hydropower generation.

Geologically, Mount Kenya is a young volcanic cone which formed during the tertiary period (i.e., it originated 3.1–2.6 million years ago) with a base diameter of 80–100 km (Winkler et al. 2010). The mountain is characterized by a wide range of spectacular landscapes including volcanic ridges, deep valleys, moorland plains,

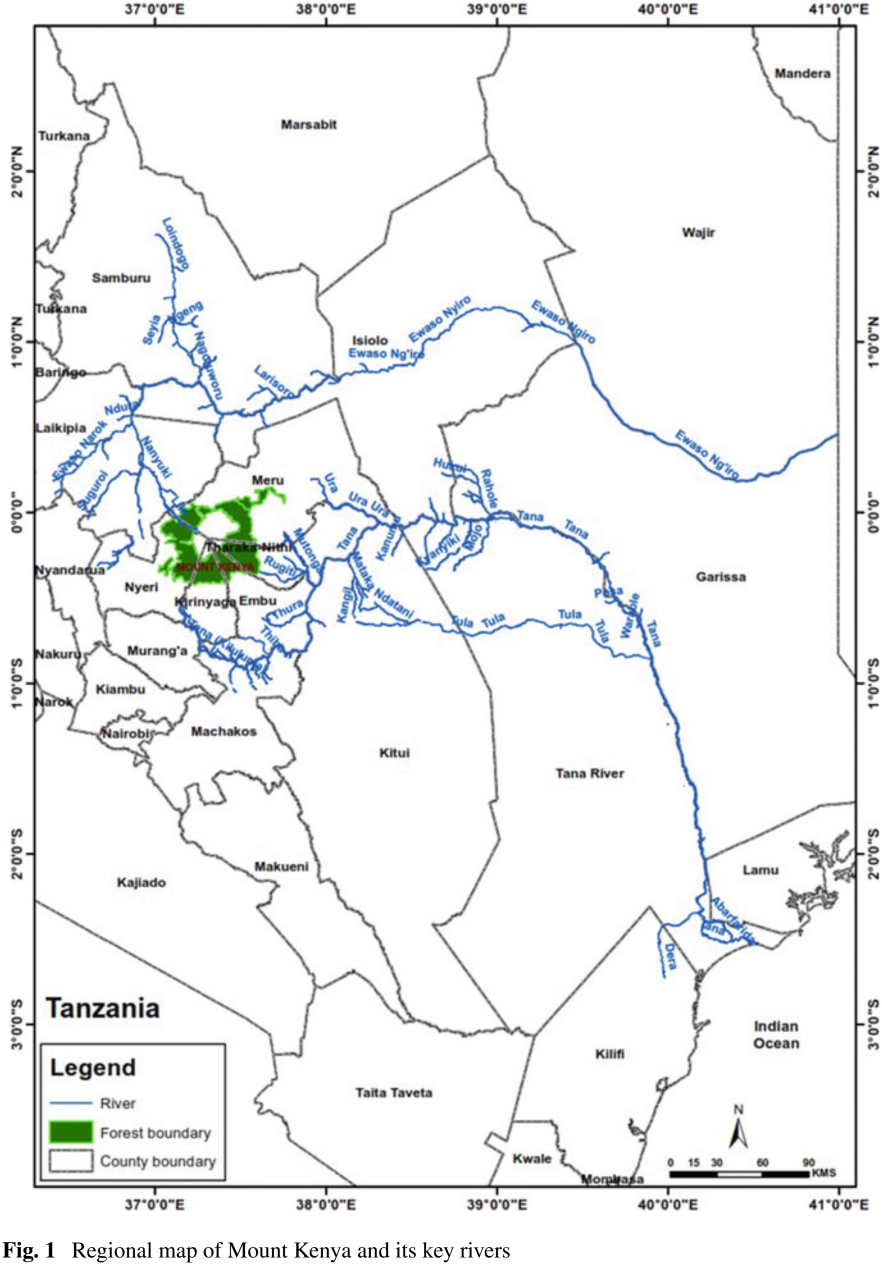


Fig. 1 Regional map of Mount Kenya and its key rivers

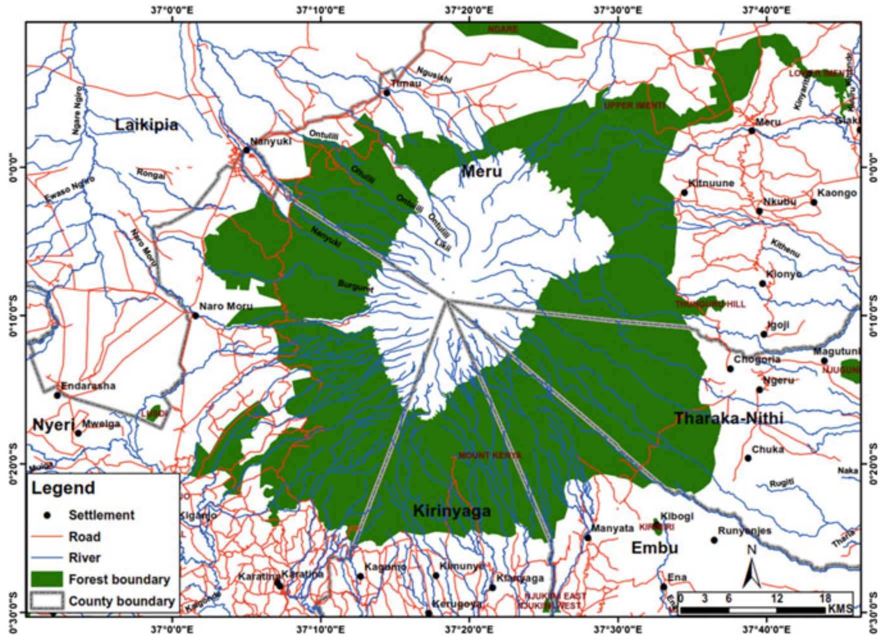


Fig. 2 Map of the six counties bordering Mount Kenya

rugged cliffs, alpine rivers, and lakes. The current summit is the remnant of a volcanic plug which remained after the progressive glacial erosion of softer rocks (Tanui 2009).

The high-altitude afro-alpine zone of the mountain, situated at an elevation higher than 4500 m, is predominantly characterized by low mean temperatures of up to 2 °C, especially during the cold rainy season (March–June), which leads to regular snowfall and glacier formation (Hastenrath 2005). The glaciers are known to enhance the hydrological stability of the mountain ecosystem by storing water in the form of ice, whose gradual release through glacial meltdown in the dry season ensures continuous flow of rivers and uninterrupted water supply to inhabitants in downstream areas (McDowell and Koppes 2017).

Mount Kenya is an important biodiversity area of Kenya with approximately 880 plant species including 11 endemic species in the lower elevation upto 3200 m (Winiger 1990; Mizuno and Fujita 2013). The mountain is characterized by distinct vegetation zones along the altitudinal gradient from dry forest in the low-lying areas (<3000 m), bamboo zone (<3200 m), montane rain forests (3700 m), ericaceous bush (4000 m), high-altitude moorland (>4000 m), and rugged afro-alpine zone at the top (Pellikka et al. 2004; Mizuno and Fujita 2013). The ecosystem supports a wide range of wildlife species including elephants, buffaloes, leopard, bongo, suni, black fronted duiker, bushbucks, water buck, elands, white tailed mongoose, tree hyrax, and giant forest hog (Nyaligu and Weeks 2013).

The mountain is a key asset of Kenya because it sustains a wide range of economic sectors both locally and regionally, namely, water supply, agriculture, forestry, fishing, wildlife conservation, tourism, and hydroelectricity generation. Based on this, Emerton (1996) estimated that the total annual economic value of the mountain ecosystem was more than \$100 million per year. Consequently, the Government of Kenya and the international community have made concerted efforts toward its conservation. In 1932, during the colonial times, a national forest reserve was established. Thereafter, a 715 km^2 national park was gazetted in 1949 while 718 km^2 of the mountain was listed as a biosphere reserve in 1978 under the United Nations Educational, Scientific and Cultural Organization-Man and the Biosphere Programme (UNESCO-MAB). Subsequently in 1997, a total mountainous area of 2023 km^2 was designated as a UNESCO World Heritage Site (UNESCO 2013).

Mount Kenya is regarded as a sacred holy mountain by the communities of the region, which includes the Gikuyu, Ndia, Gichugu, Meru and Embu communities. The snow-white cap on the mountain summit is considered divine, sacred, and the holy resting place of the Gikuyu God, "*Ngai*", *Mũrungu,* or *Mwene-Nyaga (*Kenyatta 1965). Consequently, the mountain contains a wide range of sacred natural sites in the form of hills (e.g. Karima, Kamwangi, Gakina, and Kirimiri), lakes (e.g. Thaai, Nkunga and Mbutututia), caves (e.g. M'mwenda, Naromoru, Mau, and Old Moses), sacred groves (e.g. Igandegi, Kiamonko, Kionyo), and sacred tree species such as the *Ficus natalensis* (fig tree or *Mũgumo*). The local communities use these sacred sites for various traditional rituals including worship. Some communities in Kenya usually worship while facing Mount Kenya because of its sacred nature (Kenyatta 1965).

1.2 Mountain Glaciers and Hydrology

A large number of high-altitude cold mountain summits of the world are characterized by glaciers whose meltwater is usually discharged downstream into the surrounding landscapes. Consequently, one-sixth of the world population depends on rivers flowing downstream from mountain glaciers to meet their water supply demand (Veettil and Kamp 2019). However, this benefit is less significant in Africa due to the reduced glacial coverage. Several studies have shown that the widespread incidents of climate change associated with glacial recession are expected to generate increased meltwater discharge until a peak discharge point beyond which the river flow might decline substantially as the glaciers no longer serve as water sources (Huss and Hock 2018). Consequently, shrinkage of mountain glaciers is likely to generate less discharge of melt water with negative implications on freshwater availability to the downstream consumers.

In Africa, high-altitude glaciers are common solely in three mountains located in the eastern region, namely Kilimanjaro in Tanzania (5895 m), Mount Kenya in Kenya (5199 m), and the transboundary Ruwenzori Mountain in Uganda and the Democratic Republic of the Congo (5109 m). However, the number of glaciers is quite small compared to those of other mountains in the world. For example, compared to the Himalayas with more than 54,000 glaciers spanning approximately 6,100 km^2 (Bajracharya and Shrestha 2011), Mount Kenya is currently characterized by only 10 glaciers with a total area of less than 1 km^2 (Chen et al. 2018) compared to the 18 glaciers which previously covered the mountain summit.

According to UNESCO, most mountain glaciers in the world, especially the ones in the tropics, have been retreating since the beginning of the eighteenth century due to the on-going climate change and associated precipitation reduction (Schoolmeester et al. 2018; Veettil and Kamp 2019). Rapid glacial retreat has been reported in South America including Venezuela, Argentina, Ecuador, Chile, and Colombia. According to Molg et al. (2008), tropical glaciers including those in Africa are highly sensitive to climate change and can serve as visible indicators of this phenomenon.

Mountain glaciers are known to have a strong link to both local and regional hydrology because they capture and store significant quantities of precipitation through ice formation. Thereafter, glacial runoff associated with the melting of ice due to increased temperature in the dry season (periods of low precipitation) ensures discharge modulation of downstream rivers through the glacier compensation effect. The glacial runoff is usually generated from a mix of both surface and subterranean meltwater, which flows downstream and is discharged in springs that feed into streams and subsequently into the rivers. In the wet seasons, the discharge can be accelerated by non-ice melt surface runoff.

For example, in Asia, glacial meltwater from the Himalayas, which has the largest coverage of ice outside the polar regions, is a key source of major rivers in the region such as the Indus, Ganges, and Brahmaputra in India as well as the Saptakoshi, Narayani, and Karnali in Nepal (Hasnain 2002; Gautam et al. 2013). On the overall, the Himalayan glaciers are estimated to provide water to 1.4 billion people (Bolch et al. 2012). Consequently, the United Nations Environment Program (UNEP) has previously indicated that the continued reduction of tropical glaciers is likely to affect domestic and urban water supply, agriculture, fishing, and livestock husbandry in villages and cities far away from the glacier mountains (Roer et al. 2008).

Studies have shown that the magnitude of hydrological impact of high-altitude glaciers in East Africa is significantly lower due to the smaller-sized glaciers in the region compared to the Asian glaciers (McKenzie et al. 2010). Several hydrological studies have concluded that water recharge from the dense forest zones in the high mountains of Eastern Africa constitutes the hydrological powerhouse of those ecosystems, and represents the most critical sources of water for the downstream consumers (McKenzie et al. 2010). The dense forest canopy usually intercepts rainfall and serves as a natural hub for water recharge, through which spring and river discharge is maintained. The thick forest canopy enhances rainwater interception and infiltration under the ground by creating numerous macro-pores through tree roots, which enables water seepage into the soil matrix. This process eventually facilitates the natural recharge of groundwater aquifers and subsequent discharge through springs, streams, and rivers (Mwaura et al. 2016).

Previous studies have revealed that in Mount Kenya, up to 90% of the dry season discharge in the Ewaso Ng'iro River originates from the high-altitude glaciers in the alpine zone (>4000 m), mid-altitude moorland (3000–4000 m), and discharge from the dense montane forest canopy (>2400 m). Significant changes in the glacial surface area are therefore likely to have implications on regional hydrology and the livelihoods of downstream communities.

A recent detailed study by Prinz et al. (2018) showed that the total glacier cover of Mount Kenya decreased by 121.0 × 103 m^2 in 2004–2016, which was equivalent to 44% glacial cover reduction. According to the study, Lewis, the largest glacier, lost approximately 62.8 × 103 m^2 (46%) of its area and 1.35 × 103 m^3 (57%) of its volume. An earlier study by Hastenrath (2005) demonstrated that the total area of 18 glaciers decreased from 1.64 km^2 to approximately 0.27 km^2 in 1899–2004, which was equivalent to an 84% reduction. This trend has been also reported by Mizuno (2005a, b) and Mizuno and Fujita (2013). Currently, only 10 out of the initial 18 glaciers are believed to be active in Mount Kenya, which implies that only less than one-third of the previous ice cover is remaining. The key question is whether the continued glacial recession due to climate change can negatively affect the downstream water consumers. In the Ruwenzori Mountain, a recent study has shown that glacial recession had marginal impact on the flow of the Mubuku River (Uganda) because glacial meltwater contributes to less than 2% of the river discharge (Taylor et al. 2009).

Empirical studies on the hydrological implications of climate-change-glacial recession have been undertaken in different parts of the tropical regions such as the Mount Everest glaciers (Wood et al. 2020), Bolivian Cordillera Real (Frans et al. 2015), Peruvian Cordillera Blanca (Baraer et al. 2012), Bolivian Cordillera Oriental (Soruco et al. 2015), Ruwenzori glaciers (Taylor et al. 2009), Andean glaciers (Coudrain 2005), and Nepalese Langtang Himalayan glaciers (Chaulagain 1970). Most of the empirical studies have indicated that the peak point of glacial recession has already been reached; hence, the strong likelihood of diminishing water supply on the long-term due to the depletion of glacier-related discharge.

The rapid retreat of glaciers around the world, especially in the tropics, requires knowledge of its impacts on local communities, especially in terms of water supply and related livelihoods. Despite the importance of glacial hydrology studies on this subject, there is a need for society-oriented studies to assess the perception of local communities on the shrinking glaciers. Such studies can assess the implications of glacial recession on water supply, livelihood impacts, and also probe on the intended adaptation and coping strategies especially in relation to water supply and water dependent livelihoods. Such studies are rare, especially in Africa hence the need for that focus in this chapter.

1.3 Climate Change, Glacier Recession, and Water Supply for Downstream Societies in Mount Kenya

Water is a critical physiological requirement for all societies in the world regardless of their race or economic status. According to Thomas et al. (2020), the World Health Organization (WHO) recommends the provision of a minimum of 20 L/person/day for human consumption (drinking, cooking, sanitation, and basic hygiene). For this reason, water supply was identified as one of the key issues for the global 2030 agenda, in which sustainable development goal 6 (SDG-6) on water and sanitation was established. Target 6–1 of SDG-6 aims at ensuring universal and equitable access to safe and affordable drinking water for all by 2030 (Ortigara et al. 2018). Recently, the issue of water supply has been in the headlines during the COVID-19 global pandemic because WHO has recommended handwashing as one of the most effective measures to reduce the spread of the virus.

Mount Kenya is one of the largest water towers in Kenya, which provides water to over 9 million people in six counties located directly around the mountain ecosystem (Kirinyaga, Nyeri, Laikipia, Meru, Tharaka-Nithi, and Embu) and other distant counties that are hydrologically connected to the mountain through rivers originating from the ecosystem. These include the arid counties of Northern Kenya (Isiolo, Samburu, and Garissa) and some coastal counties (Tana River, Kilifi, and Lamu). These countries are connected to Mount Kenya by the Tana River on the humid windward side, and by the Ewaso Ngiro River on the leeward side (Figs. 1 and 2). Approximately 90% of the water requirements for people in the Ewaso Ng'iro Basin (15,000 km^2) are fulfilled almost entirely from the water originating from Mount Kenya. On the other hand, the Tana River is the largest and longest river in Kenya (1000 km), which drains to the Indian Ocean and has been the source of most of the hydroelectric power (HEP) in the country since a long time.

The Mount Kenya water tower is a key player in the realization of SDG-6 in Kenya. The Constitution of Kenya (2010) considers access to clean and safe water in adequate quantities as a fundamental human right. However, its realization is likely to be affected by the impacts of climate change and global warming. Climate change studies have shown that Africa is among the regions of the world which are likely to be seriously affected by climate change. Global climatic models predict that by the year 2100, climate change in Kenya will lead to increased temperatures by approximately 4 °C, and cause rainfall variability by up to 20% (IPCC 2007). Climate change has already caused glacial recession in Mount Kenya. If the current rate of glacial retreat persists, the glaciers of Mount Kenya's are expected to be depleted before 2030 (Prinz et al. 2018). Despite this, very few studies have been undertaken to assess the perception of the local communities on glacial recession as one of the conspicuous indicators of climate change and the hydrological implications of deglaciation, especially with regard to water supply and livelihood adaptations.

Changes in mountain glaciers are considered an excellent indicator of global climate change (Winkler et al. 2010; Prinz et al. 2018). Consequently, global glacier monitoring is implemented through the Global Climate/Terrestrial Observing System

(GCOS/GTOS) according to the Global Hierarchical Observing Strategy (GHOST). Glacial changes are usually analyzed by monitoring glacial morphometrics such as length, width, surface area, and volume as indicators of trends in climate change. Although such glacial changes are usually monitored using sophisticated scientific techniques including remote sensing and GIS, the change is also visible through the naked eyes of the non-scientific society. However, very few studies have been undertaken in Africa to determine how different societies perceive such glacial change, especially in relation to climate change and its implications to their water demands and livelihood needs. The analysis and documentation of such local perceptions can enrich policy making because such studies will reflect local concerns, including peoples' fears and worries (Byg and Salick 2009). The analysis of public perception has the potential to highlight the most critical impacts of climate change on people's livelihoods. Such studies can direct the attention of scientists towards the ignored aspects of peoples' lives. Unfortunately, this line of investigation has not been popular among the scientific communities that study global climate change.

In Mount Kenya, the following research questions on the relationship between climate change and glacial retreat are withstanding from the point of view of the local people's perception: (a) how do the people perceive trends in glacier change? (b) what are their views regarding the impacts of visualized glacier change on river flows? (c) what are the likely implications of deglaciation on long-term water demands? It also interesting to determine how the local awareness on these issues varies in the society according to age, gender, and the level of education.

The overall purpose of this study was to establish whether the different local communities residing in the dry and water-scarce leeward side of Mount Kenya are aware of the on-going glacier changes and their implications on their livelihoods. The aim was to determine whether the people are accurately aware of the impacts of the on-going climate-change-driven deglaciation and their likely implications on water supply and livelihood activities (especially irrigation, urban water use, and pastoralism). The specific objectives were to determine the following:

(a) actual trend of glacier reduction in Mount Kenya from 1970s to 2000s.
(b) perceived changes of glaciers in Mount Kenya in relation to the trend in river flow and its implications on people's livelihood with emphasis on irrigation, urban water use, and pastoralism.
(c) variability in the perception patterns according to age, gender, and level of education.

2 Study Sites

Mount Kenya represents a hydrologically influential ecosystem, whose impact stretches all the way to the Indian Ocean in the humid south-eastern side (windward side) through the Tana River, and to the Kenya-Somali border in the dry north-eastern side through the Ewaso Ngiro River (leeward side). The hydrological impact is more prominent in the six counties bordering Mount Kenya, namely

Nyeri, Kirinyaga, Embu, Tharaka-Nithi, and Meru on the southern and eastern side and Laikipia on the leeward side to the north (Fig. 2). The on-going deglaciation is likely to have more serious implications on the leeward side due to the persistent water scarcity, increasing water demand, and occasional tension and conflicts related to water availability.

In this study, we conducted a public perception survey among the communities along the Naromoru River, which is located on the western side of Mount Kenya in Nyeri County (Naromoru Ward, Kieni East Sub-County), and along the Likii River, which is located on the northern side of Mount Kenya in Laikipia County (Nanyuki and Segera Wards, Laikipia East Sub-County). Figure 3 shows the location of the study area.

Naromoru River is the western-most tributary of the Ewaso Ng'iro River, whose tributaries drain water from Mount Kenya, especially Lewis, Tyndall, and Darwin glaciers (Fig. 4). The river is also sustained by water flow from several glacial lakes such as Lewis, Tyndall, Teleki, and Hut tarns, all of which lie above 4500 m (Aeschbacher et al. 2005; Nussbaumer 2015). The river flows westwards, down the mountain through Nyeri County, and forms the south-western tributary of the Ewaso Ng'iro River. The Naromoru catchment (173.4 km^2), which accounts for only 1.1% of the Ewaso Ng'iro Basin, represents a water-scarce area on the leeward side of Mount Kenya. A water abstraction assessment undertaken in the area during the early 2000s revealed that up to 80% of the river flow is abstracted through furrows, gravity pipes,

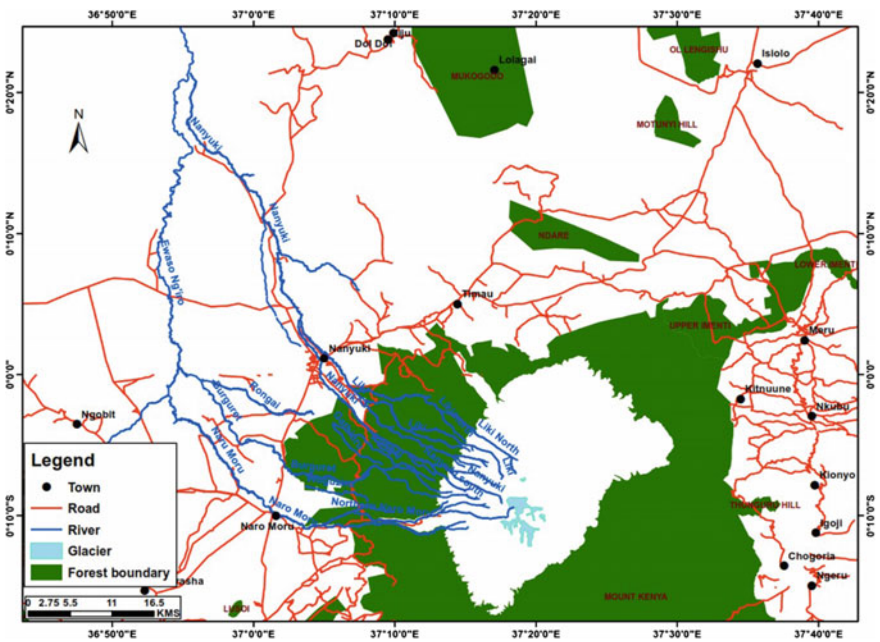


Fig. 3 Location of the study area

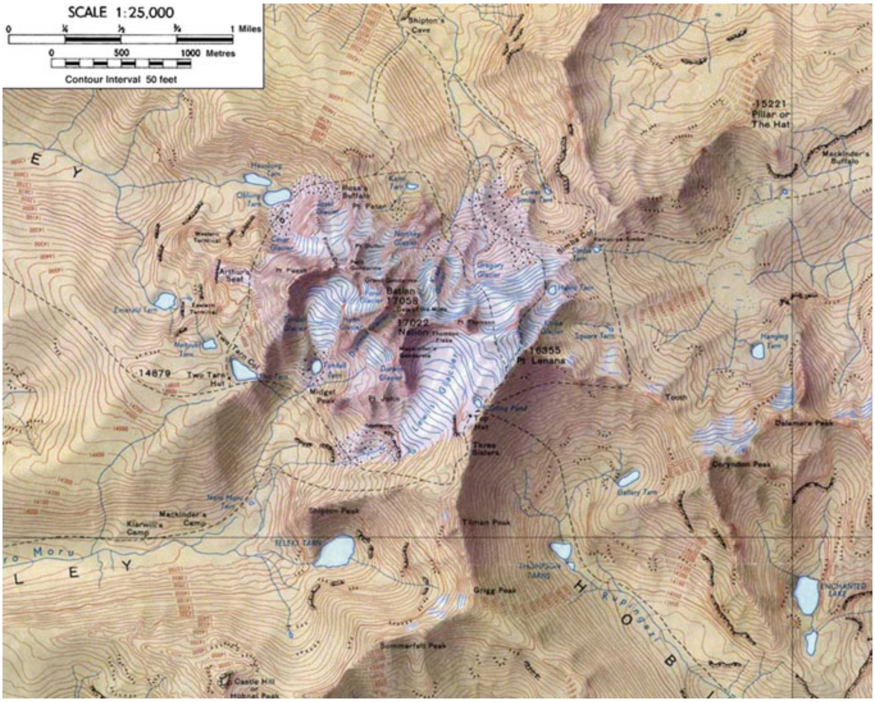


Fig. 4 Glaciers in Mount Kenya, and their connection to Naromoru and Likii Rivers

and pumps for irrigation purposes (Aeschbacher et al. 2005; Nussbaumer 2015). According to Nussbaumer (2015), the population density in the Naromoru catchment increased from 198 to 243 persons/km^2 during 1999–2009, which is equivalent to an annual growth rate of 1.9%.

The Likii River catchment area (174 km^2) stretches above 4000 m in Mount Kenya. It is associated with Tyndall, Josef, and Cesar glaciers. The river is also sustained by water flow from the Nanyuki, Emerald, Hausberg, and Oblong tarns (Fig. 4). It flows downstream through Nanyuki town before joining the Nanyuki River at an altitude of approximately 1850 m to form the south-eastern tributary of the Ewaso Ngiro River (Fig. 3). The river flows though diverse landscapes, and it supports a wide array of local communities in both the rural and urban zones. The upstream high-altitude section of the river is dominated by small-scale farmers, with land parcel size ranging between 1 and 4 acres. On the other hand, the downstream low altitude section crosses through the Nanyuki municipality within the low-income urban residential area of Likii next to the river. The lower part of the river below the Nanyuki town is dominated by Masai pastoralist activities, who rely on the river as the water source for their livestock.

3 Research Methods

A simple spatial analysis of glacial changes in Mount Kenya was undertaken using medium resolution (30 m × 30 m) low-cloud cover Landsat imageries acquired from the Regional Centre for Mapping of Resources for Development (RCMRD) in Nairobi. The analysis was undertaken for the period 1976–2016 using imageries acquired in 1976, 1987, 1995, 2007, and 2016. The analysis was carried out using ArcGIS and ENVI software.

A local perception survey on glacial change, river flow trends, and livelihood impacts was conducted via face-to-face interviews with 90 riparian residents along the Naromoru and Likii rivers (Fig. 4). This included 30 irrigation farmers along the Naromoru River, 30 low-income urban residents along the Likii River in Nanyuki town, and 30 pastoralists along the same river situated below Nanyuki town. Systematic random sampling was used to select the respondents, whereby every third farm or household in Naromoru was considered. Every third urban water user along the Likii River in Nanyuki town and every third livestock herder were interviewed using a standard questionnaire. Figure 5 shows the specific locations, marked using GPS, where the interviews were undertaken. The interviews were conducted on August 2016, between the dry and wet seasons to avoid seasonal bias.

Among the three sites, the lower section of the Likii River (pastoralist zone) has the best visual view of the mountain glaciers due to un-obstructive terrain, location approximately at the middle of the leeward zone and the prevalence of cloudless weather almost throughout the year. The Naromoru River zone, on the other hand, has the most inconspicuous view of the mountain glaciers due to obstructive terrain, frequent cloudiness, and dense forest cover. This is due to its location in the transition zone between the windward and the leeward zones (Fig. 4). Figure 6 shows a general view of Mount Kenya from the Nanyuki and Naromoru sides.

The standard questionnaire for the local perception survey included a preliminary section to determine the respondents' profile such as gender, age, and level of education. The rest of the questionnaire was carefully configured to gauge the respondents' perception regarding glacial changes in Mount Kenya, localized trends of river flow changes in relation to the perceived glacial change, implication of the latter on the livelihoods of residents, and proposed adaptation strategies. The questionnaire was structured in accordance with the Likert Scale, whereby the respondents were offered a choice of five pre-coded responses with the neutral point being "neither agree nor disagree." The non-parametric Mann–Whitney U Test was used for data analysis as a tool for comparing the local perceptions according to gender, age, and level of education, with the level of significance evaluated at $\alpha = 0.05$.

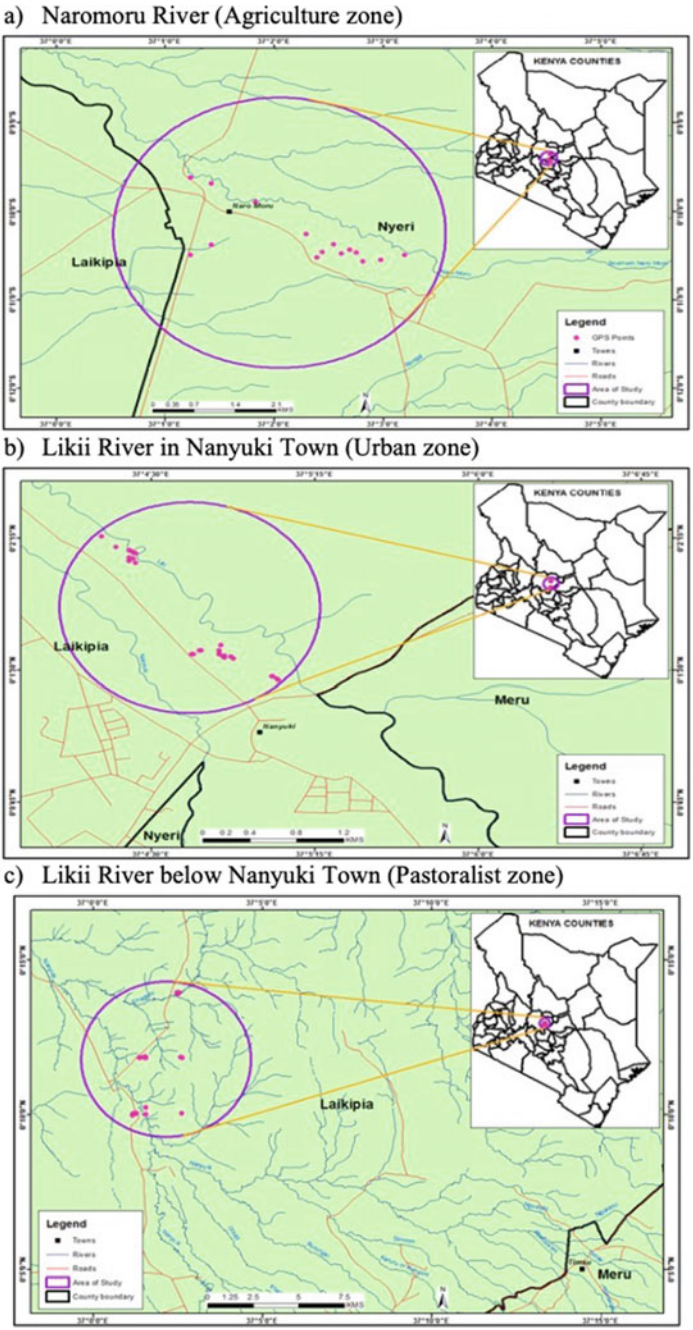


Fig. 5 Survey sites to evaluate the public perception of glacial changes

Fig. 6 General view of Mount Kenya from the Nanyuki and Naromoru sides, respectively

4 Results

4.1 Actual Changes in Glaciers

Figure 7 shows the glacier coverage in Mount Kenya during 1976, 1987, 1995, 2007, and 2016. The analysis of the satellite imageries showed that the glaciers were concentrated on the windward side of the mountain. The spatial analysis showed that the glacial surface area has been declining consistently, from approximately 1.86 km^2 in 1976 to around 0.17 km^2 in 2016.

4.2 Local Perception on the Changes of Mountain Glacial Cover

During the local perception survey, from the total of 90 respondents, 87 valid responses from 56 males (64%) to 31 females (36%) were obtained. 64% of the valid respondents were aged between 25 and 34 years, 9% were aged between 55 and 64 years, and the rest were in the middle age group (35–54 years) as shown in Fig. 8. All the age groups were considered to have a good grasp and personal internalization of the Mount Kenya glacial change trend for the 40-year duration. The level of education for the respondents was dominated by primary and secondary school education at 37.9% and 36.8%, respectively, with only 6.9% having attained tertiary education (college and university levels). Meanwhile, 18.4% of the respondents had only informal education (traditional indigenous knowledge) because they never went to school.

The sample residents included irrigation farmers along the Naromoru River, urban residents along the Likii River in Nanyuki town, and Masai pastoralists along the same river below the town. The irrigation farms in Naromoru had an average area of 1–10 acres, with approximately 1–3 acres being used for growing vegetables

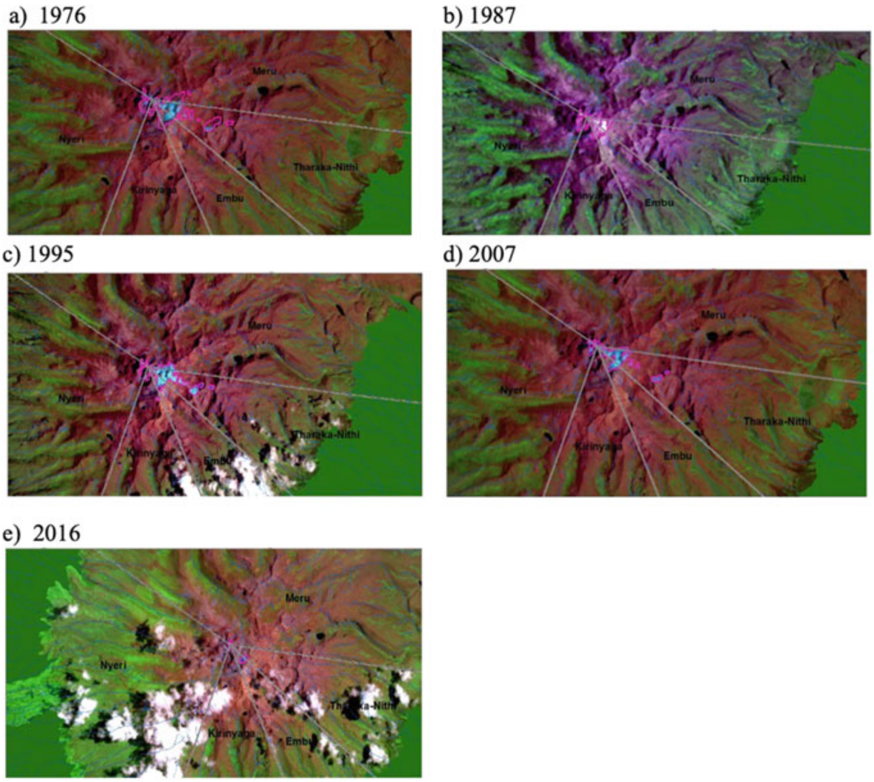


Fig. 7 Glacial coverage in Mount Kenya during 1976, 1987, 1995, 2007, and 2016

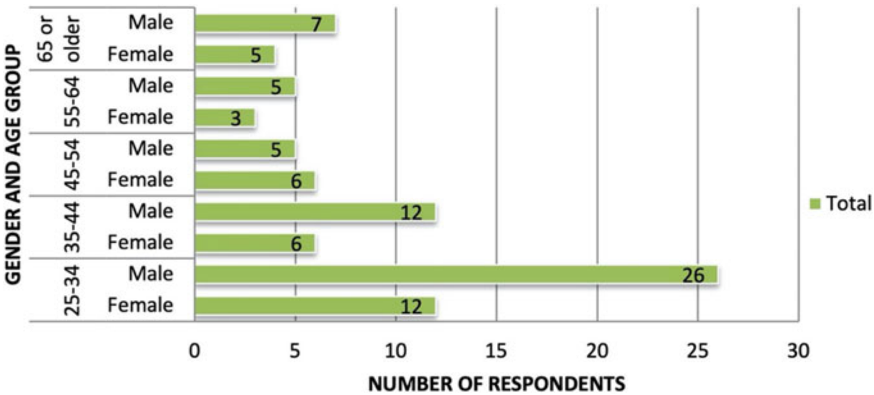


Fig. 8 Distribution of the respondents' gender and age

and maize. Most of the urban residents in Nanyuki town consisted of low-income residents, who depended on the river as a source of water for domestic use and small-scale business activities (including small-scale urban agriculture). The pastoralists along the Likii River below Nanyuki town mainly raise cattle, sheep, and goats with an average herd size ranging between 50 and 100 animals. The Likii River is the main source of water for livestock which are taken to the river almost on daily basis.

During the perception survey, 58 out of 87 respondents (67%) strongly agreed that the glaciers of Mt Kenya had reduced significantly during the 40-year period considered in the study (1976–2016). However, this view was not unanimous because 17 respondents (20%) were unsure and 1 respondent (1%) was in strong disagreement (Table 1). The survey showed that 36% of the respondents, who felt that the glaciers had significantly reduced, were from the Nanyuki region, which has an excellent view of the mountain. On the other hand, only 20% of the respondents from the Naromoru area had a similar perception (Fig. 6). The latter had a poorer view of the mountain glaciers due to more rugged terrain, frequent cloudy weather, and dense forest cover due to its location at the transition zone between the leeward and the windward sides.

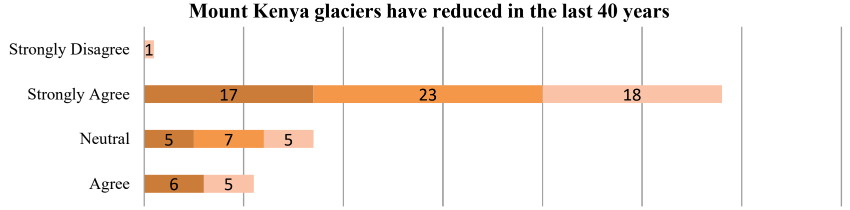
Table 1 shows that there was no significant difference among the residents' perception regarding the occurrence of glacial reduction in Mt Kenya either by age ($p = 0.712$), gender ($p = 0.115$), or level of education ($p = 0.077$). Majority of the respondents strongly attributed the deglaciation trend to the impacts of global warming due to climate change, which is in agreement with the findings of scientific studies around the world. However, there were significant differences in the perception between male and female respondents regarding the consistency of deglaciation trend in Mount Kenya, which is reflected in the Mann–Whitney U test results (Table 1).

The difference was attributed to the distant location of the glaciers for all the respondents who lived in settlements at the base of the mountain and had rarely ventured up the mountain. It is likely that the findings of the perception survey could have differed if the assessment was done among regular mountain climbers such as tour guides and porters, who interact more closely with the glacial zone while escorting both local and international tourists.

4.3 Local Perceptions on the Dynamics of Glacial Cover Changes, Water Resources, and Social Livelihoods

Table 2 shows the findings of the local perception survey on the glacial cover change, and its impact on water resources and livelihood. Majority of the respondents in Naromoru and Nanyuki strongly considered that deglaciation in Mount Kenya had significantly reduced river flows and affected the availability of water and people's livelihoods, especially for farming and pastoralism. However, some pastoralists in the lower sections of the Likii River did not associate the reduction in the river flows to glacial retreat but rather to excessive abstraction by upstream people especially the

Table 1 Community perception on Mount Kenya glacial dynamics



	Agree	Neutral	Strongly Agree	Strongly Disagree
Nanyuki Town (Lower Likii River Region)	6	5	17	
Nanyuki Town (Upper Likii River Region)		7	23	
Naromoru	5	5	18	1

Perception by age and gender

	Disagree	Not sure	Agree	Strongly agree	Total
25–34 years	1	3	3	29	36
35–44 years	0	1	0	18	19
45–54 years	0	0	3	11	14
55–64 years	0	0	1	5	6
=/> 64 years	1	0	2	9	12
Female	2	1	5	23	31
Male	0	3	4	49	56

Mann–Whitney U test

Test variable 1	Test variable 2	N	Mean rank	Mann–Whitney U	Wilcoxon W	Z	p-value
Significant glacier decrease in the last 40 years	25–34 years	36	24.81	205	283	-.369	0.712
	=/> 64 years	12	23.58				
	Female	31	40.23	751	1247	-1.578	0.115
	Male	56	46.09				
	Informal education	17	22.53	230	383	-1.866	0.077
	Formal education	34	27.74				
Inconsistent deglaciation trend	Female	31	52.74	597	2193	-.2.602	0.004
	Male	56	39.16				

Table 2 Community perceptions on glacial dynamics, river flow, and the impact of deglaciation on livelihood

Mount Kenya deglaciation has reduced river flows, and water availability and uses (%)					
	Not sure	Agree	Strongly agree	Disagree	Total
Naromoru (Irrigation zone)	13.4	31	65.5	-	100
Upper Likii (Urban zone)	-	33.3	60.0	6.7	100
Lower Likii (Pastoralism zone)	3.6	57.1	32.1	7.1	100

Table 3 Community perception analysis on deglaciation, and its impact on livelihoods

	Not sure	Disagree	Agree	Strongly agree	Total
Deglaciation and reduced river flow have negatively affected irrigation along the Naromoru River	3.4		31.0	65.5	100
Deglaciation and reduced river flow have increased water use tension along the Naromoru River	24.1	6.8	24.1	44.8	100
Deglaciation has escalated irrigation, urban, and pastoralism-related water use tension along the Likii River	26.7	33.4	13.3	26.7	100
Deglaciation and reduced river flow have negatively affected pastoralism along the Likii River	3.6	7.1	57.1	32.1	100

Mann–Whitney U test

Test variable 1	Test variable	N	Mean rank	Mann–Whitney U	Wilcoxon W	Z	p-value
Deglaciation has increased irrigation water use tension	25–34 years	6	11.08	14.5	69.5	-.1.828	0.05
	35–44 years	10	6.95				
Deglaciation has affected downstream irrigation	Females	6	9.83	38	59	-2.010	0.04
	Males	23	16.35				
Deglaciation has escalated irrigation, urban, and pastoralism-related water use tension	Females	5	18.40	38	314	-1.375	0.05
	Males	23	13.65				
Deglaciation has affected the pastoralism sector	Females	5	21.20	24	300	-2.201	0.02
	Males	23	13.04				

large scale irrigation farmers. This finding was a clear indication of the deep mistrust and potential water conflicts among the water users on the leeward side of Mount Kenya.

Sixty six percent of the respondents along the Naromoru River, who were mostly small-scale irrigation farmers, had the strong perception that Mount Kenya deglaciation was responsible for the reduced river flows and is likely to have serious negative impacts on irrigation (Table 3). However, only 45% respondents perceived that mountain deglaciation is likely to increase the water usage tension along the river. This view of residents was different from those in the Nanyuki area as explained above. The difference can be attributed to the mono-ethnic nature of the Naromoru area, which is mainly occupied by the Kikuyu people who are mostly farmers. The Nanyuki area, on the other hand, is more cosmopolitan. The Maasai pastoralists, who reside in the downstream area, have always considered themselves a disadvantaged group in terms of sharing natural resources, such as land, pasture and water resources. However, only 27% of the respondents in the Nanyuki area had serious fear that the continued glacier retreat in Mount Kenya was likely to escalate water usage tension and conflict between the downstream pastoralists and the upstream irrigation farmers and urban residents. Up to 32% of the respondents in the lower sections of the Likii River had a strong perception that continued deglaciation and reduced river flows could eventually have negative impacts on pastoralism through reduced stock sizes (Table 3).

The results of the Mann–Whitney U test indicated significant differences in local perceptions of glacial changes according to age and gender. The perception difference by gender could be attributed to the configuration of the sample size, which was dominated by males (64%). Male respondents were dominant, especially in the Naromoru River irrigation farms and in the livestock grazing fields along the lower sections of the Likii River.

The findings would probably have been different if the sample size was equally distributed across the gender spectrum. Overall, the findings showed that formal education was not a necessity in the mental internalization and personal awareness of mountain deglaciation and its implications on the livelihoods of downstream societies.

5 Discussion

The findings of the study showed that the local people on the dry leeward side of Mount Kenya were aware of the on-going glacial retreat and the changing trends of water availability in the downstream regions. This was similar to the findings of other studies, such as the study on local perceptions of glacial retreat in the Bashy Range (4800 m) of Tien Shan Mountains in Kyrgyzstan, Central Asia, where the perception of deglaciation among the respondents was not unanimous (Piersall and Halvorson 2014). The study also established that public perception on the trend of glacial retreat was largely inconsistent among the respondents. Other studies on glacial retreat, especially in South America such as that on the Peruvian Andes (Mark et al. 2010; Bury et al. 2011) and in Eastern Tibet (Byg and Salick 2009) have recorded consistent patterns between local perception and actual deglaciation trends. In South America, the findings of a local perception study on glacial recession in Cordillera Blanca mountain of the Peruvian Andes, which contains the largest proportion of tropical glaciers in the world, were concurrent with the actual trend of glacier recession determined through scientific research (Mark et al. 2010, 2017; Bury et al. 2011).

The highly accurate perception of the actual glacial retreat trend by the respondents from the Nanyuki side of Mount Kenya, which has a better visual perspective compared to the Naromoru side, is similar to the findings of other studies. For example, the studies by Byg and Salick (2009) in Eastern Tibet reported considerable differences in local perceptions on glacial retreat, which depended on topography and proximity of the village to the mountain glaciers that ultimately affect visual recognition.

Although Mount Kenya appears to have experienced a rapid glacial meltdown in recent years due to global warming and climate change, the local perception indicates that it is mostly associated with declining river flow in the downstream, and not increasing river flow. This can be considered to confirm the hypothesis that glacial recession generates increased meltwater discharge and high river flows only up to a peak point, beyond which the flow declines substantially because the glacier no longer serves as a significant source of water discharge. Furthermore, this view could also confirm the marginal impact of African mountain glaciers on river flows, which has already been established for the case of the Ruwenzori Mountain, where Taylor et al. (2009) estimated a contribution of less than 2% of the discharge in the Mubuku River (Uganda). This might support the hydrological argument that the watershed powerhouse of the mountain is actually located within the forest zone, and not in the afro-alpine glacier zone. However, these findings could also be the outcomes of misconception in the minds of the local people as a result of the increasing water demand driven by population growth. Such misconception has been reported in other places. For instance, Mark et al. (2010) observed that although the on-going glacier melt in Peruvian Cordillera Blanca was accompanied by significant increase of discharge in rivers, the local people perceived that the river flow and available water were both decreasing. This suggests that actual hydrological studies need to be conducted to identify the disparities between scientific evidence and societal perceptions.

Significant variations in local perception by gender and age were noted for several dimensions associated with the glacial retreat in Mount Kenya. The local perception on the glacial retreat trend was significantly different between the youth and the elderly as well as between males and females. The perception difference according to age group was attributed to the duration of the visual impact. The older respondents (those above 64 years) had a longer visual memory of glacial changes compared to the younger group (25–34 years). The differences in perception between male and female respondents could also be attributed to the fact that unlike females, who are restricted to their homes, males are more mobile given their responsibility as household income earners. Due to their movements to different geographic locations in the area, the males are likely to internalize a more accurate visual impression of the glacial retreat. The insignificant differences in public perception pertaining to the changes of mountainous glaciers, based on the level of education can be attributed to the view that the uneducated respondents mostly remain in their home areas in Mount Kenya area throughout most their lives without migrating to other locations for formal education (especially secondary and college education), and are therefore likely to have a clearer picture of the actual trend in glacial retreat. In contrast, the educated respondents, despite their inconsistent view of the mountain glaciers, are more likely to learn about the impacts of climate change on glacial cover change in schools and colleges, and will hence share a common view with the less educated people.

As the white surface of the glaciated zone of Mount Kenya is considered holy, one of the unclear issues regarding the on-going glacial retreat in the mountain is how the total disappearance of the glacier will eventually affect the holy, divine, and sacred status of the mountain. It is likely that glacial retreat will create spiritual distress among individuals with a strong sacred attachment to the mountain because the affected societies cannot locally intervene with the ungodly changes associated with deglaciation. The social concerns on this matter can cause cultural and spiritual anxiety and psychological stress among the local residents, and therefore further research on this issue is necessary.

6 Conclusion and Recommendations

The spatial analysis of glacial changes demonstrated that Mount Kenya has continuously experienced progressive glacial retreat during four decades between 1976 and 2016. The analysis of the perception of local people regarding glacial retreat showed that the people were aware of the on-going deglaciation; however, their perception differed slightly according to gender and age, although the level of education had negligible influence on the perspective. The accuracy of public perception on the glacial retreat with respect to the actual trend (as documented through scientific research) is likely to be influenced by the nature of visual impression, especially in terms of proximity to the mountain, topographic orientation, weather conditions, and vegetation obstruction. Although community perception does not fully correspond to the actual trend due to distant visual inspection, all local people have noticed the glacial retreat.

The local people on the dry leeward side of Mount Kenya are aware, concerned, and worried about the hydrological implications of the glacial retreat, particularly in terms of changing river flows and increasing water scarcity, and also on its implications for livelihoods and social needs. The people in Naromoru were worried about the impacts of the on-going glacial retreat on irrigation and farming along the river, while those along the Likii River in Nanyuki were concerned about sharing of water resources in future between the upstream farmers and urban consumers with the downstream pastoralists. All the respondents were worried and concerned about future water related tensions and conflicts that would likely accompany the glacial retreat progress.

The following recommendations are based on the findings of this study:

(a) The national and county governments should integrate the issue of glacial retreat and its hydrological implications in the future reviews for relevant development and natural resources management plans such as the County Integrated Development Plans and Laikipia Water Conservation Strategy.
(b) Further research should be undertaken on the following aspects: (i) comparative assessment of local perceptions on glacier retreat between communities in the dry and water-scarce leeward side and humid and water-abundant windward side of the mountain ecosystem, and (ii) cultural, spiritual, and religious implications of glacier disappearance in Mount Kenya.

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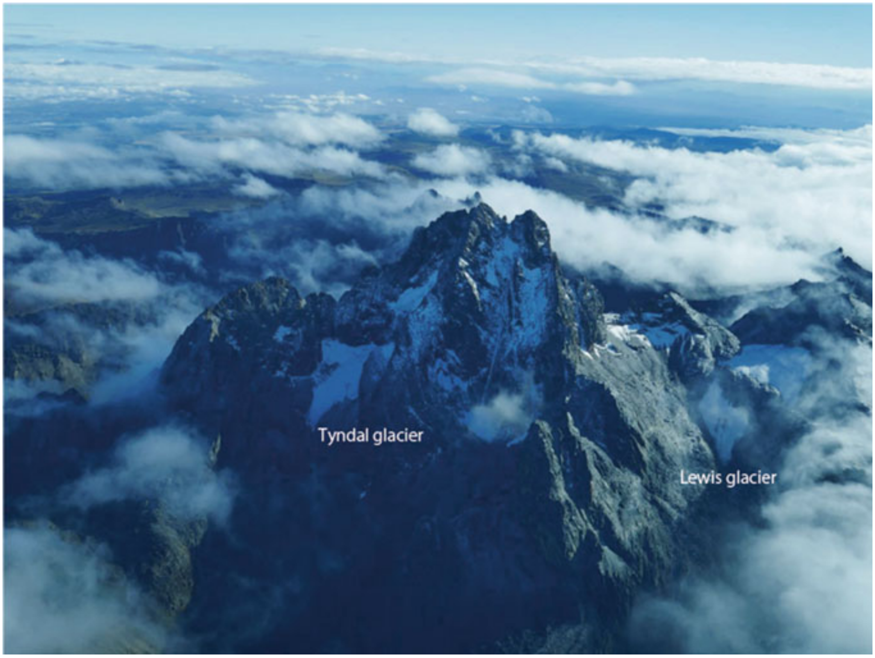
Geomorphology: Glacial Topography, Soil Development Processes in the Foreland of Tyndall Glacier on Mount Kenya

Kotaro Yamagata



The central peak area of Mount Kenya comprises volcanic plugs that have resisted glacial erosion. The slopes rise steeply on all sides with glaciers and rocky walls. This photograph was taken from the southwest direction with a view of the study areas (i.e., Tyndall and Lewis glaciers)

Abstract Glacier forelands allow us to trace back the processes of soil development by comparing the cross sections of soils that differ in time that has elapsed since the initiation of their respective development. This study discusses the relationship

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between soil development process and environmental factors in the glacier forelands of Tyndall glacier on Mount Kenya. The following six moraines were classified in the foreland of Tyndall glacier: moraines of the Lewis stage (Lewis I and II), Tyndall stage (Tyndall I–IV), and Liki III. Subsequently, the age of each moraine was estimated. The soil formation process was examined based on the observations of the soil profile. It was found that the soil layers were composed of aeolian particles, which were supplied from the surrounding bare ground. The speed of soil development fell within the range of 0.03–5 mm/year. Particularly, we identified the trend that soil development speed was higher during the earlier stages of soil development. The development speed at an early soil development stage in Mount Kenya was higher than that in other regions, and it was confirmed that the long-term development speed fell within the range observed in other regions.

Keywords Soil development processes · Deglaciation · Glacial topography · Tropical high mountains · Mount Kenya

1 Introduction

Over the years, several studies have been conducted on understanding various soil development processes. However, in reality, it is not easy to continuously monitor soil development processes as they proceed very slowly. Nevertheless, there are certain landforms that allow us to trace back the soil development processes through comparison of the cross sections of diverse soil types that differ in terms of elapsed time since the start of their respective development. These lands are those whose surfaces have been previously reset a number of times; for example, those landforms that have been repeatedly destructed by volcanic eruptions or those where river erosion or sedimentation have occurred repeatedly.

Glacier forelands are such landform. The land surfaces, when covered with glaciers, get renewed by glacier erosion or sedimentation, and thereby they do not experience weathering or biological action. The development of soil starts after the glacier retreats, which frees the land surface. Therefore, it is possible to trace back the past soil development processes by comparing the cross sections of diverse soil types developed on land surfaces located in the glacier foreland because such soils differ in terms of years elapsed after the surface was freed from the glacier (Bernasconi et al. 2011; Smittenberg et al. 2012).

During the soil development process, the soil is subjected to various environmental factors, which include not only the time elapsed but also the climate, topography, geologic features, vegetation, abundance of water, and other factors of the land where the soil develops. In particular, soil changes with interactions with vegetation. In this way, soils become diversified based on the varying environmental factors that the different locations of land get subjected to. However, the relationship of these environmental factors with soil development processes and soil diversity is not yet completely understood (Theme 2019).

This study, which focuses on the forelands of Tyndall glacier in Mount Kenya, discusses the relationship between soil development processes and environmental factors in the glacier forelands during the warming periods of Holocene.

Glacier retreats induced by global warming are being commonly observed worldwide in recent times. Revealing the soil development processes in the grounds from which the glaciers have retreated is important in understanding how the region reacts to sudden environmental changes caused by global warming. Especially, the glaciers distributed on the equator have a higher rate of glacier reduction and are currently on their way to extinction (Iwata 2010). In addition, rare ecosystems exist all around the glaciers in the tropics. Therefore, evaluating the soil development processes in the glacial peripheries of the tropical regions is important for predicting the future environmental effects of glacier retreats induced by global warming.

2 Study Region

Mount Kenya has an elevation of 5199 m. It is located at approximately 150 km north-northeast of Nairobi, almost on the equator. It is the second-highest mountain in Africa and is located in the eastern margins of the East African Rift. In addition, Mount Kenya is a stratovolcano developed by volcanic activities that occurred 3–2.6 million years ago (Bhatt 1991; Fig. 1). The mountain is predominantly composed of basalt, phonolite, trachyte, and syenite.

At an elevation of 2250 m, the precipitation reaches 2500 mm; however, it decreases at points closer to the mountain peak and drops to 900 mm at elevations of 4500 m or higher (Hastenrath 1984). At an elevation of 4750 m, the temperature remains at 0 °C almost throughout the year (Hastenrath 1991). As far as vegetation is concerned, the tree line lies at approximately 3000 m. The Erica shrubbery belt lies at approximately 3600 m height. The alpine belt, which is predominated by Poaceae and alpine plants, lies at approximately 4500 m height, and the ice belt lies at 4500 m or higher (Mizuno 1994).

The mountain peak and its peripheries (shown in this Chapter's cover photograph) were subjected to intense ice erosion during the glacial period; they formed precipitous crags, and due to glacier extension, a U-shaped valley was developed from the peak to the mountainside, which is radially present up to elevations of approximately 3000 m (Fig. 2).

Mount Kenya had 18 confirmed glaciers around its peak in 1947 (Hastenrath 1984). However, the mountain has lost nine glaciers by 2020, and currently there are only nine remaining glaciers (Narama and Arie 2022). The largest one of these is Lewis glacier, and the second largest is Tyndall glacier. The changes in these glaciers during the late nineteenth century and thereafter are recorded in detail (Mizuno 1994).

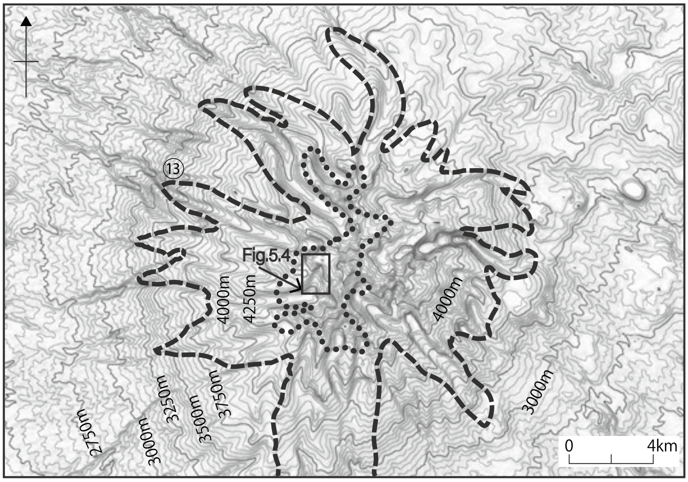

Fig. 1 Topographic map of Mount Kenya. Dashed line shows the extent of glacier expansion during the Last Glacial Maximum; Dotted line shows the extent of glacier expansion during Liki III stage (map has been modified after Mahaney et al. 1989)

Fig. 2 Naro Moru Valley, a typical U-shaped valley that was developed on the western slope. The photograph was acquired on 10th September, 2015

3 Chronology of the Foreland Topography of Tyndall Glacier

Mount Kenya has preserved the records of past glacier topographies, glacial deposits, and other traces from approximately its peak to elevations below 2900 m, which evinces that some glaciers extended in those regions (Shanahan and Zreda 2000). The moraine topography observed in Mount Kenya was classified into the following seven stages by Mahaney et al. (1989): Gorges, Lake Ellis, Naro Moru, Teleki, Liki (I–III), Tyndall, and Lewis, sorted from the oldest to the youngest. The ages of these moraines have been examined in different ways such as stratigraphic examination, paleomagnetism, radiocarbon dating, cosmogenic nuclide analysis, and lichenometry (Hastenrath 1984; Mahaney 1988; Mahaney et al. 1989; Shanahan and Zreda 2000).

Among these, analysis of cosmogenic nuclide by Shanahan and Zreda (2000) estimated that the Liki II moraine was developed during the Last Glacial Maximum (20 ka). Based on investigations on the distribution of Liki II moraine, it is believed that glaciers extended from the mountain peak to an approximate elevation of 3000 m in the Last Glacial Maximum (Fig. 1).

The age of Liki III moraine was evaluated to be approximately 12,500 years (Late Glacial Interstadial) based on radiocarbon dating of the organic materials contained in its deposits (Mahaney 1988). In addition, Shanahan and Zreda (2000) conducted a cosmogenic nuclide analysis and determined its age as approximately 10 ka. Therefore, it is considered that the age of the Liki III moraine corresponds to cold climate period of the Younger Dryas (12.8–11.5 ka) (Muscheler et al. 2008). It is believed that the glacier edges reached elevations of 4000–4200 m during this period (Fig. 1).

In the foreland of Tyndall glacier, the best moraine of Mount Kenya was developed during the Neoglaciation period, after the formation of Liki III. Baker (1967) studied Mount Kenya's glacier advancement during the Neoglaciation period, and inferred it as stage IV. Moreover, Mahaney (1984) studied stage IV moraines, and further classified this stage into advance eras of Tyndall and Lewis, which were chronologically ordered based on the physiographic positions of deposits, condition of weathering, and characteristics of cross sections of soils. Among these, the moraine in the advance era of Tyndall is found only in the foreland of Tyndall glacier.

The moraine in the Lewis stage was believed to have formed during the Little Ice Age because the degree of vegetation coverage and the lichen covering the gravels indicated it to be a new moraine that was formed later than that of the Tyndall stage (Mahaney et al. 1989; Fig. 3).

Mahaney et al. (1989) interpreted the moraines of the Tyndall and Lewis stages as individual extensions of each stage. This study further divided moraines based on aerial photointerpretation and field research. As a result, the moraines of the Lewis and Tyndall stages were further classified into two and four moraines, respectively (Fig. 4). Each of these moraines were named as Lewis I and II, and Tyndall I–IV, respectively.

In addition, another moraine that appears to block the Tyndall glacier valley can be identified at the outskirts of the Tyndall I moraine at the confluence of Tyndall

Fig. 3 View of Lewis and Tyndall-stage moraines. The degree of vegetation coverage of Lewis-stage moraine is poor, however Tyndall-stage moraines are densely covered by plants. The photograph was acquired on 9th September, 2015

glacier valley and Lewis valley (Fig. 4). This moraine was identified as the Liki III moraine as it borders the Liki III moraine, which extends to the Lewis glacier valley.

The age of the moraines of the Tyndall stage was estimated to be approximately 1,000 years based on radiocarbon dating of the organic materials contained in their deposits (Mahaney et al. 1989). However, it is uncertain which of the Tyndall moraines (i.e., I, II, III, or IV) were analyzed to obtain the age estimation. The former study was unable to obtain direct evidence of the developmental age of each moraine of the Tyndall stage. The vegetation condition and the thickness of the covering soil layers did not differ significantly between the Tyndall-stage moraines and the Liki III moraine developed during the Younger Dryas period. Therefore, it is highly possible that moraines older than 1,000 years were also included for the evaluation.

Karlen et al. (1999) examined the changes in the density of sediments and in carbon content among deposits found below the Hausberg Tarn lake, which is located adjacent to the north of Tyndall glacier astride the ridge. The study found horizons that implied six periods of cold weather during the Neoglaciation period: 5700, 4500–3900, 3500–3300, 3100–1900, 1300–1100, and 600–400 cal. years BP. It was suggested that the glacier was extended due to active transportation of materials along the slope during these periods. It is possible that these glacier extension periods correspond to Tyndall moraines I–IV. In this report, it is hypothesized that each of

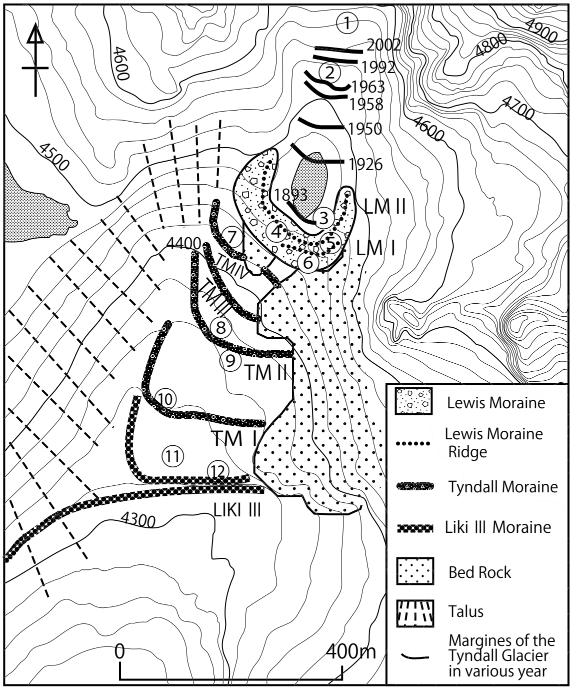

Fig. 4 Moraines and past glacier terminus position in the Tyndall glacier foreland

the Tyndall moraines I–IV correspond to the periods of cold weather, which are 5700, 4500–3900, 3500–3300, and 1300–1100 cal. years BP, respectively, because cooling indicators are commonly identified in East Africa from the sediments of these periods.

Mahaney et al. (1989) estimated the age of the moraine of the Lewis stage as Little Ice Age by lichenometry. In the present study, I re-examined this moraine by lichenometry because the moraine development has been divided into two stages in this report.

In the foreland of Tyndall glacier, no obvious moraine topography was identified on the upper stream side of the Lewis II moraine (Fig. 5). However, prior studies have identified the positions of glacier edge during several periods from 1983 to 2011 (Mizuno and Fujita 2013; Fig. 4).

The maximum diameter of *Rhizocarpon geographicum* at each location point with known ages was measured. If the diameter was significantly large, it was measured in parts using digital vernier caliper. More than 20 values were measured at one point. Figure 6 shows the relationship between the diameter measured at each location point and the age. Furthermore, a regression line was determined from these values. Onto this straight line, the diameter measured for the Lewis I and II moraines were projected to determine the age of each moraine. The study estimated that the Lewis I and Lewis II moraines were formed during 1830s and 1870s, respectively.

Fig. 5 Foreland of Tyndall glacier above Tyndall Turn. Tyndall glacier can be seen in the back. The photograph was acquired on 4th September, 2015

4 Circumstances of Soil Development on Glacier Topographies

In the foreland of the Tyndall Glacier, four rows of moraines from the Neoglaciation period (Tyndall I–IV) and two rows of moraines from the Little Ice Age (Lewis I, II) were identified, and the era of each moraine was estimated. Several observations have indicated that the present glacier terminus positions are newer than those in 1893. Based on annual data to evaluate the soil development process, the cross sections of soils observed on the topography of different eras were chronologically placed in this study.

For the moraines at the Tyndall and Lewis stages, the cross sections of soils were evaluated by creating a pit on a topography that lay between the moraine's ridge and depression. After 1919, no clear moraine topography was identified on the upper stream side of the moraines from the Lewis stage. Therefore, pits were created at arbitrary intervals between the present glacier terminus and the location of glacier terminus in 1893; subsequently the cross sections of soils were observed. The results are shown in Fig. 7.

At the time of this study in 2015, the intrusion of plants was identified up to a point located at approximately 17 m from the glacier edge. However, no soil layer

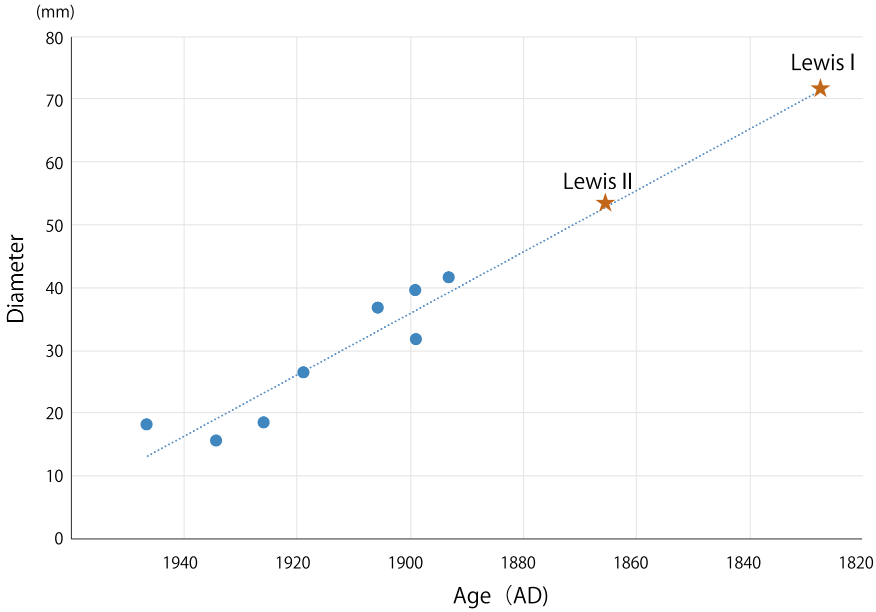

Fig. 6 Relationship between the diameters measured at each location point and the corresponding ages of the moraine. The diameter value was measured at the part where the diameter was the largest with a digital venire caliper. More than 20 values were measured at one point

was confirmed in that location. At the glacier edge position of 2011, where four years had passed since the land was freed from the glacier, the soil layer closest from the glacier terminus in 2015 (Fig. 7 column 1) was identified. While plants existed very sparsely at this location, these plants had a soil layer around their roots with a thickness of approximately 2 cm. This soil layer was sandy silt and pale brown in color. The fact that the tint was almost the same as that of the underneath glacial deposits indicates that the organic material content was very low. Near the glacier terminus of 1997, where 18 years had passed since the land was freed from the glacier, we found that the surface layer had A horizon of 6–8 cm thickness with a dark brown tint and was enriched in organic materials (Fig. 7 column 2 and Fig. 8 picture 2). Moreover, the glacier terminus position of 1893 showed a soil layer with a thickness of 10 cm (Fig. 7 column 3).

Among the moraines of the Lewis stage, which were developed during the Little Ice Age, A horizon of 10 cm was identified on the ridge of the Lewis II moraine, which was estimated by lichenometry developed in the 1870s (Fig. 7 column 4 and Fig. 8 picture 4). A horizon is a black, sandy silt layer, which is rich in organic materials and contains almost no gravel. Under A horizon, a non-sorted layer composed of sand gravel and rubble was identified. The upper 8 cm of this sand gravel layer had a gravel size of maximum 5 cm; it was brown in color and rich in matrices. On the other hand, the underneath section was dark gray in color, and contained gravels with diameter of 10 cm or more. The characteristics of this dark brown deposit indicate

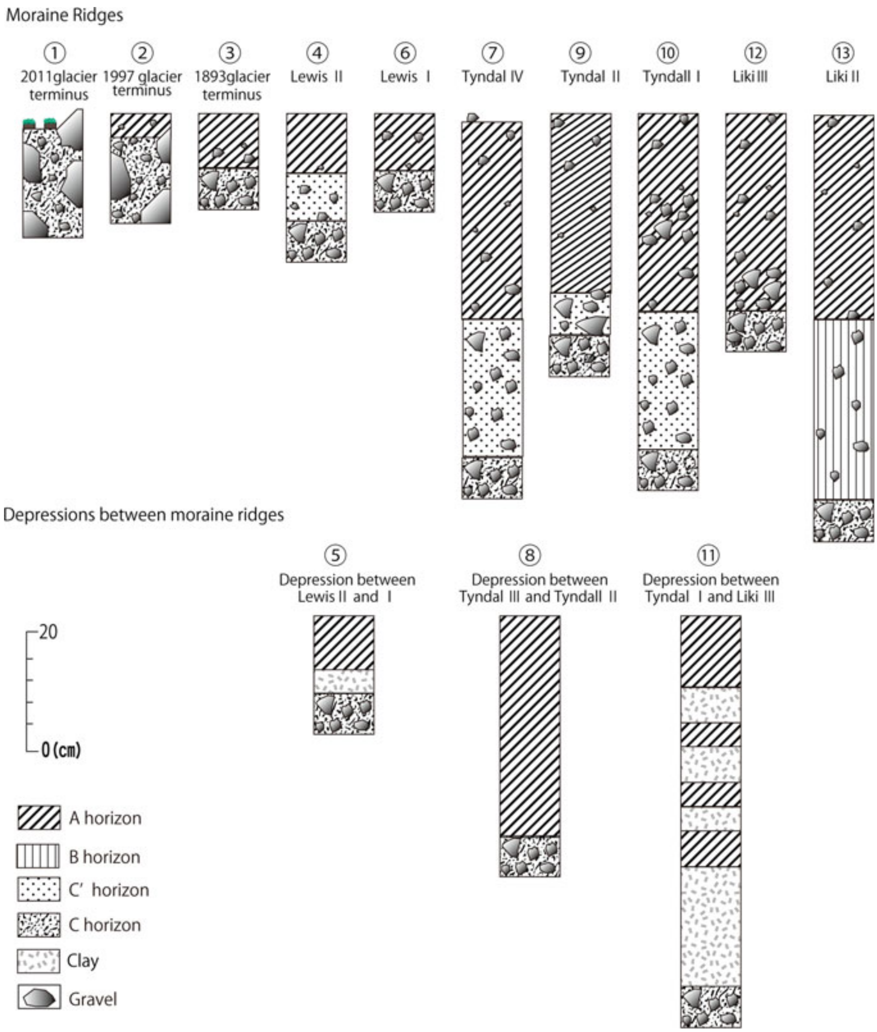

Fig. 7 Columnar sections of soil profiles in Tyndall glacier foreland. The locality of each column is shown in the Fig. 4

it to be glacial till deposit, and being un-weathered, this horizon retains the original characteristics of the glacial till deposit. Therefore, this layer was classified as C horizon.

On the other hand, despite of several similar characteristics, the upper brown layer was different from C horizon, especially in terms of tint, gravel size, and material composition. This brown layer also retained the characteristics of glacier till deposit. As this layer had characteristics different from those of the underlying C horizon, this layer was classified as C′ horizon.

Fig. 8 Pictures of soil profiles. The numbers are the same as in Fig. 7

An 9.5 cm organic matter enriched horizon was identified on the ridge of the Lewis I moraine, which was located immediately outside the Lewis II moraine, and was developed in the 1830s (Fig. 7 column 6). Under this, a thick, dark gray glacial till deposit was identified, and this location did not exhibit any deposit similar to C′ horizon.

There was a depression with a width of approximately 5 m between Lewis I moraine and Lewis II moraine. Although this depression had no running water during the time of this research, there were flat areas in certain places below the moraine. These flat areas were covered with fine-particle deposits, which were transported from the peripheries by running water during the melting of snow.

Pits created in these flat areas showed a surface layer deposit, which was rich in black organic materials and had a thickness of 12 cm (Fig. 7 column 5 and Fig. 8 picture 5). The deposit was composed of silt clay and had a negligible amount of gravel. Its underneath layer was made of dark brown silt clay followed by a gray-brown glacial deposit. We classified the surface layer rich in organic material as A horizon, and the layer underneath this, as C horizon. The soil at the bottom of the depression was rich in fine particles with a higher clay content compared to that of the moraine ridge's soil surface. This could be attributed to the difference in transport processes of the particles composing the soil surface.

On the ridges of the Tyndall-stage moraines (Tyndall I–IV) that were developed in the neoglacial period, the A horizon was found to be enriched in organic materials and was composed of sandy silt, similar to the outermost A horizons of the Lewis-stage moraines (Fig. 7 column 7, 9, 10 and Fig. 8 picture 7, 10). The thickness of A horizon was approximately 30 cm; the thickness of the layer increased with increasing development period of the moraines, i.e., with the age of the moraine. Sediments were present underneath A horizon; these originated in non-sorted glacial deposits and contained gravels. At every location, the uppermost layer of the glacial deposit displayed a dark brown matrix, which was poor in gravel, similar to the Lewis-stage moraines. This part was classified as C′ horizon, and the lowermost dark gray deposit showing the original characteristics of glacial deposit was referred to as C horizon. The thickness of C′ horizon ranged from 8 to 23 cm, and the trend of thicker deposits with increasing age of moraine was not necessarily evinced.

The depression between the moraines of the Tyndall stage had running water originating from melted glacier water. There was dense distribution of vegetation around the stream, and a thick soil layer was developed under this vegetation (Fig. 7 column 8 and Fig. 8 picture 8). The thickness of the layer ranged from 38 to 53 cm, and the trend in the increase of the layer's thickness with increasing age of topography was not necessarily observed.

The ridge of the Liki III moraine developed in the Younger Dryas period showed the development of 33 cm A horizon (Fig. 7 column 12 and Fig. 8 picture 12). Moreover, the Liki II moraine, developed approximately 20 ka ago during the Last Glacial Period, had a soil layer with a thickness of 65 cm. This layer had almost no gravel and covered weathered glacial deposits containing large amounts of sub-angular to sub-rounded gravels (Fig. 7 column 13 and Fig. 8 picture 13). The black layer rich in organic materials at the 35 cm depth from the surface layer was classified as A horizon, and the underneath brown part with rich clay content was classified as B horizon.

5 Soil Development Process in the Foreland of Tyndall Glacier

The soil layer developed on the glacial topography in the foreland of Tyndall glacier was classified into A–C horizons based on their respective facies. A horizon, which is a black surface layer composed of deposits of fine particles, is rich in organic materials and contains almost no gravel. Under this layer, C horizon occurs, which is a glacial till deposit with gray-brown to dark gray tints, and is composed of clay-rich matrix with copious amounts of angular to sub-rounded gravels. On the ridges of moraines that are older than those of the Lewis stage, the uppermost part of C horizon ubiquitously exhibits an area with brown to dark brown tint and negligible gravel content. This layer retains the characteristics of glacial till deposits, and is no different from C horizon with respect to the degree of weathering. However, it was classified as C′ horizon because of its distinct tint and particle size compared to that of the C horizon. As mentioned earlier, the thickness of C′ horizon does not necessarily increase with the age of the topography.

Yamagata (2016) studied the soils in the foreland of Charquini western glacier, Bolivian Andes. Based on observations, the author classified C′ horizon as the layer that has characteristics similar to the C′ horizon of the area analyzed in the present study, which is the uppermost part of C horizon. It was presumed that during the development process of C′ horizon, the surficial A horizon was mixed with the underneath glacial till deposits (C horizon) via periglacial processes. The C′ horizon of the area examined in this study can be also be considered as a product of a similar process.

No evident traces of the currently active periglacial process on the land surface of the foreland of Tyndall glacier were observed within the study area, as shown in Fig. 4. On the other hand, traces of frost pillar formation in areas of with vegetation were identifiable. It is likely that the freezing-and-thawing process might be currently restricted to an extremely shallow region near the land surface. It is believed that during the Little Ice Age and the Neoglaciation period, thawing action had effects till depths equivalent to approximately the thickness of C′ horizon under colder climatic conditions.

A horizon, which dominantly contains silt particles, had a clearly different particle composition compared to the underneath glacial till deposits (C horizon). Therefore, it is believed to have developed by a process different from that of the glacial deposits. In addition, there is almost no trace of weathering in the underneath glacial deposits, except in the Liki II stage. Furthermore, it can be observed that the A horizon was developed only four years after the land was freed from the glacier. Therefore, there is no evidence that it was developed due to weathering.

Yamagata (2016), who observed the soils in the foreland of the Charquini western glacier, Bolivian Andes, found that A horizon was composed of sand-silt sized particles, and the particles were relatively well sorted. Therefore, the layer was supposed to be composed of aeolian particles, which were supplied from the surrounding bare ground. The A horizon of the area examined in this study, which is relatively well sorted and composed of sandy silt sized particles, is also believed to be aeolian deposits. The aeolian particles, which were supplied from the bare ground around the glacier terminus or around the mountain peak were probably trapped into vegetation, and subsequently deposited to form the layer.

On the other hand, the soil layers deposited on the depressions between moraines were higher in clay content compared to those in the A horizon on the ridge. In part, stratifications were also observed. It is possible that the particles transported to the depressions by running water or through periglacial processes were relocated and

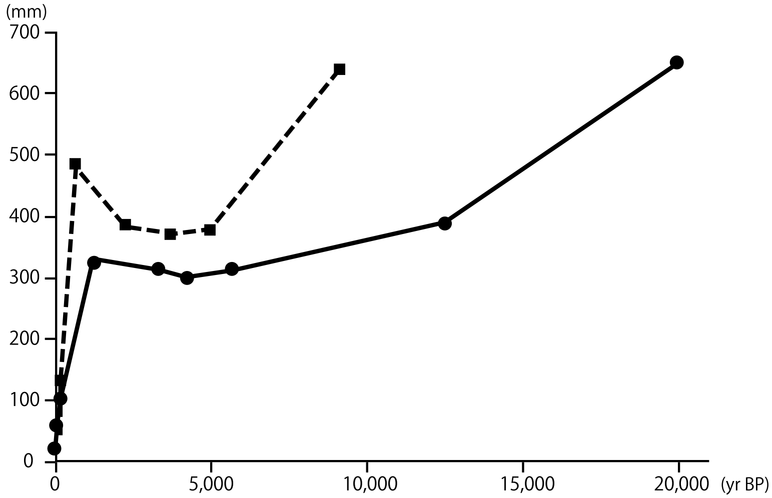

Fig. 9 Relationship between layer thicknesses of the soils and the estimated ages of topographies at the location points where the soil cross sections were observed

redeposited from the moraine or surrounding slopes by the running water. The difference in tint between layers A and B is supposed to reflect the sedimentation speed and the conditions of the surrounding vegetation, which grew when sedimentation was proceeding.

Figure 9 plots the observed thicknesses of the soil layer with respect to the estimated ages of topographies at locations where the soil cross sections were studied. The inclination in the graph represents the speed of soil development. Table 1 shows the calculated speed of soil development in each topographic unit. The soil thicknesses, which are individually classified as layers A and B, represent the sum of the thicknesses of all the layers. The graphs in Fig. 9 from left to right show the trend of thickening soil coverage of the glacial till deposit (C horizon) with increasing time that elapsed after the land was freed from the glacier.

The soil layers on moraine ridges of the Tyndall stage, which are approximately 300 mm in thickness at most of the moraines, did not show any significant differences. Some younger soil layers grew thicker than the older layers. The ages of the Tyndall I–IV moraines were hypothesized to be 5.7, 4.2, 3.4, and 1.2 ka, respectively (Fig. 9), based on the study of Karlen et al. (1999). However, it is likely that the moraines were developed in a shorter time span because there was almost no difference between the thicknesses of the individual soil layers.

The relationship between the ages of the depression between moraines and the thicknesses of soil layer also demonstrated the trend that the layer thickness increases with increased time elapsed after glacial retreat (Fig. 9). Compared to the soil on the ridges, the rate of soil development was found to be faster in the depression. This could be attributable to the differences in particle transportation through aeolian and aqueous process.

Table 1 Age, thickness of soil layer, and the rate of soil development in each topographic unit

Topography	Age (year)	Soil thickness (mm)	Soil development rate (mm/year)
Moraine ridges			
2011	4	20	5.00
1997	18	60	3.33
1893	122	90	0.74
Lewis-II	135	100	0.74
Lewis-I	150	95	0.63
Tyndall IV	1200	330	0.28
Tyndall III	3400	310	0.09
Tyndall II	4200	300	0.07
Tyndall I	5700	310	0.05
Liki-III	12,500	390	0.03
Liki-II	20,000	650	0.03
Depressions between moraines			
1893/Lewis II	129	40	0.31
Lewis II/I	143	130	0.91
Lewis I/Tyndal IV	675	480	0.71
Tyndal IV/III	2300	380	0.17
Tyndal III/II	3800	370	0.10
Tyndal II/I	4950	380	0.08
Tyndal I/Liki III	9100	640	0.07

The speed of soil development, which was determined from the thickness of soil layer on each topographic unit, varied widely from 0.03 to 5 mm/year. It was observed that soils developed relatively faster during the earlier phases of soil development, which could be attributed to the following factors: (a) effects of plant roots, (b) degraded material supply due to vegetation development, and (c) effects of erosion. The outermost soil layers were largely occupied by plant roots, and therefore, the layer thickness possibly appeared larger than the amount of the constituent particles of the soil present. In the foreland of Tyndall glacier, as more time passed since the land was freed from the glacier, the density of vegetation covering the land surface became larger. Therefore, the glacial peripheries during their infancy, after being freed from the glacier, had poor vegetation, while the aeolian particles were actively produced. In contrast, it is believed that the supply of aeolian particles from the surrounding land surfaces was reduced as the density of vegetation increased with time. Similar trend could also be identified in the aqueous deposits present in the depression.

The numerical values expressing the soil development rate in Mount Kenya obtained in this study were compared with those of other glacier forelands across the world (Table 2). The soil thicknesses on moraine ridges were compared in this table,

Table 2 Comparison of soil development rates on different moraines worldwide

Region	Age (year)	Soil development rate (mm/year)	References
Mt. Kenya	4–20,000	0.03–5.0	This study
Bolivian Andes	33–8,600	0.02–0.47	Yamagata (2016)
Swiss Alps	150–10,000	0.1–0.13	Egli et al. (2001)
southern Norway	50–250	0.05–0.11	Mellor (1987)
Sichuan, China	39–183	0.16–0.5	He and Tang (2008)
Alaska, USA	10–250	0.1–0.3	Ugolini (1968)
Kamchatka, Russia	60–2,500	0.01–0.05	Yamagata et al. (1999)

which reveals that the maximum soil development rate of 5 mm/year was obtained in the initial stages of soil development in Mount Kenya, and it was significantly greater than those observed in other regions. This is probably because this research was conducted during the initial phases of soil development process, and not long after the land was freed from the glacier. As mentioned earlier, it is believed that the layer thickness appeared larger because the soil was occupied by a large proportion of plant roots when the soil layer was still thin in its initial development stage.

However, the soil development speed of 0.6–0.7 mm/year obtained for the Lewis-stage moraines, which are believed to have developed during the Little Ice Age, was also higher than that obtained under the same criteria in other regions. This might be because the aeolian particles were actively produced due to the sparse vegetation and rough terrain near the peak of Mount Kenya, or due to the lower ratio of relocation, or erosion by wind or periglacial processes.

On the other hand, the rate of long-term soil development was obtained to be 0.03–0.1 mm/year. The speed of moraine development during the Neoglaciation period (Tyndall stage) to the Last Glacial Maximum (Liki II stage) falls within the range of the values obtained for other regions.

The soil development process in the foreland of Tyndall glacier on Mount Kenya reveals the important role of vegetation in soil development. Developed vegetation traps soil particles, and sedimentation begins. Along with continued sedimentation of soil particles, soil layers grow rapidly due to the supply of organic materials from plants.

In addition, soil development also plays a key role for vegetation. Based on a research on the retreat process of Tyndall glacier and the surrounding vegetation, Mizuno (1994) explained that a key requirement for the location of vegetation are the ages of the deposits and the stability of the land surface. In areas with younger deposits (close to the glacier terminus), it is difficult for plants to intrude and stay rooted because of relatively immature soil. Therefore, vegetation coverage and diversity are usually low. On the other hand, in places with older deposits (far from the glacier terminus), soil development proceeds rapidly and the pioneer species improve soil conditions, which favors the growth of the upcoming plants. This contributes to an increase in vegetation coverage and diversity. In this way, soil development and vegetation are believed to proceed while interacting with each other.

Due to these close relationships between soil and vegetation, soil plays a key role in the ecosystem of the region. Consequently, this serves as an important factor to monitor the changes in vegetation. As confirmed in this study, during the initial stages of soil development in the glacier foreland, the characteristics and thicknesses of soil layer show significant diversity in a small range depending on the time that elapsed after the land was freed from the glacier. The diversity also depends on the topographical conditions of the site where soil was developed, deposits composing the land surface, relocation of materials caused by frost creep, wind or running water, and vegetation conditions. This diversity connects to biodiversity. An increase in this diversity with the development of soil in glacier foreland leads to the generation of vegetation diversity in the region (Khaziev 2011).

The development of soil in the glacier foreland, which forms a thin cover of deposit onto the surfaces of rocks, plays a hydrologically important role. In a thicker soil layer, the layer itself can contain more water. This weakens the peak of water runoff and influences the upkeep of steady runoff, even during the dry season. These roles of soil will prove to be significant when glaciers will be lost in many high mountains in the future (Haeberli et al. 2007). Overall, soil plays a key role in the hydrology and ecology of glacial basins.

6 Summary

The relationship between soil development processes and environmental factors was studied by investigating soil layers that covered those land surfaces that were freed from the glacier during different eras from the foreland of Tyndall glacier on Mount Kenya.

First, the classification of the moraines developed in the foreland of Tyndall glacier was reviewed. As a result, six moraines of the Lewis stage (Lewis I and II) and the Tyndall stage (Tyndall I–IV) were classified. Subsequently, the age of each moraine was estimated using lichenometry and based on the ages of horizons that exhibited traces of cooling periods in deposits under the nearby lake. The estimation suggests that the moraines of the Lewis and Tyndall stages were developed during the Little Ice Age and the Neoglaciation period, respectively, and those of Liki III were formed during the Younger Dryas period.

In a location where four years had passed after the land was freed from the glacier, a soil layer with a thickness of 2 cm was identified in the position closest from the present glacier edge. On the moraine ridges of the Lewis stage, soil layers with thicknesses of 9.5–10 cm were identified, and on the moraines of the Tyndall stage, the layers had a thickness of 30 cm. The trend of increasing thickness of the soil layer with higher development age was evinced at the study location. A similar trend in the change of soil thickness was observed in depressions between the moraines. Relatively, the soil layers in the depression tended to be thicker than those on the ridges.

The soil layers identifiable on the ridges, which are sandy silt and are relatively well sorted, had distinctly different characteristics from the underneath glacial deposits. In addition, glacial deposits were fresh, and exhibited negligible trace of weathering. Therefore, it was evinced that the soil layers were not the weathered products of glacial deposits, and were deposited through a different mechanism. The characteristics of the deposits indicated that they were presumably aeolian dust deposits. On the other hand, the soils in the depression were believed to be fine-particle materials that were transported by running water, and subsequently deposited.

The rate of soil development was determined from the thicknesses of soil layers and the ages of land surfaces. The speed of soil development fell within the range of 0.03–5 mm/year. Particularly, we identified the trend that the speed of soil development was higher during earlier stages of soil development, the possible reasons of which might include the effects of plant roots, degraded material supply due to vegetation development, and the effects of erosion. Furthermore, the numerical value of soil development speed obtained in Mount Kenya was compared with that of the glacier forelands of other regions. While the development speed at an early soil development stage in Mount Kenya was higher than that of other regions, it was confirmed that the long-term development speed fell within the range obtained in other regions.

It was found that aeolian dusts were trapped and deposited by vegetation. On the other hand, the growth of soil seems to have played a key role in vegetation development. In this manner, soil growth and vegetation development proceeded while interacting with each other. Therefore, understanding the relationship between the two is important for evaluating the environmental changes around the glaciers, as well as their future implications.

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Geoecology I: Retreating Glaciers, Plant Succession on Mount Kenya Due to Climate Change

Kazuharu Mizuno

Pictures of Lewis Glacier, the largest glacier on Mount Kenya, captured in 1992 and 2017, respectively. The rapid retreat of glacier is evinced from these two images

Abstract Tyndall Glacier on Mount Kenya has retreated notably in recent years due to warming atmosphere, i.e., climate change. It was evinced that the fronts of four pioneering plant species have migrated uphill following the retreating glacier. Specifically, the front of *Senecio keniophytum*, the first to appear in areas exposed by glacier disappearance, migrated a speed similar to that of the glacial retreat. A permanent plot that was adjacent to the glacier terminus in 1996 exhibited a drastic increase in *Senecio keniophytum* population and cover in 2011. Near the terminus of the recently disappeared glacier, the population and cover of vegetation increased notably; however, this increasing trend was slower after the passage of 10 years since the disappearance of the glacier. *Helichrysum citrispinum*, a plant species which was not previously reported near the glacier terminus, was first confirmed in 2009, and its increasing distribution might be a direct result of increasing temperature. With the passage of years after the disappearance of the glacier, gravels become weathered and soil particles become finer. As the humus of the pioneering species

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accumulates, nutrient rich soil develops. The development of soil is also affected by the number of years elapsed after the disappearance of glacier and by the degree of plant establishment that stabilizes the soil layer.

Keywords Retreating glaciers · Climate change · Plant succession · Pioneer plant species · Large woody rosette plants

1 Introduction

In Africa, only the following three mountains have glaciers: Kilimanjaro, Mount Kenya, and Rwenzori Mountains. However, these glaciers have rapidly melted in recent years (Thompson et al. 2002). In the next 10–20 years, it is likely that these glaciers will disappear.

The proglacial areas associated with retreating glaciers have been well studied in North America, Scandinavia, other polar regions, and European Alps; however, such studies are lacking in tropical mountain regions.

Several studies worldwide have recorded and described the chronological changes in plant species in moraines from different time periods over the past hundreds of years (Mori et al. 2008). However, studies recording real-time glacial retreat and plant migration based on the chronological record of glacial expansion and historical records are largely lacking. Studies by Mizuno (1998, 2005a, b) elucidated the relationship between the process of glacial retreat and succession of a series of plant species in real time in over 50 years based on previous studies on Tyndall Glacier on Mount Kenya (Nagy and Grabherr 2009).

Several studies have shown that the main factor that the dominates distribution of plant species is the time implied by the age of till (Matthews 1992). For example, it has been shown that plant succession on ground moraine could take several hundred years to reach the climax of alpine vegetation (Raffl and Erschbamer 2004). In general, pioneering plant communities with low cover grow on 20th century sediments. Meanwhile, communities with high cover were established on moraines that formed in the 19th century (Caccianiga and Andreis 2004). Garbarino et al. (2010) examined the distribution of larch on the Ventina glacier in central Italy; they demonstrated that the factors that had the greatest impact on the density and the age of larch were plant litter cover, elevation, distance to glacier terminus, and seed source.

Coe (1967) studied the plant communities in the individual vegetation belts on Mount Kenya, specifically, the invasion and establishment of plants in alpine zones. The study demonstrated the retreat of Tyndall and Lewis glaciers, and the advancements of distinct plant species. Spence (1989) detailed the retreat of these glaciers and the advancements of each plant community between 1958 and 1984. Mizuno (1998, 2005a, b) and Mizuno and Fujita (2014) showed that the pioneering plants that grew near the terminus of Tyndall Glacier have advanced as the glacier retreated between 1992 and 2011. In addition to the time elapsed since the disappearance of the glacier, the stability of ground surface also has had a notable impact on plant distribution, specifically on glaciers located in tropical alpine environments, where daily temperature fluctuation is significant (Mizuno 1998, 2005a, b; Mizuno and Fujita 2014).

In contrast, plant species that were not previously reported around the glaciers of Mount Kenya were discovered in 2009. It was apparent that certain plant species had advanced their distribution regardless of glacial retreat. However, no study has yet examined the impacts of both glacial retreat and climate changes on plant succession, and their relationship is not yet clear.

In the present chapter, we discuss the recent climate changes, and the pattern of glacial retreat and landform development. We also discuss the reactions of each plant species to recent glacial retreat, environmental changes in relation to the distribution and succession of plants, and relationship between climate change and plant succession.

2 Surveyed Area

Mount Kenya or "Kirinyaga" is the second highest mountain in Africa and is located on the equator. The African country Kenya has derived its name from the mountain. Mount Kenya is an old volcano in the Great Rift Valley. The height of the Batian Peak is 5199 m. This volcano was formed through intermittent eruptions that occurred 3.1–2.6 million years ago. Its peak was eroded over a long period of time, leaving solidified lava that filled the pipes, thereby creating a sharp peak (Bhatt 1991). The rock types present in this region include basalt, phonolite, trachyte, and syenite, amongst others (Mahaney 1990; Bhatt 1991).

By the end of the 19th century, there were 18 glaciers in Mount Kenya; however today, there are only Lewis, Tyndall, and a few other glaciers remaining.

Annual precipitation on Mount Kenya is higher on the southeastern slope, and reaches approximately 2500 mm at an elevation of 2250 m. In contrast, on the northern slope, it is below 1000 mm (Mahaney 1984; Hastenrath 1991). The annual precipitation is the highest at elevations of 2500–3000 m on the southern, western, and eastern slopes. It becomes lesser close to the peak (900 mm or less at 4500–4800 m). At elevations of 4500 m or higher, most of the precipitation occurs in the form of snow or hail.

Mount Kenya has the following belts: Nival belt (above the snowline), Alpine belt, Hagenia-Hypericum belt, Bamboo belt, Montane forest belt, and Savannah belt (cultivation and grassland), from top to bottom (Coe 1967). The lower Alpine belt has tussock grasses that are dominated by *Festuca*, *Agrostis*, and *Descampsia*: a community that includes *Lobelia keniensis*. The upper Alpine belt has communities of *Senecio* (Asteraceae), especially *Senecio keniodendron* and *Senecio brassica*, and *Alchemilla argyrophylla*.

Although there are glaciers on the peak of Mount Kenya, pioneering plant species such as alpine plants from Asteraceae (e.g., *Senecio keniophytum*) and Brassicaceae (e.g., *Arabis alpine*) can be found immediately below the peak, and their distributions are increasing with the retreat of the glaciers. On the relatively stable slopes below, large woody rosette plants such as *Senecio keniodendron* and *Lobelia telekii* are found. These plants are characteristic of tropical alpine landscapes where daily temperature fluctuations are high.

Senecio keniodendron is also identified as *Dendrosenecio keniodendron,* when woody *Senecio* is considered as a subgenus of *Senecio*; this book adopts the term *Senecio keniodendron.*

3 Recent Climate Changes: Glacial Retreat and Landform Development

The temperature at Nanyuki Meteorological Station (0.03°N, 37.02°E), located at an elevation of 1890 m on the western foothills on Mount Kenya, has increased by more than 2 °C in 48 years from 1963 to 2011 (Fig. 1). In contrast, no notable decrease in precipitation at the same location has been recorded from 1956 to 2011.

Based on temperature data at Mount Kenya Global Atmosphere Watch (GAW) Station (0.06°N, 37.30°E), which is situated at a higher elevation of 3678 m, it was inferred that the rate of temperature decrease in Mount Kenya was 0.63 °C/100 m. Based on this rate, the temperature of the glacier terminus located at an elevation of 4500 m was calculated.

There was a significant relationship between the changes in the monthly mean minimum temperature at an elevation of 4500 m and the glacial retreat process ($y = 5.882x + 45.427$, $R^2 = 0.6625$; $P = 0.0085$) (Mizuno and Fujita 2014). Therefore, we can suggest that the glacial retreat at Mount Kenya is mainly caused by climate change (warming).

Figure 2 shows the terminus of Tyndall Glacier and its surrounding landforms. Around Tyndall Glacier, Lewis Moraine is found, which is estimated to have formed approximately 100 years BP (100 years before 1950). On the lower slope, Tyndall Moraine was estimated to have formed at approximately 900 years BP (Fig. 3) (Mahaney 1989, 1990; Mizuno 1998; Mizuno 2005a). The location of Tyndall Glacier terminus shown in Fig. 2 reflects that the glacier has continuously retreated in the past 150 years. Therefore, it is evinced that no moraine was formed in this location during the past 150 years.

On the eastern side of Tyndall Tarn, talus is found, which is a sedimentary landform where weathering debris from the surrounding cliff accumulates at the base. Since talus forms an unstable slope consisting of debris, it is difficult for plants to get established in this location. On the lower slope of moraines lies the outwash fan, which is a landform created by sediments that were carried and deposited by debris flow and outwash (glacial meltwater flow).

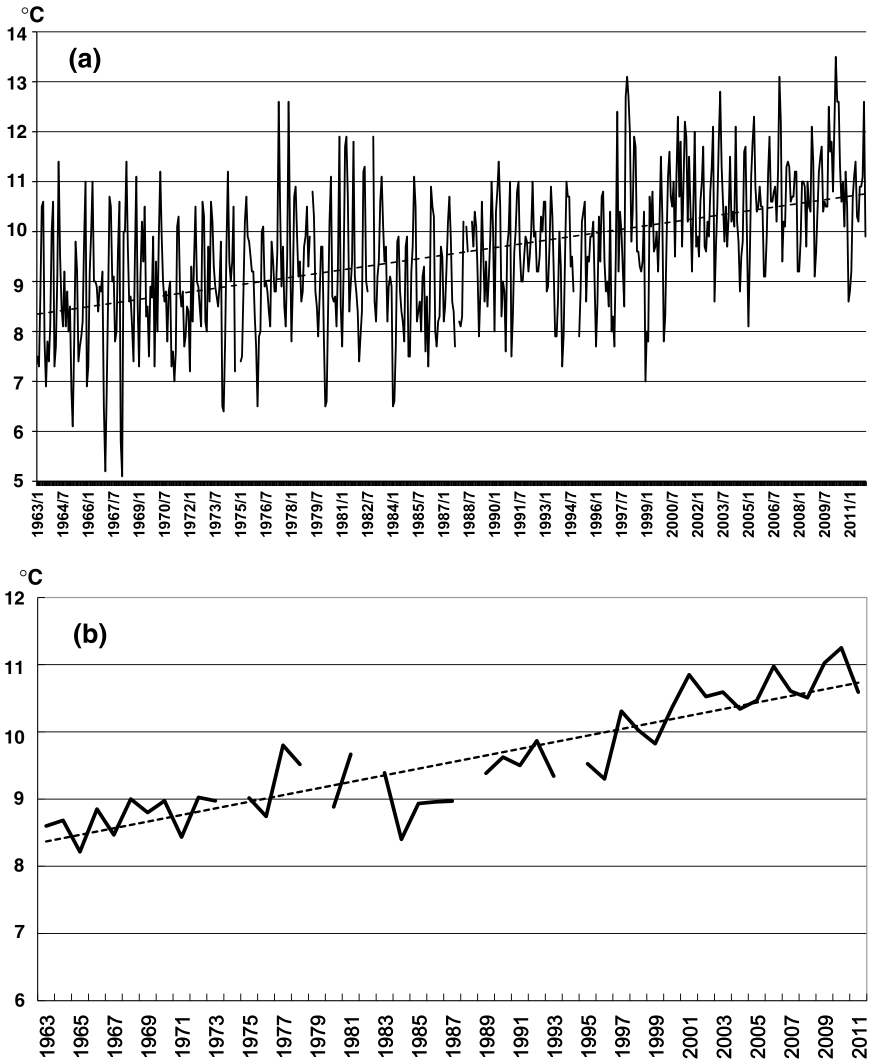

Fig. 1 Temperature variations between 1963 and 2011 in the foothills of Mount Kenya situated at an elevation of 1890 m. **a** Monthly mean minimum temperature, **b** annual mean minimum temperature (data obtained from Kenya Meteorological Department)

During the 1997 survey, I discovered the remains of a leopard, half of which were protruding from the ice at the terminus of Tyndall Glacier (Fig. 4). The remains were subjected to radiocarbon dating using an accelerator mass spectrometer, and it was found that the remains were 900–1000 years old (Mizuno 2005a, b). This timing was associated with climate shift from warm period to cold period, which is consistent with cold climate until the 19th century.

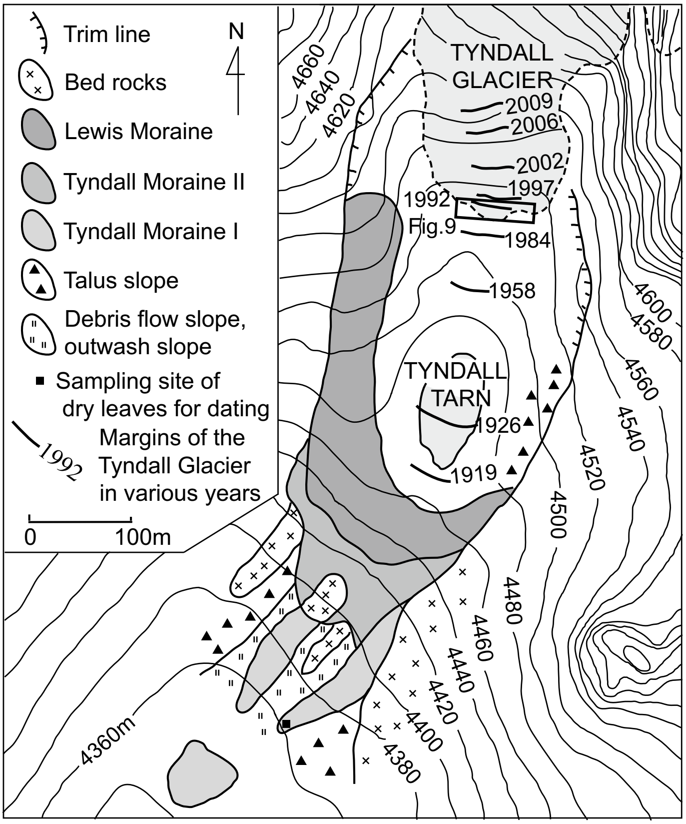

Fig. 2 Geomorphological map of Tyndall Glacier on Mount Kenya (Mizuno and Fujita 2014). Location of the terminus of Tyndall Glacier in the respective years was obtained from the following studies: 1919 and 1926: Hastenrath (1984); 1958: Charnley (1959) and Coe (1967); 1984: Spence (1989); 1992–2009: Mizuno and Fujita (2014). Names of Lewis Moraine (Lewis Till) and Tyndall Moraine (Tyndall Till) are based on Mahaney (1984, 1989) and Mahaney and Spence (1989). The map is prepared by Kazuharu Mizuno based on the contour map of Hastenrath et al. (1989)

4 Reactions of Each Species to Recent Glacial Retreat

4.1 Glacial Retreat and Plant Succession

Several studies have been conducted on the dynamics of glaciers on Mount Kenya (Hastenrath 2005, 2008). The relationship between glacier dynamics and sediments has been also examined (Mahaney 1990). Tyndall Glacier rapidly retreated between 1992 and 2019 (Fig. 5), and the rate of retreat was approximately 3 m/year between 1958 and 1996, 10 m/year between 1997 and 2002, 15 m/year between 2002 and 2006, 8 m/year between 2006 and 2011, and 9–18 m/year between 2011 and 2019.

Fig. 3 Main peak of Mount Kenya, Batian peak (5199 m). The glacier on the left is Tyndall Glacier in 1992. The moraine in the front is Lewis Moraine

Fig. 4 The remains of a leopard discovered in Tyndall Glacier in 1997. The remains were dated back to 900–1000 years via radiocarbon dating

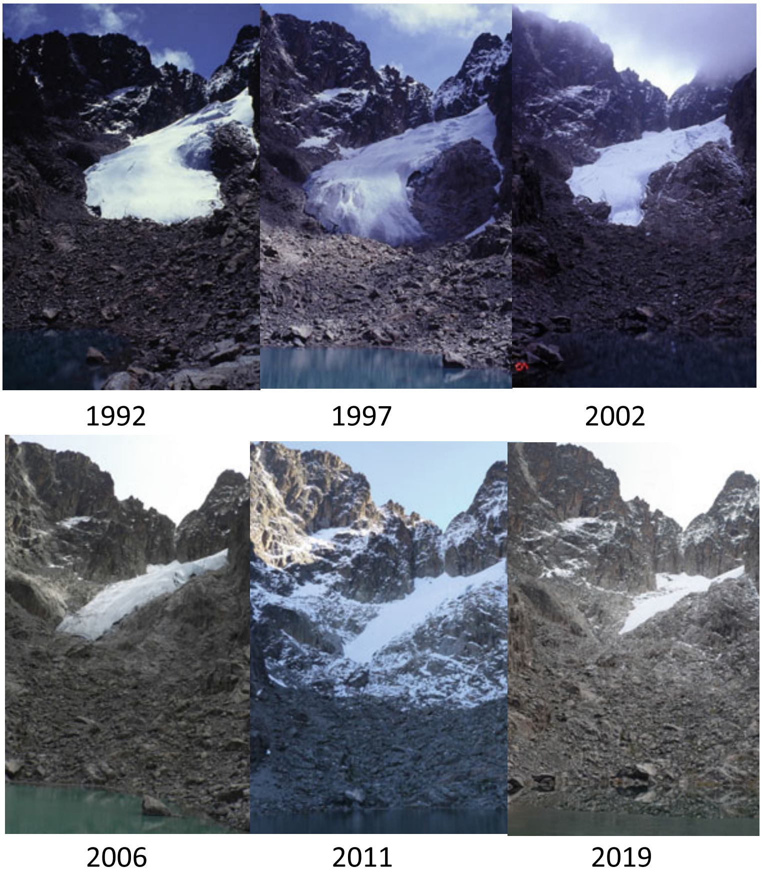

Fig. 5 Tyndall Glacier in 1992, 1997, 2002, 2006, 2011, and 2019

It was observed that four pioneering plant species have advanced their respective fronts to uphill following the retreat of the glacier. Specifically, *Senecio keniophytum* (Fig. 6), the primary pioneering species that grows in areas where glaciers have melted, was found to have advanced at the same pace as the glacial retreat (Fig. 7). The rate of glacial retreat was significantly correlated with the migration of *Senecio keniophytum* ($y = 0.8635x + 1.5631$, $R^2 = 0.7205$; $P = 0.0047$). Other pioneering plant species such as *Arabis alpina*, *Agrostis trachyphylla*, bryophytes, and lichens have also advanced at an increasing rate since 1997 (Fig. 7).

Carex monostachya and *Agrostis trachyphylla* have advanced faster in recent years; between 2015 and 2019, they advanced especially faster, at 37 m/year and 27 m/year, respectively. For a long time, the first species to appear after the disappearance of glacier was *Senecio keniophytum*; however, in 2016 and 2017, a species of lichen, *Rhizocarpon geocumum,* appeared as the first pioneering plant species closest to the glacial terminus (Fig. 7).

Fig. 6 First pioneering species, *Senecio keniophytum*, that appeared after the disappearance of the glacier

Seeds of *Senecio keniophytum* (3 mm) and *Arabis alpina* (1–1.4 mm) are extremely small. Therefore, these species can spread their seeds over relatively wider areas. Dispersal capacity of seeds varies between species, which has an impact on the composition of plant communities (Fuller and del Moral 2003). The characteristics of seed dispersion might be related to invasion by pioneering species in those areas that were recently vacated by glaciers.

The changes in the front of large woody rosette species, *Lobelia telekii* and *Senecio keniodendron* (Fig. 8) appeared unrelated with glacial retreat until 1997; these species have been advancing ever since (Fig. 7).

4.2 Succession at a Permanent Plot in the Cirque Bottom

A survey of the distribution of plants was initiated in 1996 in a permanent plot (80 m × 20 m) located at the terminus of the glacier in the cirque bottom (Fig. 2). The survey demonstrated that the population and cover of *Senecio keniophytum* has significantly increased in 15 years after 2011 (Fig. 9). In these 15 years, the average number of individual plants per sampling quadrat (2.5 m × 2.0 m) increased by 14 times, while the average cover (the ratio of ground surface covered by plants) per sampling quadrat increased by 183 times (Mizuno and Fujita 2014). In 1996, only *Senecio keniophytum* grew in the plot; however, in 2011, three additional species appeared although *Senecio keniophytum* was still predominant. In areas that were recently vacated by glaciers, the number of individual plants and cover had increased

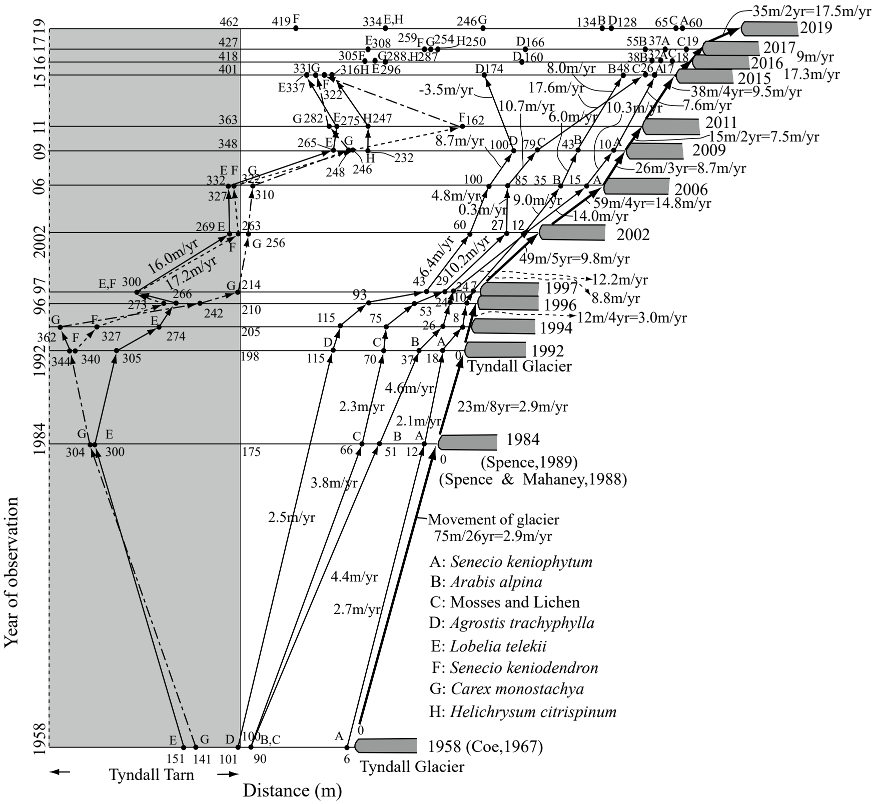

Fig. 7 Fluctuations of Tyndall Glacier and the succession of alpine plants. Horizontal axis: Distance (m) from Tyndall Glacier terminus to the leading edge (upper distribution limit) of each plant species. Vertical axis: Years of observation, whereby the length of the vertical axis indicates years. The arrows indicate the movement of Tyndall Glacier terminus (thick line) and changes in the leading edge of each plant species. The inclination of arrows shows the speed of movement

at a distance of 16–18 m from the glacier terminus; however, this trend disappeared after some years. Within five to six years of the disappearance of glacier, several seedlings of *Senecio keniophytum* grew (Mizuno and Fujita 2014).

Fig. 8 Large woody rosette plants, *Senecio keniodendron* (center) and *Lobelia telekii*

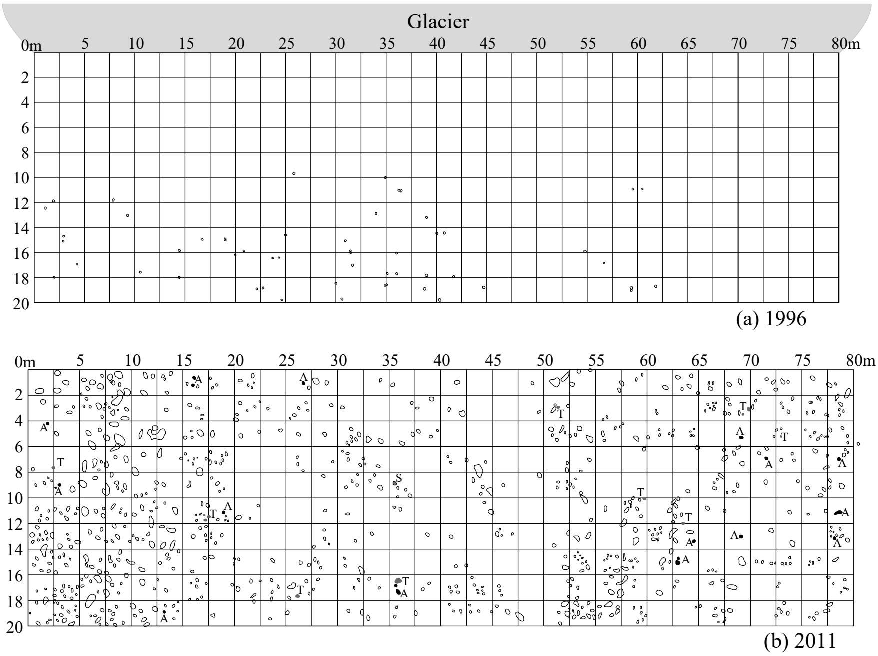

Fig. 9 Distribution of *Senecio keniophytum* in **a** 1996 and **b** 2011 in the permanent plot (80 m × 20 m) established in 1996 adjacent to the glacier terminus (Fig. 2) (Mizuno and Fujita 2014). A: *Arabis alpina*; T: *Agrostis trachyphylla*; S: *Senecio keniodendron*

5 Environmental Parameters in Relation to the Distribution and Succession of Plants

5.1 Plant Distribution Based on Moisture Conditions and Slope Stability of Landforms and Sediment

It was observed that near the glacier terminus, *Senecio keniophytum* tends to grow on ridge-shaped convex slopes in the cirque bottom. It grows within the cracks in bedrocks and in gaps between rocks because finer particles tend to collect in cracks and gaps. In Fig. 9, the areas that are densely populated with plants correspond roughly to such ridge-shaped convex slopes. When seeds fall in these areas, they receive sufficient moisture retained by fine particles, and as they grow, roots stabilize these particles. Stable bedrocks and boulders play an important role in stabilizing the habitats as the ground surface is not easily mobilized.

I examined the environment in the habitat of large woody rosette plants, *Senecio keniodendron* (giant *Senecio*) and *Lobelia telekii* (giant *Lobelia*) in a wider area including cirque bottom, moraine, talus slope, debris slope, and outwash slope (Fig. 2). I found that *Lobelia telekii* is mostly found on debris flow and outwash slopes, while *Senecio keniodendron* is found on moraines (Mizuno 2005b) (Fig. 8). The inflorescence of *Lobelia telekii* withered every year (for several years); however, that of *Senecio keniodendron* did not wither for decades. Their stalks grew upwards, and new rosette leaves grew on the top of the stalk. The difference in the specific characteristics of these plants likely led to their adaptation in different sites, such as debris flow, outwash slope, and moraines. In other words, the present debris flows and outwashes inhibited the growth of plants on concave debris flow and outwash slopes. However, their landform indicated that soil moisture was high, which made it suitable for *Lobelia telekii* to grow. In contrast, convex slopes, such as that of Tyndall Moraine I, do not often experience impact of debris flow or outwash after formation, and owing its stable surface, *Senecio keniodendron* was able to grow for years to reach their large size. The locations like Tyndall Moraine I, where large boulders accumulate, are the perfect habitat for *Senecio keniodendron.* This is because the rocks become warm during daytime, and the increased heat favors the growth of *Senecio keniodendron.* In addition, seedlings and saplings can use water dripping through rocks, while being sheltered from snow and rain.

5.2 Development of Soil and Plant Succession Associated with Glacial Retreat

In areas where soil conditions make it difficult for the general plants to grow, only pioneering plant species can invade. *Senecio keniophytum* can grow in those locations that were freed from glacier 5–15 years back. It such areas, the soil was coarse, and

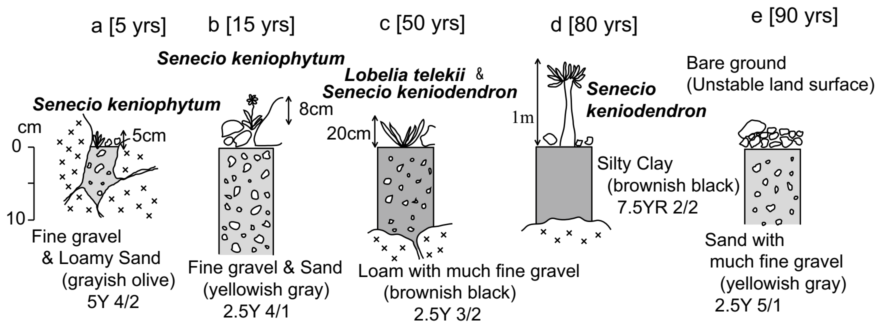

Fig. 10 Typical soil profiles at the survey sites (Mizuno 1998; Mizuno and Fujita 2014). Number in bracket is the age of till (years after the disappearance of the glacier). Age of till (years) was estimated based on the distance from the glacier terminus and from the following rate of glacial retreat: 3.8 m/years [–1958] (Charnley 1959); 2.9 m/years [1958–1997]; 9.8 m/years [1997–2002]; 14.8 m/years [2002–2006]; and 8.7 m/years [2006–2009]. Soil profiles were drawn based on the soil profile data observed between 1992 and 2009

consisted of grayish olive and yellowish gray colored loamy sand with small gravels. Gray color was observed owing to low humus content (Mizuno 1998; Mizuno and Fujita 2014) (Fig. 10). After many years since the disappearance of the glacier, gravels became weathered, soil particles became finer, and soils were developed that were relatively rich in nutrients due to accumulation of humus from pioneering species. In locations where the glacier disappeared nearly 50 years back, enough humus was accumulated from pioneering plant species, and soil became black and turned into brownish black loam with a finer grain size. Seedlings of large woody rosette plants, *Senecio keniodendron* and *Lobelia telekii*, began to grow, which changed the environment in such a way that it became suitable for several other plant species. In locations where the glacier disappeared 80 years previously, the height of *Senecio keniodendron* reached 1 m, and the soil became fine silty clay with brownish black color due to the accumulation of humus.

5.3 Vegetation and Land Surface Stability

After 100 years since the disappearance of glacier, if the ground surface remains covered in fine gravels and if it undergoes movement, plant invasion and establishment become difficult, which leaves the site bare (Fig. 10). In August 1994, I drew a 1 m line on the bare ground surface with 27° slope of Lewis Moraine using yellow paint to evaluate the changes in the line. During two years, from August 1994 to August 1996, the line moved to a maximum of 6.1 m, and subsequently, it moved to a maximum of 32 m over eight years between August 1994 and August 2002 (Mizuno 2005a, b). During the dry season, freezing of land surface in the morning and thawing in the afternoon was observed along the slope. The solifluction of the thawed layer with oversaturation in the dry season was also monitored, and the results indicated that the gravels moved due to the freeze-thaw actions and solifluction.

In tropical alpine areas, diurnal temperature fluctuation was large, which could be 10 °C or more around glaciers on Mount Kenya. Mount Kenya has a snow season of approximately five months and a dry season of approximately seven months. Therefore, the diurnal temperature of air and soil fluctuated between above and below 0 °C during the dry season, leading to notable freeze-thaw actions and solifluction on the ground surface. Soil in such locations was underdeveloped, similar to locations that have remained free from glacier only for a short period of time. As such, the development of soil was impacted by the establishment of plants associated with the number of years elapsed since the disappearance of glacier and establishment of plants due to the stabilization of the ground surface, i.e., without any movement of surficial materials.

6 Relationship Between Climate Change and Plant Succession

6.1 Growth of Large Woody Rosette Plant and the Climatic Environment

Giant *Senecio* has a stalk of 1–6 m. It has large rosette-shaped evergreen leaves at the top of the stalk, avoiding colder temperature at the ground surface (Fig. 8). While aging, instead of falling down, their leaves droop, wrap around the stalk, and turn woody, which creates a heat insulation layer. Rosette-shaped leaves open during the day and close at night. As giant *Senecio* does not have tree rings, the relationship between its height and age has remained unknown. Thus, the growth rate of giant *Senecio* was examined using dried leaves on stalk. In 2019, dry leaves were collected from three places on each of the stalks of two giant *Senecio* (*Senecio keniodendron*) plants on Tyndall Moraine I (Fig. 2). The age of six samples was determined through radiocarbon dating (^{14}C, AMS: accelerator mass spectrometer) (Table 1). The average rate of growth was found to be 3 cm/year for *Senecio keniodendron* A, which had a height of 283 cm (208 cm for the stalk and 75 cm for the crown). Its date of germination and age were estimated to be 1940 and approximately 80 years, respectively. The average growth rate was 4.5 cm/year for *Senecio keniodendron* B, which had a height of 337 cm (241 cm for the stalk and 96 cm for the crown). Its date of germination and age were estimated to be 1950 and approximately 70 years, respectively. It is likely that the age of giant *Senecio*, whose height exceeds 5 m, is 100 years or more (Fig. 8).

The giant *Lobelia, Lobelia telekii,* has stalk height of 2–3 m. Its structure is like a hollow cylinder with a diameter of 5–8 cm that is filled with liquid up to approximately 1 m from the ground surface. The outer surface of the stalk is covered

Table 1 Dates obtained through radiocarbon dating (^{14}C, AMS) of three dry leaf samples collected from two *Senecio keniodendron* plants in Tyndall Moraine I (Fig. 2)

Sampling height from the ground (cm)	Date (^{14}C, AMS)	Beta ID
Senecio keniodendron A (height 283 cm; 208 cm stalk and 75 cm crown)		
48	1958–1960	537356
118	1978–1981	537357
168	1996–2000	537358
Senecio keniodendron B (height 337 cm; 241 cm stalk and 96 cm crown)		
20	1959–1960	537359
120	1984–1987	537369
200	1999–2002	537361

with hairy buds. It was found that the liquid in the stalk began to freeze at night when the temperature reached 0 °C or lower, which released latent heat and warmed the air in the upper stalk through convection (Krog et al. 1979). In this manner, these large woody rosette plants adapted themselves to the large diurnal temperature changes, which are typical of tropical alpine areas.

6.2 Climate Changes and Plant Succession on Mount Kenya

Although most pioneer species advanced according to the glacial retreat from 1958 to 2019 (Fig. 7), *Helichrysum citrispinum*, *Lobelia telekii*, and *Senecio keniodendron* did not undergo such migration.

Helichrysum citrispinum (Fig. 11) was not present on the upper slope north of Tyndall Tan until 2006; however, 32 plants were found on a lateral moraine located above the northern edge of Tyndall Tarn in 2009. This species did not advance according to the glacial retreat; however, it is likely to have advanced towards higher elevation with increasing temperatures (Mizuno and Fujita 2014). As the temperature between March and September 2009 was more than 1 °C higher than the average of 2007 to 2011, its habitat range increased rapidly up the slope.

The large woody rosette plants, *Lobelia telekii* and *Senecio keniodendron* did not migrate up the slope between 1958 and 1997, however, they moved up the slope between 1997 and 2011 (Fig. 7). For this species, their succession was not directly related to the glacial retreat; however, the improvements in soil conditions through upslope advancement of pioneering species, warm climate, and changes in the environment of the habitat resulted in the upslope migration of these plant species.

Fig. 11 *Helichrysum citrispinum*, also called the everlasting flower

7 Conclusions

1. Tyndall Glacier on Mount Kenya is retreating rapidly every year. The retreat of this glacier is influenced by warm climate owing to climate change.
2. Along with the glacial retreat, four pioneering plant species expanded their front upslope. The first pioneering species that appeared in areas vacated by the melting glacier, *Senecio keniophytum*, advanced at almost similar speed as that of the glacial retreat. In 2016 and 2017, a species of lichen appeared close to glacier terminus as the first pioneering plant species.
3. In a permanent plot adjacent to glacial terminus in 1996, the number and cover of *Senecio keniophytum* significantly increased in 2011. Near the glacier terminus, where the glacier had recently disappeared, the number of plants and its cover increased drastically; however, such increasing trend slowed after the passage of 10 years since the disappearance of the glacier.
4. *Senecio keniophytum* tended to grow on relatively stable slopes, while *Senecio keniodendron* grew on stable moraines. In contrast, *Lobelia telekii* grew on debris flow and outwash slopes, where soil moisture content was high. As such, the difference in sediments, moisture conditions, and surficial stabilities of landforms impacted the distribution of the pioneering plants.
5. *Helichrysum citrispinum* was not observed near the glacier terminus earlier; however, its growth was first confirmed on a lateral moraine at an elevation of 4470 m in 2009. It is likely that the increase in its distribution is not directly related to glacial retreat, rather it might be related to increasing temperature.

6. Areas that have been free of glaciers for 10 years or less have coarse soil with small, gray gravels due to limited humus. Over time, the gravels progressively weathered, soil particles became finer, and humus from pioneering species accumulated, which led to the development of nutrient rich soil. In places where 50 years or more have elapsed since the disappearance of glacier, humus was accumulated, which created finer blackish brown soil.

   Due to the strong freeze-thaw actions and solifluction on the ground surface of Mount Kenya, it was difficult for plants to get established in areas composed of fine gravels due to movements of the ground surficial materials, which in turn did not allow soil to develop. Thus, we can suggest that the development of soil is influenced by the number of years elapsed since the glacier disappeared and the degree of plant establishment associated with the movements of the ground surficial materials.
7. Changes in the front of large woody rosette plants, *Senecio keniodendron* and *Lobelia telekii,* appeared to be unrelated to the glacial retreat until 1997. Since then, however, the distribution of these plant species has been advancing. The increasing distribution of these species was influenced by the transition from unstable to stable slope and the maturating of soil through the accumulation of humus from the pioneering plant species. Radiocarbon dating of dry leaves showed that the growth rate of two *Senecio keniodendron* plants were 3 cm/year and 4.5 cm/year, respectively. The age of *Senecio keniodendron*, which has a height of 5 m, is likely to be 100 years or more.

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Geoecology II: Growth Dynamics and Distribution of Giant Rosette Plants on Recently Deglaciated Terrain Below the Tyndall Glacier on Mount Kenya

Koki Teshirogi

Vegetation on the upper slopes of Mount Kenya is characterized by *Senekio keniodendron* and *Lobelia telekii*. Image was acquired at the head of Teleki Valley, close to Tyndall Glacier

Abstract The vegetation of tropical alpine environments is characterized by giant rosette plants, of which, two species, *Senecio keniodendron* and *Lobelia telekii*, were found to have grown on deglaciated terrain below Tyndall Glacier on Mount Kenya. The species are one of the most attractive elements of the landscape, which captures the attention of visiting eco-tourists. Therefore, the plants are of conservation interest, particularly during a period of climate change. In this study, I analyzed the growth

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dynamics and distribution of the two species. Field surveys were conducted in 2016 and 2018. The rates of mortality and recruitment were found to be closely similar, and therefore, the population numbers were stable. The heights of the surviving plants were found to have increased over the two years. When the heights of *Lobelia telekii* rosette leaves were >20 cm in 2016, the elongation rates of anthotactic spiral inflorescences tended to increase. The amount of solar radiation affected the distribution of the giant rosette plants, i.e., plants were distributed in areas where total solar radiation levels were high.

Keywords Giant rosette plants · *Senekio keniodendron* · *Lobelia telekii* · Digital elevation model · Tyndall Glacier

1 Introduction

Giant rosette plants occur on the slopes of the East African mountains. Giant forms of *Senecio* and *Lobelia* are abundant and widespread taxa that are endemic to the alpine zone of Mount Kenya (Coe 1967). The vegetation on the volcanic land is characterized by giant rosette species, including *Senekio keniodendron* (*Dendrosenecio keniodendron*; SK; Fig. 1) and *Lobelia telekii* (LT; Fig. 2). These species and other giant rosette plants are typical of high-elevation tropical landscapes with large diurnal temperature fluctuations (Hedberg 1964; Coe 1967; Rehder et al. 1988). These

Fig. 1 Photographs of *Senekio keniodendron* (adult and juvenile) in Teleki Valley, Mount Kenya

Fig. 2 Photographs of *Lobelia telekii* (adult and juvenile) in Teleki Valley, Mount Kenya

unusual plants are an important natural resource of Mount Kenya, which has been designated a World Heritage site and has received the status of national park in Kenya. Eco-tourism is a major industry in Kenya. As these species attract the interests of tourists, an expanded knowledge of the distribution dynamics and habitats of these unusual plants is expected to contribute to the development of this industry. The data will also improve our understanding of the changes in vegetation associated with recent climate changes. The giant rosette species are relatively long-lived, a trait that enables investigation of the effects of long-term changes in local environments (Young 1994).

In this study, I investigated an early vegetation succession on Mount Kenya in areas that were recently deglaciated. I examined the distribution of SK and LT on this terrain. Vegetation distribution at the foot of a glacier in tropical alpine zones is determined by the timing of deglaciation and a range of other environmental factors such as soil development (Matthews 1992). Mizuno (2005a) showed that giant rosette plants, which are distributed around the glacier, are affected by geomorphological conditions and gravel size. Young (1991, 1994) and Young and Peacock (1992) conducted biological surveys of giant rosette plants. Smith and Young (1982, 1987, 1994) examined the population dynamics of these plants. The studies found that LT occurs mainly on dry rocky slopes at elevations of 3500–5000 m (Young 1994). Smith and Young (1994) showed that changes in the population of SK are related to slope aspect and elevation. However, micro-scale analyses of the relationship between giant rosette plant distribution, vegetation succession, and habitat conditions are yet to be explored. The dynamics of seedlings and the growth period in high-elevation zone are especially unclear. I investigated the distribution dynamics of giant rosette plants through field studies in 2016 and 2018.

2 Research Area

Mount Kenya is an isolated, extinct volcano located on the Equator (0°6′S, 37°18′E). The summit (Batian) is at an elevation of 5199 m. Rocks on the volcanic massif consist of basalt, phonolite, kenytes, agglomerates, trachyte, and syenite (Bhatt 1991). This study was conducted below the snout of Tyndall Glacier (Fig. 3), which is the second largest glacier on the volcano. The snout is at an elevation of 4600 m. The glacier has continually retreated for at least 100 years (Hastenrath 2008).

The Tyndall Glacier retreated at a rate of 0–3 m/year during 1958–1997, the rate of retreat was increased to 7–15 m/year between 1997 and 2011 (Mizuno and Fujita 2014). The recent trends of deglaciation are strongly related to global warming (Mizuno and Fujita 2014). Mizuno and Fujita (2014) also showed that pioneer plant

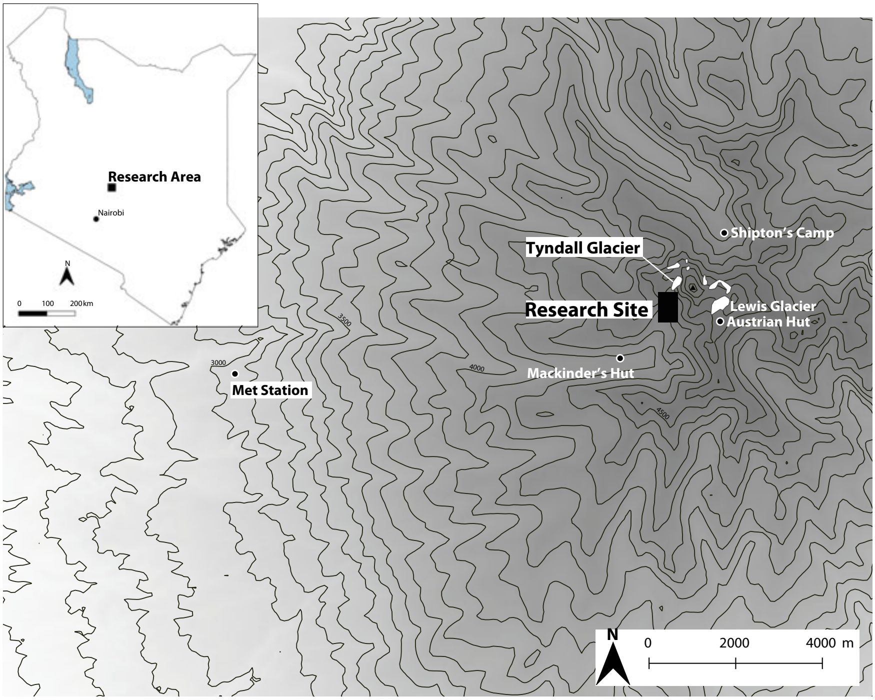

Fig. 3 Location of the research site (contour map generated by the SRTM-3 DEM model)

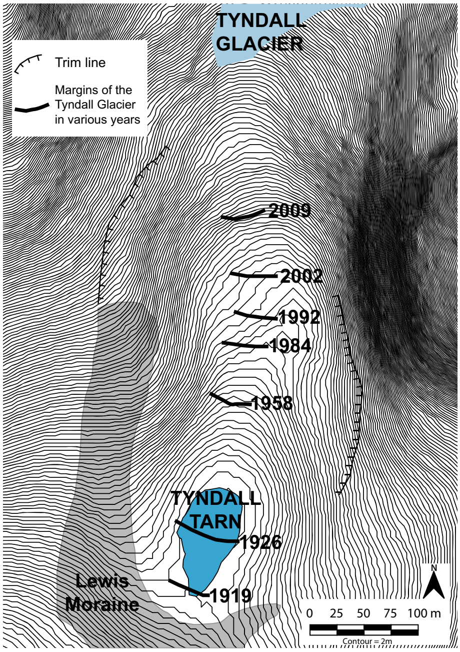

Fig. 4 Contour map of the terrain below the snout of Tyndall Glacier, Mount Kenya. The margins of Tyndall Glacier and geomorphological features are described in Mizuno and Fujita (2014). (Contour map generated by the AW3D DEM model)

species have advanced with the retreat of the glacier. The movements of some species did not appear to be spatially related to glacial retreat; however, they might be related to an increase in air temperature, soil development, seed dispersal limitation, and the interval of masting (Mizuno and Fujita 2014). Tyndall Glacier has developed glacial moraines during different developmental periods since the last glacial period (Mahaney 1990). For example, Lewis moraine was formed 100 years ago (Fig. 4). Although the abundance of plants was very low on this youngest moraine, several species were able to get established in this location (Mizuno 2005b). The characteristics of vegetation on the deglaciated moraines in this area have been reported by Mizuno and Fujita (2014).

Data from the Centre for Training and Integrated Research in ASAL Development (CETRAD) indicate that the average rainfall from 1978 to 2019 was 1493.5 mm/year at Naro Moru meteorological station (Altitude: 3050 m). The maximum rainfall recorded was 2030.3 mm in 1981, and the minimum rainfall recorded was 939.2 mm in 2000. During 2016, 2017 and 2018, when the study was conducted, the average annual precipitation was 1194.2 mm, 1304.0 mm, and 1914.4 mm, respectively. Therefore, we can suggest that precipitation near the study site was lesser than the average in 2016 and was higher than the average in 2018.

3 Research Methods

The field survey was conducted in August 2016 and August 2018. The research area was located inside a ridge of Lewis moraine on a trim line (Fig. 4). The positions of all individual types of giant rosette species of SK and LT that are taller than 3 cm were mapped in 2016. In this study, the growth and death of all existing individuals of the two species in 2018 were analyzed, and the appearance of new species was recorded. The distribution maps of SK and LT were plotted using these data. A contour map was generated with a 5 m-mesh using the ALOS World 3D topographic data digital surface model (AW3D; NTT DATA, RESTEC included JAXA).

I analyzed the relationship between the distribution of giant rosette plants and elevation, slope angle, and slope direction using AW3D data. Solar radiation (W m^{-2} day^{-1}) was calculated using AW3D and the r.sun package in GRASS GIS. The procedure was influenced by the shadow of the summit, and not by the amount of cloud cover. Therefore, the calculated values were ideal for this study.

4 Results

4.1 Distributions of Giant Rosette Plants

Table 1 lists the changes in the number of SK and LT plants in 2016 and 2018. The number of SK and LT plants in 2018 were 171 and 217, respectively. During the period 2016–2018, 14 individuals of SK species died and 15 were recruited; and 31 individuals of LT died and 34 were recruited. Hence, the population densities were stable over this two-year period.

The average height of SK was 21.0 cm (maximum: 112 cm). The average height of LT was 17.7 cm (maximum: 199 cm). Figures 5 and 6 show the distributions of

Table 1 Changes in the number of live and dead individuals of *Senekio keniodendron* and *Lobelia telekii* during 2016 and 2018

	Senekio keniodendron	*Lobelia telekii*
Number of individuals in 2016	170	214
Number of individuals in 2018	171	217
Alive (identified both in 2016 and 2018)	156	183
Dead (identified in 2016/died in 2018)	14	31
Newly recruited (identified only in 2018)	15	34

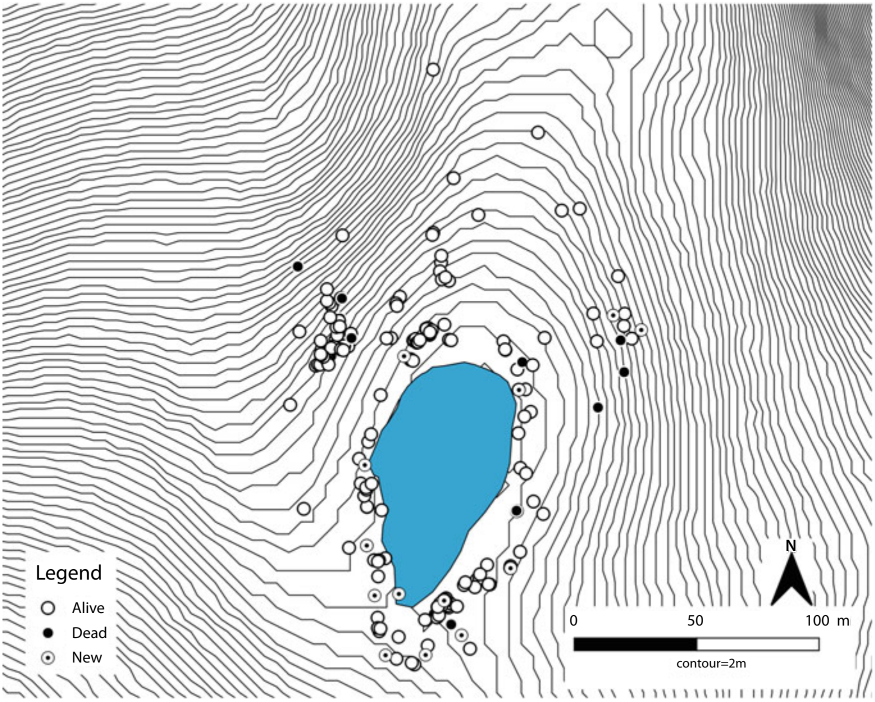

Fig. 5 Changes in the distribution of *Senekio keniodendron* between 2016 and 2018; the area lies below the snout of Tyndall Glacier, Mount Kenya

SK and LT, respectively. Both species were distributed around Tyndall Tarn. The distribution area was approximately 400 m distant from the glacier. The two species were mostly distributed on the north-western slope and on the southern side of the tarn. They were less frequent in the northern sector of the tarn, which was near to the glacier, and on the eastern side of the tarn. Dead individuals and new recruits were sparsely distributed.

4.2 Growth of Senekio Keniodendron *and* Lobelia Telekii

The heights of SK and LT changed over two years. The average increase in the height of SK and LT was 3.7 cm and 8.7 cm, respectively; the corresponding maximum height was 22 cm and 124 cm. SK and LT possessed similar growth patterns; however, their growth processes differed. The growth of LT was caused by the elongation of anthotaxis (Fig. 7).

Figure 8 is a scatter plot showing the differences in the height of LT between 2016 and 2018 (newly recruited plants and dead individuals are not included in the

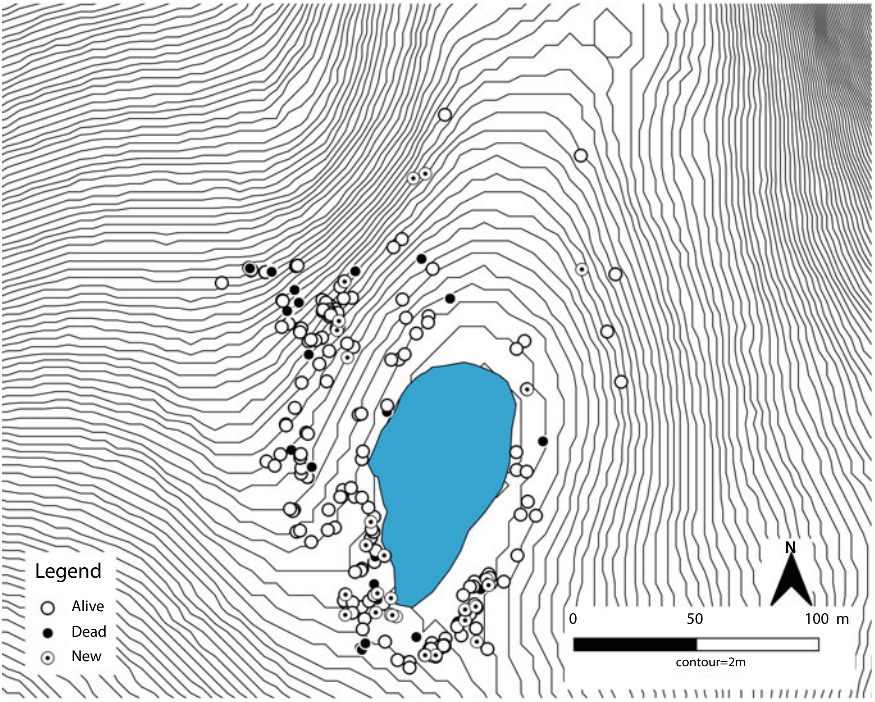

Fig. 6 Changes in the distribution of *Lobelia telekii* between 2016 and 2018; the area lies below the snout of Tyndall Glacier, Mount Kenya

plot). It can be observed that the size of almost all individuals was increased, but the height of certain species was reduced in 2018. Height losses could be attributed to the foraging animals, such as tree hyraxes. When the heights of rosette leaves were >20 cm in 2016, the elongation rate of anthotaxis tended to increase (Fig. 8); when the heights were <20 cm in 2016, anthotaxis did not develop.

4.3 Environmental Factors

The distribution pattern of both species was related to elevation. Figure 9 shows the number of live, dead, and newly recruited individuals in relation to changes in elevation. Generally, the number tended to increase at lower elevations and decrease at higher elevations. The distribution was patchy, even at lower elevations. This patchiness was related to local topography. However, the relationship between elevation and the number of dead and newly recruited individuals was not clear.

Fig. 7 Photographs of grown anthotaxis in *Lobelia telekii*

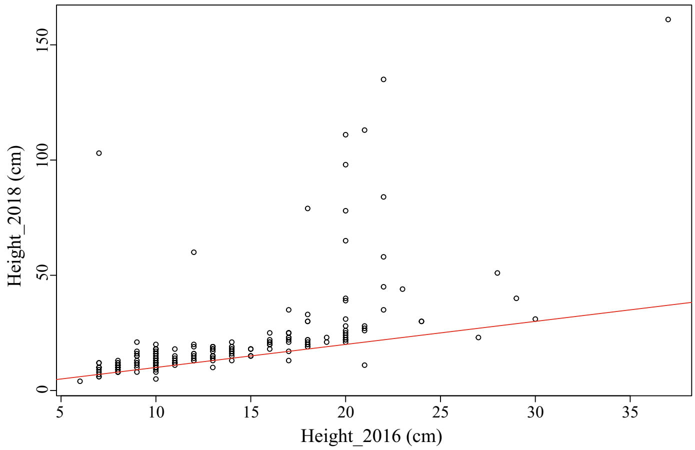

Fig. 8 Growth rate of *Lobelia telekii* during the period 2016–2018. The red line indicates a zero-growth rate

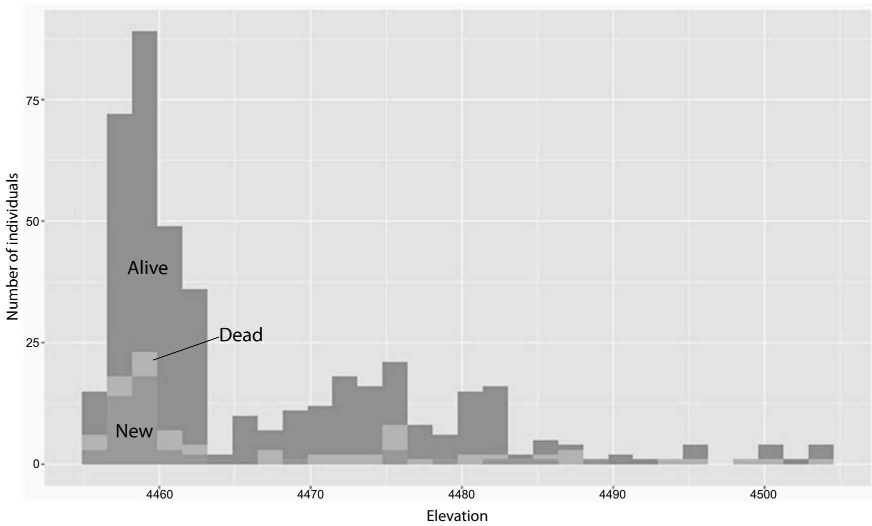

Fig. 9 Number of *Senekio keniodendron* and *Lobelia telekii* individuals in relation to changing elevation

Both species generally occurred on flat terrain with a slope of 10°; however, certain species were also found on the relatively steep slopes of approximately 30°. Most individuals occurred on slopes with a southeast aspect.

Figure 10 shows the density plot of number of individuals in relation to solar radiation. The two curves in the figure are (i) the probability density function of SK and LT, and (ii) the probability density function of random points generated by

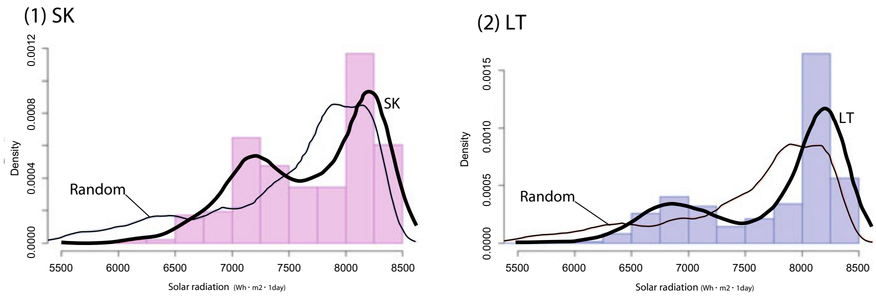

Fig. 10 Density plot showing the number of *Senekio keniodendron* (1) and *Lobelia telekii* (2) in relation to solar radiation levels. The curves represent plots of (i) the probability density function of *Senekio keniodendron* and *Lobelia telekii*, and (ii) the probability density function of 2000 random points generated by GIS software

GIS. SK and LT tended to occur in areas with elevated solar radiation. Kolmogorov–Smirnov tests showed that the distributions of both species were significantly different ($p < 0.01$), indicating that their abundance was related to the amount of solar radiation. Although most plants occurred in strongly illuminated sites, a few individuals did not; hence, solar radiation might not be the only factor influencing the distribution pattern. Seed dispersal ranges and other factors such as differences in distributed gravel size might have been also influential.

Figure 11 is a box plot showing the relationship between the status of each individual (dead/alive/newly recruited) and solar radiation. Dead individuals tended to occur in areas with reduced solar radiation. On the other hand, the new recruits occurred primarily in areas with strong solar radiation. Hence, solar radiation was

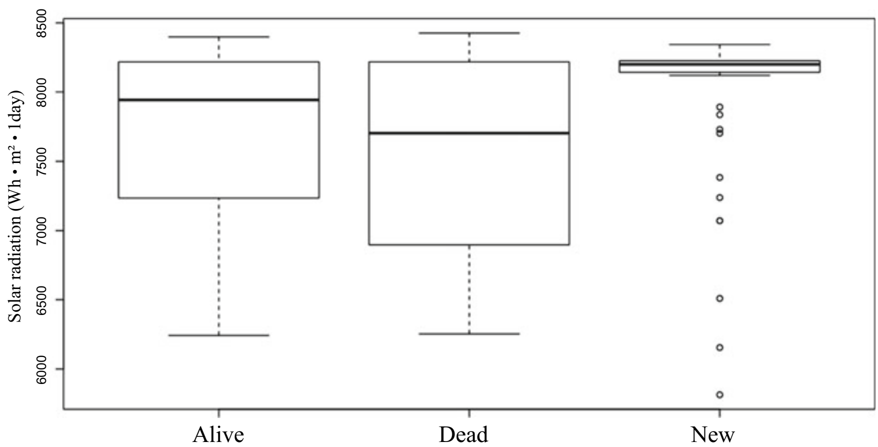

Fig. 11 Box plot showing the relationship between the status of each plant individual (dead/alive/newly recruited) and solar radiation

closely related to the status of each individual. Dead individuals were found mostly at high elevations, where the slope was steep and the amount of solar radiation was limited. The new recruits occurred mostly at low elevation, where radiation was high and slope was gentle. A multi-year investigation of seedling dynamics showed that giant rosette species present in the research site have expanded their distribution in areas with favorable environmental conditions.

5 Conclusion

I studied the growth dynamics and distributions of SK and LT over two years using data collected during field surveys conducted in August 2016 and August 2018. The number of SK and LT did not change markedly over the two years. Growth processes differed between the species. The floral inflorescences of LT increased in length when the height of the rosette leaves was >20 cm. The species also had similar habitat preferences; i.e., they tended to occur at low elevations on terrains that were exposed for 60 years after deglaciation.

The preferential occurrence of individuals at low elevation was related to the amount of solar radiation. Similarly, the status of plant individuals (dead, alive, newly recruited) was related to the amount of solar radiation. Young (1984) indicated that increased solar irradiation increases floral development rates in LT; however, this research focused only on slope aspect. The present work demonstrated a quantitative relationship between plant status and solar radiation and showed that the species' distributions were affected by factors other than soil moisture (Young 1994) and gravel size (Mizuno 2005b).

Nevertheless, apart from light, plant status and distribution were found to be related to the following environmental factors: soil moisture, ground temperature, and snow melt. The influence of these additional factors warrants further study.

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Ecological Anthropology: Local Perceptions and Their Responses to Changes in Water Environment and Land Use in the Mount Kenya Region

Xiaogang Sun

Sprinkle irrigation in farmland in the mid foot zone of Mount Kenya

Abstract Over the past 50 years, local farmers residing at the foot of Mount Kenya have noticed various changes in the water environment. The volume of water in rivers has decreased, which is particularly evinced during the dry season; and rainfall has become irregular. In addition to these changes in the water environment, changes in land use and population growth have also affected the agricultural industries, and eventually caused water shortages. To provide a sustainable water source and avoid conflicts, furrows have been banned, and projects using pipelines to draw

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and distribute water have been promoted in the upper and intermediate zones of the foothills of the mountain. Furthermore, local farmers have developed various strategies to cope with the problems of water shortages. These include dividing their farmland into different plots and planting different crops, choosing crop varieties that are adapted to dry environments, practicing crop rotation and mixed planting, and building small ponds to store water. Meanwhile, water shortages in the lower foot zone have remained potential sources of conflict.

Keywords Water shortage · Land use · Water use · Water project · Mount Kenya

1 Introduction

The region around Mount Kenya is locally believed to have three zones. The zone located above 3300 m is known as alpine and moorland zone, and is managed by the Kenya Wildlife Service (KWS) at the Mount Kenya National Park, where any type of local use of the natural resources is strictly prohibited. The forest zone is located between 2400 and 3300 m and is managed by the Kenya Forest Service (KFS) at the Mount Kenya Forest Reserve. Local residents are allowed to graze their livestock (mainly cattle and sheep) at the bottom edge of the forest zone during daytime. The alpine zone and the forest zone function as an important water tower of the region. The lower slopes and foot zones below 2400 m are densely settled and are one of the most important areas for agricultural production in Kenya. Coffee and tea plantations are carried out on the northern, eastern, and southern slopes of the mountain. Large-scale wheat farms are found on the northwest slope, while rice fields cover the southeast foot of the mountain. In addition to large-scale farming, individual farmers who grow maize, beans, and vegetables reside below the forest throughout the region (Fig. 1).

Most of the agricultural areas on the lower slopes and in the foot zones receive an annual precipitation of approximately 1250 mm. The region experiences two rainy seasons: the long rains (April–June) and short rains (November–December). The eastern slopes are relatively humid, while the north and northwest slopes are much drier. Both the alpine and forest zones are vital water sources, and water supply from several perennial rivers and subsurface aquifers are used by the agricultural zones located lower down (FAO 2002).

In recent years, the water environment of Mount Kenya region has changed due to the combined effects of global warming and human activities. Glaciers near the summits have shrunk rapidly and changes in plant succession have been also reported (Mizuno and Fujita 2014). Deforestation and water shortages in the rivers from the mountain have led to conflicts between upstream and downstream users during the 1990s–2000s (Aeschbacher et al. 2005). The impacts of glacial reduction and changes

Fig. 1 From the summit to the foot of Mount Kenya, the entire region is divided into the alpine zone, forest zone, large-scale farms, and individual farmlands

in the water environment from the alpine zone to the slopes and the foot zones of the mountain are likely to severely impact the agricultural zones in the near future (Otani 2018).

This chapter describes how local residents perceive and respond to changes in the water environment of Mount Kenya from an ecological and anthropological point of view. Fieldwork was carried out in the Naro Moru location on the lower western slope and on the foot of the mountain. The population was approximately 35,000 in 2016, and most of the residents were individual farmers. The area, which is regarded as the driest place of all the agricultural areas that surround the mountain, had an annual precipitation of 800 mm. Residents rely heavily on the river for water for domestic use and for agricultural purposes. The only river flowing in this area is the Naro Moru River, whose water sources are both glacial lakes near the summit and the forest. Therefore, changes in the water environment of the mountain are likely to have significant impacts on local livelihoods and on agricultural production in the area. In this study, we have examined the land use and water use on the lower slopes of the mountain by local residents between 2016 and 2018.

2 Local Perception on the Changes of Water Environment in Mount Kenya Region

Although most residents inhabiting the lower slopes and foot zones of Mount Kenya are farmers, the interaction between them and the mountain is not limited to agricultural activities in the Naro Moru region. The Naro Moru route is one of the major routes leading to the summit of Mount Kenya. The Mount Kenya Guides and Porters Safari Club was established in the 1970s in Naro Moru to organize trips to the mountain. In 2017, the club had 149 qualified guides and porters. Among them, 17 people (11%) were registered in the 1970s, 46 (31%) in the 1980s, 40 (27%) in the 1990s, and 46 (31%) in the 2000s. Therefore, approximately 70% of guides and porters had more than 20 years experiences on the mountain. The club also hires another 100–200 porters during high season. As most of these guides and porters also engage in farming in the region, interviewing them provided detailed information on the changes in the water environment, both on the mountain and in the farming areas.

They first pointed out that the glaciers near the summit had not only shrunk more rapidly but also the snow on the top of the mountain had declined dramatically. According to the guides and porters who visited the mountain in the 1970s and 1980s, the area from the Mackinders Camp (at approximately 4200 m) to the summit was covered by more than 30 cm of snow throughout the year. Most of the glaciers were large, and were covered by snow. Some climbers used to ski on the Lewis Glacier, which is Mount Kenya's largest glacier. The temperature near the top of the mountain was low due to the presence of the glaciers. Snow fell during the rainy season and melted slowly during the dry season, which fed the streams and marshes and provided plenty of water that fed the river flowing down to the foot of the mountain. However, with the decline of the glaciers, the snow disappeared rapidly, and the ground near the summit became exposed or covered by vegetation (Fig. 2). As a result, the rivers that pass down the lower slope and foot zones of the mountain have suffered a dramatic reduction in water volume during the dry season. A local elder resident, who first climbed the mountain in 1975 and had served as a mountain guide for more than four decades, described the current situation as "the mountain is sickening."

"In the 1970s and 80s, the mountain was in very good condition. Most of the time, it was snowing and raining. Therefore, there was always plenty of water and snow. However, it is **getting sick nowadays**, it is mostly dry, very dry. Sometimes it gets very dried and dusty around the top."

On the other hand, the belief and respect for the mountain have also changed from generation to generation. The majority of people living in the Naro Moru area are Kikuyu, who believe that God lived on Mount Kenya when he came down from the sky (Kenyatta 1962). Several important ritual ceremonies such as praying for rain during drought were held at sacred sites on the mountain. Interviews with the first generation of residents who came to the Naro Moru area in the 1960s revealed their great respect and deep knowledge of the mountain. Some elders mentioned that they could forecast the weather by watching the shape of the clouds and monitoring the snow on the mountain from their villages, and by smelling the scents brought

Fig. 2 From the Mackinders Camp (about 4200 m) to the summit, the ground is either exposed or covered by vegetation

about by winds or from specific trees. During severe drought, they used to conduct a traditional ceremony and pray while walking around the mountain. However, due to the influence of modern education and conversion to Christianity, newer generations do not share this special appreciation for the mountain. Young farmers mentioned that instead of watching the clouds and the snow on the mountain, they receive the weather information from the radio, television, and mobile phones.

The second point that people emphasized is that the rainfall has become irregular in the Naro Moru area. The rainy season has been delayed several times since the 1980s, especially after the severe drought of 1984–1985. The long rainy season between April and June has had considerably less rainfall recently. In contrast, there was more rainfall during the short rainy season in November and December. Local residents have explained these changes in different ways. Young, educated people believe it is caused by global warming and climate change, while some elders relate it to the large-scale deforestation that took place in the late 1980s. Nevertheless, they all agree that the volume of water in the Naro Moru River in the dry season has decreased dramatically, and that changes in the rainfall pattern have affected agricultural production.

The third issue raised by the local people was the rapid increase in the demand for water by local farmers and people living in Naro Moru town. The riverside of the Naro Moru River used to be covered by dense forest. However, with the expansion of farmlands, the trees along the river were cut down for construction and furrows were made to access water. In addition, rapid urbanization and population growth of Naro Moru town have also increased the demand for water over the past two decades.

3 Changes in the Land and Water Use in Agricultural Areas

Both land use and water use have changed significantly in the Naro Moru area over the past 50 years. Compared to the eastern, northern, and southern slopes of the mountain, the settlements and farming in Naro Moru area are relatively new. According to local residents, the area was used mainly by Maasai and Samburu nomadic pastoralists as a seasonal rangeland until the late nineteenth century. During the colonial period of the early twentieth century, some white settlers arrived and established large cattle ranches. Following independence in 1963, the Kenyan government split up the ranches and sold them as farmlands via loans to the former ranch employees and farmers, who had migrated from neighboring populated areas. As the population of the area was small, the farmers were able to purchase large areas of farmland in the fertile mid foot zone of the mountain. They planted maize, beans, and vegetables, and their production mostly relied on rainfall.

In the 1970s and 80s, the number of immigrants from the surrounding areas increased. The early settlers divided the farmland and sold part of it to repay the land loan. Most of the land in the mid foot zone of the mountain was occupied. New immigrants had to find land along the border of the Forest Reserve at the upper foot zone of the mountain. Between 1988 and 1990, as landless or land-poor farmers from the north and eastern sides of the mountain continued to arrive in the search for farmland, a section of forest at the bottom edge of the Forest Reserve was cut down to create farmland under a government development scheme. As most farmers only had small pieces of land, and farming that relied solely on rainfall was not stable, water furrows were created to draw water from the Naro Moru River to the farmlands. Cash crops such as cabbage were planted when irrigation became popular. In the 1990s and early 2000s, with the increasing urbanization in Naro Moru town and the expansion of the farmland in the lower foot zone, water shortages became significant and water conflicts occurred in the area.

To provide a more in-depth view of the land and water use along the Naro Moru River, we divided the agricultural area into three sections (Fig. 3).

The upper foot zone of the mountain is the area below the Forest Reserve at an altitude of approximately 2300 m. The temperature in this zone is cooler than that at the mid and lower foot zones, and this area is usually covered by fog in the morning. The slope is relatively steep, and the soil nutrients are considered to be poor. Most residents arrived in this area in the 1970s and 1980s after the mid foot zone became fully occupied. Since the population density was relatively low, the residents were able to farm an area of land between 5 and 50 acres. They cultivated staples such as maize, beans, and potato, and also grew cash crops such as cabbage and carrots.

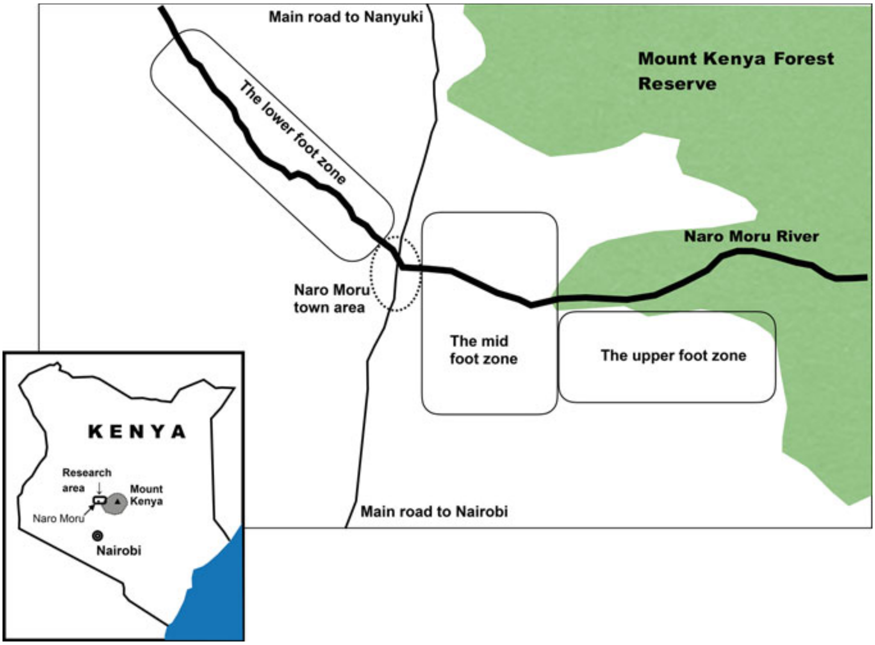


Fig. 3 From right to left, the upper foot zone, the mid foot zone, and the lower foot zone of the Naro Moru area (the base map was set up by the Water Resource Management Authority (WRMA) office in Naro Moru town)

Some residents also raised cattle and sheep, and these animals were allowed to graze at the bottom edge of the Forest Reserve during the day. People used spring water from the mountain; however, most residents connected the pipelines set up by the water project and used this water for both domestic and farming purposes.

The mid foot zone is the area between the upper foot zone on the east and Naro Moru town on the west. The land is relatively flat and fertile, and the temperature is warmer than in the upper area. It is regarded as the most suitable area for agriculture, and has been densely occupied since Kenya became independent. Most residents of this area are the offspring of the first generation of settlers. As a result of land division and inheritance, farmers own small farms of less than 3 acres. To be able to harvest both staples and cash crops, people practice crop rotation on these small plots. Several homesteads also keep milk cows and sell milk. Irrigation projects using furrows and pipelines were introduced by international development agencies in 1970s to draw and distribute water from the Naro Moru River. Water project committee was established by development agencies to manage the project. The officials of the committee, including a chairman, a secretary, a treasurer, and other officials were selected by the members of the water project.

The lower foot zone lies from the west of Naro Moru town to the point where Naro Moru River meets the Ewaso Ng'iro River. This is a semi-arid area with an annual rainfall of less than 600 mm. The area is normally used for grazing livestock. However, over the last two decades, new settlers have established large-scale farms and took water from the Naro Moru River. With increasing numbers of these new settlers, conflicts over water sharing have increased among residents of the lower, mid, and upper foot zones of the mountain.

4 Local Responses to Changes in the Water Environment and Land Use

4.1 Managing the Water Shortage Through Water Projects

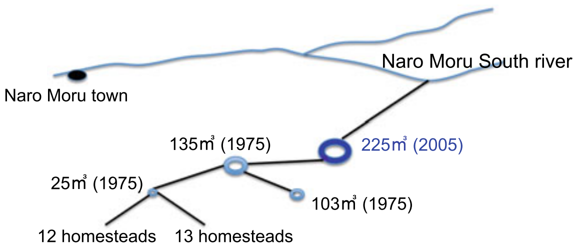
As mentioned above, the water shortages are not only caused by changes in the water environment of Mount Kenya but also by changes in land and water use in the agricultural areas. Local residents recall serious conflicts among themselves in the late 1990s and early 2000s, which was related to water shortage and included the destruction of furrows and irrigation facilities and the attacks on villagers. In the early 2000s, the Kenyan Water Resource Management Authority (WRMA) stepped in to extend their help for solving such problems. As a result, in 2005, all furrows in the upper and mid foot zones were banned. Water projects using pipelines to draw and distribute water, which is managed by water project committees, became the only legal way to access water. Under the guidance of WRMA, water project committees gathered together and formed the Naro Moru Water Users Association (WRUA) to solve water problems and conflicts. However, as no water project was established in the lower foot zone, farmers were allowed to take water directly from the river using their own electric pumps.

Currently, nine water projects have been set up to distribute water in the upper and mid foot zones in Naro Moru area. Among them, four projects are connected to the northern branch of the Naro Moru River (locally known as Tereki River), while five projects are connected to the southern branch of the river (locally called the Naro Moru South River). Figure 4 shows the typical facilities of a water project. For example, each project consists of a reservoir dam across the Naro Moru River. The dam has an intake that connects with the main project pipeline (a 6-inch diameter metal pipe). There is a valve between the intake and the pipeline to control the water flow. The main pipeline is connected to storage tanks. Sub-pipes send water to different locations from the storage tank. Each user of the water project is connected to the sub-pipe by a narrow rubber pipe as well as a faucet in their home and sprinklers on their farm. During the rainy season, sometimes the valve has to be closed to avoid overflow of the tank because people only use the project water for drinking, and the crops are irrigated by the rainfall. During the dry season, the valve is opened only at night to fill the storage tanks, which enables people to use water from the tanks from morning until evening. Below are two examples of the water project in action.

Fig. 4 Typical facilities of a water project

The Gw Water Project was established in 1975 and was the first project in the Naro Moru region. It currently covers a region that contains approximately 900 homesteads, with 3850 people who live in the mid foot zone of the southern side of the Naro Moru River. Among these, 470 homesteads (52%) have joined the project and 530 pipes were connected to the project pipe. When the project was initiated in 1975, four small storage tanks (135, 103, 25, and 25 m^3) were built. A large tank (225 m^3) was added in 2005 to meet the demand of the increasing number of water users (Fig. 5). There is no record of the initial phases of the project; however, records for 1990 showed that 183 pipes were connected. In comparison, in 2018, 530 pipes were connected, which implies a three-fold increase in the number of users since 1990.

Fig. 5 Water distribution map of the Gw Water Project



Project officials explained that population growth, land division and inheritance, and new immigrants were the main reasons for the increased water demand. This number accounts for 52% of the total number of homesteads in the project area. The main reasons why people are not being able to join the project include its high registration and construction costs. According to the project committee, the registration fee was 1200 ksh when the project started in 1975. It rose to 15,000 ksh in 2000 and 35,000 ksh in 2018. Furthermore, new immigrants are asked to pay 65,000 ksh as registration and construction fees to join the project, which is equivalent to four months of living costs for a homestead.

The Kb water project was established in 1992 on the northern side of the Naro Moru River. It is the biggest water project in the area and covers a region that contains approximately 1500 homesteads (6500 people) and 8000 livestock. Among these, approximately 700 homesteads (47%) have joined the project. When the project was initiated in 1992, it had approximately 300 members. Furrows were dug to draw water from the Naro Moru River to serve the members. These furrows were used until 1998 when serious conflicts occurred in the area due to concerns over water use. Following the conflicts, 3.2 km of pipelines were laid and a 225 m^3 storage tank was built to replace the furrows. Currently, the tank has seven sub-pipes that provide water to 700 users along different directions of the region. In 2018, it costed 61,500 ksh for an individual to become a member of the water project.

According to officials and members of the water project committee, a water rationing program for all projects was introduced by the WRMA, which was operated through WRUA. During the dry season, when water shortages are reported, WRUA holds a meeting and gathers together all the officials of the nine projects and the representatives of the lower foot zone. Subsequently, these officials discuss and prepare a rotation schedule for all the projects to draw water from the river, which is then distributed to all the members. Each project hires staff to open and close the valve at the intake of the reservoir dam according to the schedule. Generally, water is first stored in the storage tank after the valve is opened. Following this, project members are able to store water in their own tanks at home for their daily use and for their crops. For example, during the long dry season of 2016, the members of the Gw Project were allowed to draw water from the river from 4:00 PM to 6:00 AM the next morning every day to fill all five storage tanks, after which they were allowed to use the water in the storage tanks from 6:00 AM to 4:00 PM. Meanwhile, members could only use water from 9:00 AM to 11:00 AM in August 2018 due to lack of water. During an interview, officials of the projects tended to argue the limitation of storage tank as the major problem for all projects and indicated the requirements of financial investment in building more storage tanks. However, the shortage of water in the Naro Moru River in the dry season is obviously the crucial factor of the problem. When the water level in the river fell, the water was only allowed to be used for humans and livestock.

4.2 *Managing Water Shortages by Individual Farmers on the Upper and Mid Foot Zones*

Although the water-rationing program helped to reduce tension between the members of the different water projects, the problem of water shortage prevailed. It takes considerable effort on the part of the local farmers to maintain water supply for both domestic and farming use.

In comparison to the rainfall on the northern, eastern, and southern slopes and the foot of the mountain, that on the western side is relatively lesser in amount and also highly unreliable. The Naro Moru area has a limited annual rainfall of approximately 800 mm. Figure 6 illustrates the main crops that are planted and grown in the region. Maize is the staple food for the local people. According to the farmers, several varieties of maize have been introduced to the area by the government, the seeds of which are sold in shops in Naro Moru town. The favorite variety is a cultivar, known as 614, which crops after six and a half months and produces large grains. Another favorite variety is 04, which, despite its smaller grain size, crops shortly after three to four months and requires less water. Farmers said that when water is freely available, they prefer to grow 614; if the water supply is less certain, they grow 04. Generally, farmers start plowing in March and seeding before the rainy season starts. Maize grows well if it receives a stable rainfall during the long rainy season between April and June, which allows farmers to harvest it in August. If the maize grows well, farmers can harvest approximately 1200 kg per acre. After the maize harvest, the farmland is left fallow for one month. At the beginning of October, the farmers start to prepare for the next season.

Potatoes and beans are secondary foods for people living in this area. Potato is relatively resistant to cold temperatures. Therefore, it can be planted in the upper food zone of the mountain. Potato is planted with fertilizers between March and April. Farmers explained that after covering the potato with soil, it becomes warm

	dry season			long rainy season			dry season				short rainy season	
main crops	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
maize (staple)	→	harvest	plow seeding →					harvest		plow seeding →		
potato, beans (secondary)	→harvest		plow planting →					harvest	plow planting →			
cabbage (cash crop)	→harvest	seedbed	planting →		harvest	seedbed	planting →		harvest	seedbed	planting →	

Fig. 6 Major crops grown in the Naro Moru area

and wet because it releases its own moisture and starts to germinate before the rains come. When rainfall starts and potatoes grow, farmers check them to ensure that their stems are straight, and sometimes soils are added to ensure this effect. Potatoes are harvested during July and August. Beans are normally planted with maize, and do not need fertilizers. Both potatoes and beans are planted twice a year.

The major cash crop in the Naro Moru area is cabbage. It was introduced to the area in the 1980s and spread rapidly in the 1990s when farmers made furrows for irrigation. Since cabbage needs large quantities of water, both rainwater and water from the Naro Moru River are used. The farmers said that if the water supply remains stable, cabbage could be planted and harvested three times a year. Generally, a seedbed of cabbage is prepared between February and March using water from the river. The cabbage seedlings are planted in March and April, when the rainy season starts. If the rainwater supply is stable, cabbage grows well, and it can be harvested by the end of May. Subsequently, the farmers start to prepare the seedbed for the next season if the rain prevails in June. As cabbage crop grows during July and August, it is totally reliant on water from the river. However, in recent years, the water volume in the river has reduced during the dry season, making the cultivation of cabbage difficult. The third cabbage planting starts in early October. Farmers prepare the seedbed using water from the river, and subsequently plant seedlings, when the rainy season arrives at the end of October. As the short rainy season in November and December has become more stable than the long rainy season between April and June, it was found that cabbage grows well during this season and is harvested in January.

Farmers with ownership of different areas of land have developed various strategies to cope with the water shortage situations. Most farmers with large areas of land of more than 3 acres are located in the upper foot zone of the mountain, where the temperature is relatively cool and the soil nutrients are poor. Figure 7 illustrates the crop planting scheme and water use requirement of a farmer with a plot of 3 acres in August 2017. The farmland is divided into four plots. Maize, cabbage, and potato are planted intensively in one plot each. Maize is reliant on rainfall and the other two crops use project water. All these crops are cash crops. The farmer explained that in case lands are available, it is better to plant different crops to avoid the risk of unpredictable rainfall and unsatisfactory use of the project water. For example, maize was planted in March, and the farmer waited for the long rainy season of April. However, the rainy season started in May, and all the maize crops failed. Meanwhile, he planted potato and cabbage in another two plots when the rain started and continued to water these crops with project water after the rainy season. He expected a good harvest of potato and cabbage in September and October. The remaining plot was subdivided to accommodate the house, kitchen, two cow enclosures (one for calves and one for adults), a small garden area for yams, sugar cane, and bananas. Another small area of land was reserved for the cultivation of maize and potato. The farmer mentioned that all the crops in this area were for their own consumption, especially yam, which is a traditional food of the Kikuyu people. The farmer had approximately 10 cows, which are taken to the grassland near the Forest Reserve during the daytime. Milk was used for both home consumption and for selling. After harvesting the maize, the

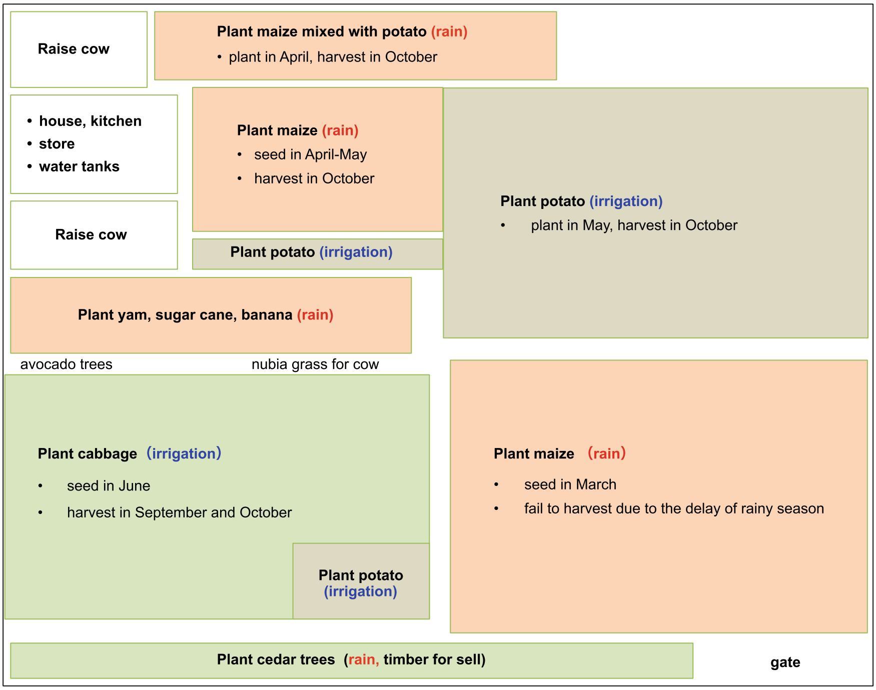


Fig. 7 A schematic diagram of crop planting scheme and water use requirements of a farmer with a plot of 3 acres in August 2017

cows were taken to the area where the maize was grown so that the cows can feed on the stems. Farmers living in the upper foot zone emphasized the importance of keeping cattle and allowed them to graze on the farmland after the harvest to enrich the soil with their manure.

As most farmers living in the mid foot zone of the mountain have only small farms with areas of less than 3 acres, it is important for them to use the land more efficiently than those in the upper foot zone. Figure 8 shows an example of the crop rotation that a farmer, who owned one acre of land, used to follow in August 2017. Both the farmer and his wife were approximately 50 years old and were born in the Naro Moru region. Their children worked in Nairobi after their education. The farmer divided the land into 10 plots. One was used for housing, kitchen, and water tanks, and another was used for keeping a heifer. The other eight plots were used to plant crops. Among them, five plots were used for planting maize, two for cabbage, and one was fallow land, where he planned to plant cabbage in the next season. Maize was planted for home consumption and its production depended on rainfall. Of the five plots of maize crops, one was planted in March; however, the harvest failed due to the delay of the long rainy season. Two plots of maize crop were planted in May, when the long rainy season started, and these were expected to be harvested in October. Furthermore, two plots of land were planted with maize in

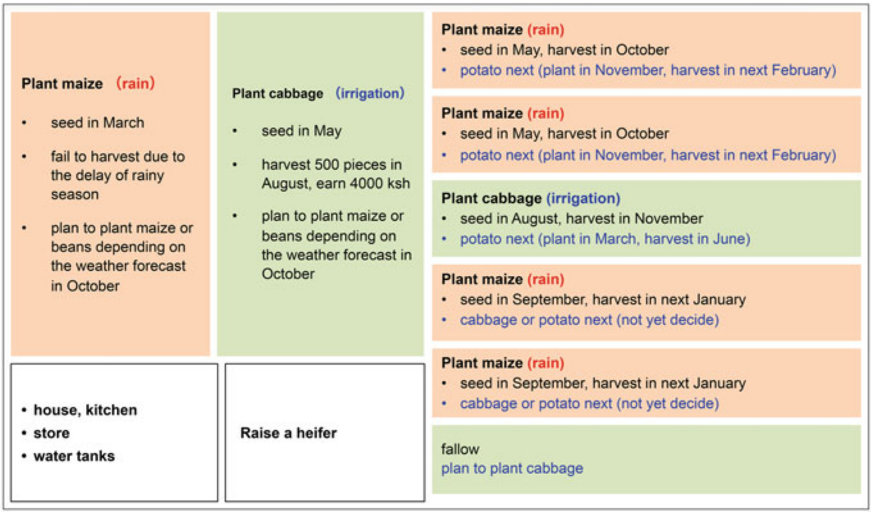


Fig. 8 A schematic diagram of crop rotation for a farmer with 1 acre of land in August 2017

September. The farmer explained that if the maize received enough rain during the short rainy season in November and December, it would be harvested in January. The two plots planted with cabbage were watered using project water. One was planted in May and was harvested in August. The farmer harvested approximately 500 pieces of cabbage and sold them for 4000 ksh. It was planned that either maize or beans would be cultivated on the land depending on the weather forecast in October. Maize was planted in August, and the farmer expected to harvest it in November. If more water was available, he could reduce the amount of maize cultivation and plant more cabbages. In addition, as both land and water were limited, the farmer emphasized that he had to plant for the current season and make plans for water supply and land fertility in the next season. Sometimes, the farmer has to leave some plots fallow for one season to enable them to recover their fertility.

As approximately 40% of homesteads in the upper and mid foot zones did not join the water project, it is important to understand how they coped with the water shortages. These farmers fell into one of two categories: one, who could not afford to join the project, and two, who had recently migrated to the area.

As an example of the first category, the case of Farmer E is considered, who is a young man in his 30s and lived in the mid foot zone with his wife and one daughter (aged 4 years). His father came from Nanyuki in 1963 and died in 2012. The father had five sons and a daughter. Each of them inherited three quarters of an acre of land. However, the father had only one pipe from a water project, and this was inherited by his daughter. This meant that all of his five sons had to join the project by themselves. Farmer E did not have enough money to join the project. He divided his land into four plots, and planted maize, mixed with beans and potatoes, in each plot in different seasons for his own home consumption. He also dug a small pond to store rainwater.

Without project water, he had to choose only those crop varieties that required less water, and therefore, he was unable to plant cash crops. To generate income, he worked as a porter during the mountain climbing seasons and as a day laborer in Naro Moru town. His wife borrowed water for their daily use from his brothers, who have joined the water project. He insists that as soon as he saves enough money, he will join the water project so that his family will have enough water for themselves and to grow cash crops.

We will now discuss a case of the second category of farmers who recently migrated to the area. Although the mid foot zone in Naro Moru has been densely occupied, some of the first-generation farmers, who own large plots of land had to occasionally sell off their portions. It is also possible to find small pieces of land in the upper or lower foot zones because these places are settled and cultivated later. Therefore, landless farmers from the surrounding areas such as Mulanga, Kianbu, Kalatina, Nyeri, and Meru come to buy land in Naro Moru because land is very expensive in their own regions. Most of these immigrant farmers cannot join the water project immediately because of the high cost or the large distance between their land and the project pipe. Here we have considered Farmer K as an example of a new immigrant farmer. He was born in the 1980s in Karatina (a town on the southern foot of the mountain) and came to Naro Moru in 2009 with his wife and children. His relatives live in the Naro Moru area, and they helped Farmer K find a piece of land in Naro Moru. He bought a quarter of an acre that costed him 50,000 ksh. He said that the price of an equivalent plot would have been 10 times higher in Karatina. He grew some onions, potatoes, pumpkins, and beans for his home consumption, and also prepared a cabbage seedbed. He did not join the water project because his plot of land was too small and the enrolment fee was too high for an immigrant farmer. He also rented another half an acre of land, which is connected to a water project. He grows cabbage for selling to support his family.

During interviews with the farmers, who were not the member of a water project, all of them showed their strong willingness to join the water project even though they did not have the financial ability to do so. Therefore, it is necessary for WRMA and local government, local community, and water projects to establish a social support program so that all the people living in the project area can have access to water for their basic life needs.

4.3 Managing Water Shortages by Individual Farmers on the Lower Foot Zone

The lower foot zone lies in between the west of Naro Moru town to the zone where the Naro Moru River meets the Ewaso Ng'iro River. This is a semi-arid area with an annual rainfall of less than 600 mm. The area has been used as a grazing land by Maasai and Samburu nomadic pastoralists for hundreds of years and by white settlers, who set up cattle ranches during the colonial period. However, over the past

Fig. 9 Collection of water directly from the Naro Moru River using a private electric pump in the lower foot zone

two decades, with an increasing population and higher demands for farmland, new settlers from neighboring areas such as Nyeri and Meru have invested in large-scale and intensive farming along the Naro Moru River. There is no water project in this zone. Individual farmers take water directly from the river using private electric pumps (Fig. 9).

Interviews with farmers living in this zone have revealed the difficulties and challenges faced by the farmers in this location. During the dry season, farmers have to pump water from the river daily, which requires the use of diesel that is expensive. When the water level of the river falls and water projects operating in the upper and mid foot zones use large amounts of water, downstream areas might face water shortage. Lack of water significantly affects the crops and causes conflicts between the upper-mid zones and the lower zone. Whenever the water does not flow all the way downstream, the farmers complain to WRMA and WRUA and request a public meeting to solve the problem. On the other hand, if it rains heavily in the mountain area during the rainy season, floods may occur in the lower foot zone and all the crops along the riverside might get washed away. Due to these high risks and high cost, instead of seeking stable productivity, most farmers tend to undertake intensive farming of cash crops, which has the potential to be economically productive if the conditions are favorable (Fig. 10). According to one farmer who plants cabbage in a half-acre plot of land, there was a time when he harvested around 10,000 cabbages

Fig. 10 Irrigation of an intensive cabbage farmland in the lower foot zone

and earned 250,000 Ksh in three months, which is equivalent to 16 months of living costs for a homestead. However, there were other times when he harvested nothing due to a lack of water in the river. Although the use of water from the Naro Moru River is currently controlled by the WRMA and WRUA, water shortages in the lower foot zone remain a potential source for conflict.

5 Conclusion

Over the past 50 years, local farmers living at the foot of Mount Kenya have noticed various changes in the water environment. As the glaciers near the summit have retreated more rapidly, the temperature at the top of the mountain has increased and the snow in the alpine zone has melted. As a result, the water volume in the rivers has decreased during the dry season and rainfall has become irregular. The long rainy season between April and June has seen a reduced rainfall; by contrast, higher rainfall has been observed during the short rainy season in November and December. Furthermore, rapid urbanization and population growth in the Naro Moru area have increased the demand for water over the past two decades. All these changes have led to water shortages in the region as most farmers rely both on rainfall and on water from the river originating from the mountain.

To ensure a sustainable supply of water and avoid conflicts, furrows have been banned and water projects that use pipelines to draw and distribute water have been promoted in the upper and mid foot zones of the mountain. Although the water rationing programs introduced by the WRMA and WRUA have helped to reduce tensions in the area, the problem of water shortages remains. Local farmers have developed various strategies to cope with this issue; these include dividing their farmland into different plots and planting different crops, choosing crop varieties that are adapted to dry environments, practicing crop rotation and mixed planting, and building small ponds to store water.

However, as approximately 40% of homesteads have not joined the water project, a social support program is required to enable access to water for meeting the basic needs of all people living in the project area. On the other hand, the population has increased and the demands of farmland have also increased because new settlers have invested in large-scale and intensive farming in the lower foot zone over the past two decades. As most farmers take water directly from the river using private electric pumps, water shortages in the lower foot zone remain a potential source of conflict.

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Development Studies: Sustainability and Local Participation in Community-Based Water Resources Utilization: A Case Study of the Matengo Highlands, Tanzania

Minako Araki

A woman using a water supply facility shared with her neighbors

Abstract Local people in the Matengo Highlands of Tanzania took an initiative to harness water resources and constructed a hydro-milling machine, a micro-hydropower generation system, and water supply facilities, which have shown to

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have great potential. Although such initiatives are important, undertaking the sustainable use of those facilities is not an easy task. This chapter examines the process of constructing them and discusses the various factors that affect their sustainable use and management. The results show that local participation and community-based organizations play significant roles in the construction of hydro-milling machine as well as in its sustainable use and management, which have resulted in scaling up the micro-hydroelectric generation system. In terms of water supply facilities, factors such as leadership and water users' association functioned as key elements throughout the process. Despite the promise of advancements and considerable potential, however, the case study indicates that continued use of water resources portends conflicts as well as cooperation both within the village and among different villages along the river basin.

Keywords Water resources · Hydro-milling machine · Micro-hydroelectric generation · Water supply facility · Tanzania

1 Introduction

The use of water resources in rural Africa holds significant potential. For example, the construction of water supply facilities has opened up access to safe drinking water and has reduced the need to draw water from rivers and springs by women and girls. Improved access to water was a target of the Millennium Development Goals (MDGs) from 2000 to 2015; however the lack of access to safely managed water supplies and sanitation facilities were serious problems of MDGs, particularly in sub-Saharan Africa. The subsequent Sustainable Development Goals (SDGs), which were initiated in 2016, placed greater emphasis on ensuring the availability and sustainable management of water and sanitation (Goal 6). It also emphasized on the access to affordable, reliable, sustainable, and modern energy resources for everyone (Goal 7). In view of the importance of accessing energy without jeopardizing climate stability, the generation of renewable energy, such as that derived from micro-hydroelectric systems, holds significant potential in rural Africa.

Construction of water resource facilities and their sustainable use and management have been considered and examined from various aspects. To investigate the sustainability of water resource systems, various studies have combined diverse factors such as political contexts, economic factors, technology, environmental aspects, local and community participation, and capacity building. Some studies also examined the role of water user group or water user association for the management of common pooled resources such as irrigation systems (Ricks 2015) and communal water and sanitation services (Cleaver and Toner 2006; Terry et al. 2015). Spaling et al. (2014) pointed out that most studies on water projects focus only on a snapshot of sustainability although it is more important to examine how the various factors of sustainability have changed over time, and also to evaluate how the changing conditions might affect the sustainability of a community rural water supply project in the long term. This could be achieved by conducting a case study of more than 10-year period and evaluating the associated aspects by performing pre-project and post-project analyses.

There is also an increasing concern about conflicts and competition as well as cooperation over water resources. By examining the complexities that prevail at the local-level, politics, uncertainties, and varied responses to scarcities of water resource, Lankford (2010) argued for an allocation and 'share' response to manage water scarcity in a case study of Tanzania. On the other hand, Jairath (2010) focused on the social and political factors that affect water management and cause inaccessibility and exclusion of water in India. Gyawali and Dixit (2010) described conflicts over water and power due to development projects in Nepal. Akimichi (2009) focused on the composition of numerous stakeholders of water resources, including upstream/downstream, farmer/farmer–fisher, businesses/communities, and residents. By examining different spheres of competition such as the agricultural sector and the public service sectors, Ikeno (2018) investigated whether there has been an increase in conflicts between the stakeholders of water resources in and around a town in north-eastern Tanzania.

This chapter examines the process of constructing the water-related facilities in the Matengo Highlands of Tanzania by evaluating various factors affecting their sustainable use and management and changing conditions over the years. In Sect. 2, the process of constructing a hydro-milling machine is examined, followed by its long-term sustainable use and management. Section 3 investigates different initiatives and approaches by the people regarding water supply initiatives. Section 4 examines the potential and constraints of micro-hydroelectric generation project based on the sustainable use of the hydro-milling machine. To this end, fieldwork was carried out in the Matengo Highlands of Tanzania. Having participated in the Sokoine University of Agriculture, Centre for Sustainable Rural Development (SCSRD) project for approximately 3 years as a Japan International Cooperation Agency (JICA) expert, I lived in Village K for 5 months in 2005, and since then have carried out fieldwork, which primarily included interviews and participant observation for 3–4 weeks in each year, beginning in 2006 until 2019.

2 Process of Constructing a Hydro-Milling Machine

The Mbinga District, situated in the Matengo Highlands of south-western Tanzania, is located in a remote area near the border of Malawi and Mozambique at approximately 1100 km from Dar es Salaam (Fig. 1). It is divided into mountainous/hilly region and the riparian terrains. The mountainous/hilly area is named Matengo Highlands after the Matengo people who inhabit the area (Fig. 2). Along with Kilimanjaro in the north and Mbeya Region in the south, the region is well known as a coffee-producing

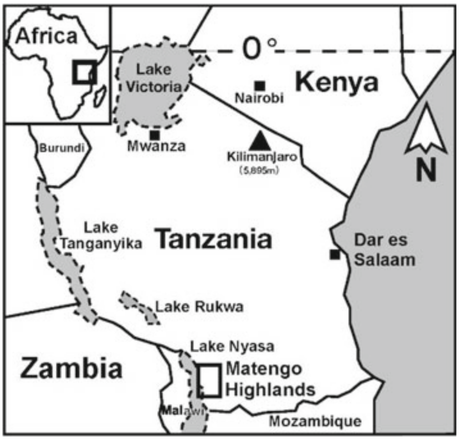

Fig. 1 Map of the Matengo Highlands of Tanzania

Fig. 2 Numerous layers of precipitous mountains across the Matengo Highlands

region. The villages of the Matengo Highlands are divided into "old villages," which are distributed within the mountainous region at an elevation of greater than 1300 m, and "settlement villages," which are located along the hilly terrain below 1300 m, and to which residents from the old villages have immigrated. The SCSRD project, which was conducted from 1999 to 2004, targeted two villages, one from old villages and the other from settlement villages. Village K is an old village, in which people have

Fig. 3 *Ngolo* farm on the slope of the mountain

lived over a long period of time (JICA 1998). It is divided into seven sub-villages, and has a population of approximately 2400 people. The local residents implement an intensive conventional farming method called *ngolo* to cultivate the staple foods of maize and beans (Fig. 3), and they also grow coffee as a cash crop (Fig. 4). Rainfall starts in November or December, and terminates in April or May. The mean annual rainfall is higher than 1000 mm. The residents are mostly engaged in rainfed farming and rely solely on rainfall without any irrigation scheme.

As a result of fieldwork and interviews held with villagers when the SCSRD project was launched, the installation of a hydro-milling machine was proposed as a significant requirement in the village. Traditional maize grinding and processing are conducted exclusively by women, which requires them to engage in heavy labor, and includes carrying water and collecting firewood apart from maize grinding. In Tanzanian villages, maize is ground using diesel-powered mills, if the latter are available. As mills that do not use diesel or other fuels can help reduce costs, the decision of instigating the construction of a hydro-milling machine was taken in Village K. In 1999, six hydro-milling machines were already operational in the Mbinga District, which was supported by the Catholic church-affiliated Caritas, and thus, the local people were familiar with these devices. In addition, due to its steeply layered mountainous terrain, Village K had the perfect geographical and natural requirements for the utilization of hydropower.

An intake was constructed to receive water from the M River that runs through Village K, followed by a conduit to channel the water, which allowed the water to flow naturally along a gentle incline. A reservoir was also constructed at the end

Fig. 4 A woman harvesting coffee cherries

of a 330 m aqueduct to cascade water from its dropping point via a hydraulic pipe. Meanwhile, the energy of water surging downward was utilized to power a turbine in a milling house and operate a machine for grinding grains. During the initial stages, it was hoped that the villagers would use hydroelectric power generation. The SCSRD project's purpose, however, was not the development of infrastructure. As it was considered important for villagers to strengthen their capacity to plan and execute projects by building the hydro-milling machine and engaging in other associated initiatives, the plan for electric power generation was ruled out in favor of focusing exclusively on the construction of the hydro-milling machine. In addition to the villagers, numerous stakeholders, including SCSRD/JICA, the Mbinga District, and Caritas, were involved in its construction. These stakeholders continually engaged in negotiation and coordination, and as a result, the villagers established a committee, which was subsequently named the *Sengu* Committee. *Sengu* refers to the Matengo social tradition of communal dining, whereby extended families living within the same community would eat meals together while simultaneously discussing various issues. It was hoped that the spirit embodied in *Sengu*, whereby problems are solved through the process of engaging in dialogue would be put into action during the construction of the machine (Araki 2011).

The *Sengu* Committee took the responsibility of overseeing the project on the village's side. With the district government, SCSRD, Caritas, and the church providing assistance from the side-lines, all local villagers carried out tasks such as

Fig. 5 Women grinding maize by using the hydro-milling machine

building a 330 m canal, making bricks, and constructing a mill house to accommodate the milling machine. The hydro-milling machine was completed in May 2002 (Fig. 5). However, during the nearly 2-year period required for the completion of the hydro-mill, various actors were engaged in conflicts as they dealt with issues such as heavy rains, work-related delays, and unexpected incidents of trouble. For example, a conflict arose whereby SCSRD and the Mbinga District believed that the utilization and management of the hydro-milling machine should be overseen by the villagers following its completion, whereas Caritas and Village K's church believed that this should instead be undertaken by the church, similar to that of other milling machines in the Mbinga District. An agreement was reached through discussions held over an elongated period of time as well as through mediation by a neutral third party. Moreover, within Village K itself, a power struggle arose between the village government and the newly formed *Sengu* Committee, while confrontations occurred simultaneously among the villagers themselves regarding access to the machine. While some of these issues were easily resolved, others remained controversial. Through the process of resolving the conflict with the village government and villagers, the *Sengu* Committee worked to coordinate the interests of various actors while also proposing and carrying out several new initiatives (Araki 2011).

During the construction of the hydro-mill machine, the villagers became aware that environmental conservation would be the key to sustain it. Therefore, after the completion of the hydro-mill in 2002, the villagers created a nursery around the mill house under the supervision of the *Sengu* committee. The hydro-mill's construction, rehabilitation of the primary school and clinic, and the construction of a secondary school were initiated at the village-level, while farmers' groups were established at the grassroot level. Several farmer groups were formed in the vicinity, and all of them were engaged in valley bottom cultivation, bee-keeping, tree planting, micro-financing, and other activities. Thereafter, they committed to help themselves with water supply and micro-electric generation schemes. At that time, public services such as water and electricity from local governments to villages were slow, and several rural areas had no access to such services. Rather than waiting for government's assistance, Village K began to take steps towards supplying itself with water, and subsequently with electricity. In the following sections, I examine the self-help water supply initiatives in Sect. 3 and the micro-hydropower generation scheme in Sect. 4.

3 Self-help Water Supply Initiatives in Rural Tanzania

In Tanzania, the government put high priority on rural water supply in 1971. During the 1970s and in the following International Drinking Water Supply and Sanitation decade of 1980s, considerable efforts were made to improve the access to safe water by rapidly building water supply facilities. However, due to poor performance of those water schemes, the government introduced a new National Water Policy (NAWAPO) in 1991. In 2002, the Ministry of Water commenced the Rural Water Supply and Sanitations Project (RWSSP), which promoted decentralized, district-based implementation, and water supply service to rural areas managed by communities (Gine and Perez-Foguet 2008).

According to the Mbinga District Water and Irrigation Office, the water supply facilities in Ruvuma Region achieved approximately 60% coverage during the early 2010s, which was lower than the average coverage of the country's water supply. Mbinga District is among the six districts in Ruvuma Region, and the coverage rate of water supply facilities of Mbinga District was 43.8%, lower than that of Ruvuma Region. Although coverage of water supply facilities in Village K was extended to only 5.7% of the households (i.e., 151 out of 2651 people), these data did not include people's access to self-help water supply initiatives. In some villages, the peoples' self-help initiatives were observed. For example, Kurosaki (2010) investigated the water supply works initiated by the local people partly assisted by the local government and donor; they also made efforts to access water in various ways. Taking examples from two sub-villages in village K, this section investigates how people initiated self-help water supply schemes through negotiation with different actors, and whether any conflict or problem due to water supply, in addition to other reasons and conditions, were behind this movement.

3.1 Community-Based Water Supply Scheme Initiated by Church

Sub-village N is situated in the center of Village K, where the primary and secondary schools, dispensary, church, and offices are located. In 2000, the priest at Village K's Roman Catholic church initiated a water supply project, which was aimed to support primary health care and help alleviate women's responsibilities for carrying water from springs or rivers. He planned to support three sub-villages in constructing intakes and tanks. The conditions of support from the church were the receipt of donations from people as partial funding for the initiative, in addition to their labor and connection of pipelines to each household from the self-help base. Taking advantage of the village's mountainous location, a gravity-based water supply system was introduced. A water source was identified in the neighboring village located above Sub-village N, and the intake was constructed there, from which the long main pipeline was installed to the end of Sub-village N.

Initially, people did not actively participate in the initiative. However, several activities took place simultaneously, beginning with the construction of the hydro-mill machine, rehabilitation of the primary school and dispensary, construction of a new secondary school, and the farmers' group activities. People's capacity of achieving the requisite objectives and solving necessary problems developed through these activities, and in the late 2000s, people got highly committing to the water supply initiatives. From the main pipeline constructed by the church in the early 2000s, people installed branch pipelines to each household (Figs. 6 and 7).

Here, I shall examine sustainable use and management of the scheme. As approximately 100 households were involved in this scheme, they decided to form a water users' committee to oversee the water supply facilities. Five members were selected from different locations. The water users' committee has played important roles in coordinating and negotiating within and outside the sub-village.

First of all, the committee discussed and investigated the current situation regarding formal water rights. In Village K, water for domestic purposes was being obtained from natural sources such as springs and rivers for a long time, and crops such as maize, beans, and coffee were rainfed without any irrigation scheme. In this context, customary approaches to water management were undertaken without any experience of obtaining formal water rights. However, the National Water Policy 2002, which outlined the basic objectives for Tanzania's water sector, transformed its comprehensive plans for the development and management of water resources by designating the river basin as basic unit, rather than the overall state (Tanzania 2002). The Water Resources Management Act No. 11 and Water Supply and Sanitation Act No. 12 were enacted in 2009. According to the former Act, the use of surface water and groundwater requires a permit. Considering the changing situation, a discussion took place regarding the acquisition of permits, and an application was submitted in 2012 for obtaining permits to be used for water supply schemes. These were granted approximately nine months later, in July 2013. As Lein and Tagseth (2009) indicated that customary or traditional rights to water coexisted with the statutory water

Fig. 6 Villagers installing branch pipelines

licenses, the villagers in Village K had lived within the context of informal practices. However, as the formal water rights system came into place, they had to deal with a double standard of water use.

Second, the committee set rules for the annual clean-up of intake and tanks, and collected donations for repairs. During the early stages of the scheme, they noticed that not all residents had equal access to water; for example, those living above the intake level or far from the main pipeline faced difficulties in accessing water, and they were forced to identify alternative options. Therefore, they called up meetings, discussed possible ways to avoid expected conflicts, and implemented a rule whereby people facing problems could fetch water from their neighbors' facilities until they were able to access their own pipes. In the actual operation, N sub-villagers were divided into small groups containing several households, and each small group maintained their own surrounding environment and dealt with minor everyday problems. This small group as well as the water users' committee to supervise the whole region functioned well, and until 2019, the water supply facilities were being sustained without any major problems.

Fig. 7 A man burying the pipeline in the ground

3.2 Water Supply Scheme in Collaboration with the Private Coffee Buyer

Sub-village M was one of three sub-villages that expected to receive support from the priest of Village K's church. As explained above, a church located in Sub-village N supported the entire Sub-village N to build main tanks and pipe lines. However, Sub-village M was aware that it would take time, being the third sub-village in line to undergo water supply works supported by the church. In those days, women and girls were obliged to draw and carry water from springs or rivers and climb mountain slopes to bring heavy water-filled containers to their households several times each day. In addition, Sub-village M is located far from the newly constructed hydro-milling machine, and thus women had to walk a long distance, carrying heavy bags filled with crops of maize and wheat. Under this situation, not only women but also the men in Sub-village M felt the urgent necessity of implementing water supply facilities to reduce women's burden. They held meetings and considered alternative options without simply waiting for assistance from the church. Along with Sub-village N, taking advantage of geographical characteristics, they planned a gravity-based water supply scheme. JK became the leader of this water scheme and played an important role in its execution. As the neighboring Village U had abundant water resources, he approached his maternal uncle, who allowed the access to water on his land. He subsequently secured permission from the government of Village U, where the intake was located, as well as from the ward government office.

JK sought supporters besides the church for the water supply scheme. At that time, there were several private coffee buyers (PCBs) in Mbinga town, who competed with one another for greater access to more coffee. Amongst them, some were large companies, both foreign and local, while others were smaller, local enterprises. JK approached one local PCB, which had begun as a small-scale company and gradually developed. This PCB was sympathetic to the farmers' situations and problems and began lending money for agricultural inputs and food as well as for paying school fees, which the farmers could later repay in coffee. One of the staff members stated, "While visiting villages to collect coffee, we noticed the problems that the farmers faced. We believed that we could support them in several ways in addition to buying coffee. Subsequently, we decided to loan them amounts required for purchasing food during shortage periods, school expenses, agricultural inputs, and water supply, and later farmers would repay us in coffee or cash." JK negotiated with them and agreed to accept help for purchasing materials such as pipes and cement and for measuring various geographical constraints required to establish water supply systems by technicians, while paying back the expenses either in cash or coffee in the future, with the amount being calculated according to price rates fixed by the government. Some debts were not repaid in full; however, the PCB waited until the villagers could repay, rather than pressuring them. JK had initially planned to establish just a single water scheme to cover all households in Sub-village M. However, 12 households, which were located far from the intake, decided to implement their own water supply scheme because they could not access sufficient water, due to their locations. Instead of these 12 households, two U sub-villages around the intake joined the water supply scheme, and thus JK coordinated with approximately 80 households in total. In 2006, people started digging water lines from the intake for a distance of about 2–3 km and finished digging within a week (Araki 2011).

In terms of sustainability of the water supply facilities, similar to N sub-villagers, the residents of M sub-village also set up a water users' committee that conducted annual clean-ups of intakes and tanks, collected donations, and solved problems if any. For example, those living above the intake level faced difficulties in accessing water, and some pipes were cut and stolen. In addition, in the early stages, some households shared a single water source; however, with the increase in the number of households, pipeline extension was attempted that led to the water resources becoming depleted, and some households could not get water at all. To solve this problem, the residents planned to build a tank to store water. In contrast to that of Sub-village N, the water users' committee of Sub-village M was not so highly active, except JK who became the chairman. As years passed by, he grew older, and could not perform the work like before any more. However, no leader came forward to replace him. As a result, various plans such as building a tank and maintaining the main pipe lines were delayed, and once water stopped coming out of some waterpoints, no one was able to repair them. On the other hand, those 12 households, which did not join the scheme, took the necessary materials from town, and constructed their own water supply facilities and maintained them without any major problems until 2019.

3.3 Factors and Conditions Enhancing Water Supply Schemes

The villagers' self-help schemes aimed to establish water supply facilities spread rapidly and widely throughout Village K, and the same was observed regarding the construction of water supply facilities in other sub-villages. These facilities cut the need to fetch water from springs and rivers as water was being delivered directly to the households (Fig. 8), gardens, and coffee farms. In addition, as Strauch and Almedom (2011) determined direct links between water quality and diarrheal diseases, it was found that the water supply facilities reduced the occurrence of diarrhea and the related diseases in village K.

It is pertinent to ask the reason for the wide implementation of self-help water supply schemes in Village K. There are several possible reasons and conditions that led to this. First, Village K's geographical characteristics should be considered. The presence of slopes and springs along mountain ridges allowed for the easy allocation of water lines. Once the infrastructure was established, running costs became very low because water transportation was largely based on gravity. Second, indigenous knowledge on how to manage water and dig lines on mountain slopes, which people acquired as a result of *ngolo* farming and coffee production in sloped fields, was utilized to its full potential. Third, the villagers have long engaged in the production

Fig. 8 A woman using the water supply facility to wash clothes

of coffee as a cash crop, and almost all households pay for materials from the proceeds of coffee sales. The price of coffee was low during the late 1990s and early 2000s. However, from the mid-2000s, it increased, which provided people with the financial resources required to engage in water supply schemes. Fourth, the cooperation with actors such as church and the PCB played a key role. Finally, the villagers had empowered themselves through their commitment to various activities, and their enhanced capacity for planning, implementation, and managing projects drove the successful construction of the water supply facilities (Araki 2011).

4 Micro-hydroelectric Generation Project

4.1 Micro-hydroelectric Generation in Public and Private Spaces

Over the years, the villagers moved their attention to electricity and began seeking ways to extend micro-hydropower generation while maintaining the hydro-milling machine. Village K succeeded in securing financial support from a German NGO “Licht für Afrika”, which evaluated the long-term sustainable use and management of the hydro-milling machine supervised by the *Sengu* Committee. They commenced Phase I of a hydroelectric power network, and the public spaces such as the primary and secondary schools, church, and dispensary were electrified in 2010. A power generation infrastructure, which included a generator, switchboard, transformer, and other components, was installed in the mill house where the hydro-mill machine was placed (Figs. 9 and 10).

Thereafter the *Sengu* Committee launched Phase II, which involved electrification of the entire village. Hence, the scale of the project became far more significant, and to achieve the goal, substantial funding was required. The committee, with help from the German NGO, submitted an application to the Rural Energy Agency (REA) under the Energy Resource Ministry, and succeeded in securing financial support. Unlike the water supply schemes, whereby once the infrastructure were established, no water fees were levied and no expenses were required beyond nominal fees for repair and maintenance, the support from REA for the electrification project did not cover the cost of wiring required to bring electricity from the utility poles to houses. This also required a monthly electricity fee, and thereby increased the financial burden on individual households. Furthermore, beyond the initial investment of funding that had been received from the REA, each household was required to pay an initial fee of 150,000 Tsh as part of the village’s self-reliance efforts. Few households were able to pay the full fee, however, and several of them paid it in installments of 20,000 or 30,000 Tsh. The income for most households derives mainly from coffee sales, of which the vast majority was used to purchase fertilizers and pesticides, as well as for paying educational expenses. When coffee-based income was insufficient to cover expenses, they were paid with loans or through sale of their domestic animals such as

Fig. 9 Power generation infrastructure along with the milling machine

Fig. 10 Picture reflecting the connectivity of electrical wires from the mill house to the center of the village

Fig. 11 Secondary school where students are able to study until evening because of electrification

pigs (Araki 2016). Phase II did not merely involve an expansion of Phase I. In contrast to social entities such as schools (Fig. 11), dispensary, and church in the public sphere, it involved the electrification of the private houses (Fig. 12). This did not mean that all households received electricity equally; rather, some households could receive electricity while others could not, depending on the financial status of the individual households. By 2019, around one third of the villagers had already installed electricity in their households, and the others have continuously made efforts.

4.2 Environmental Conservation and Relationships Among the Villages Along the River Basin

With respect to the long-term utilization of water resources, it will be necessary for the villagers to adopt a perspective that transcends that of their own village by considering issues such as environmental conservation and the relationships with other villages in the region. Regarding the efforts that are underway for environmental conservation, this section examines the existing relationships with neighboring villages along the river basin and the government. The region where Village K is situated has a high population density, with land cultivated up to the mountain peaks. As steep inclines and intense rainstorms during rainy season cause continuous topsoil runoff,

Fig. 12 Private houses receiving electricity

the response to environmental degradation has become an important issue. Consequently, during the construction of the hydro-milling machine, there was a mutual understanding among all villages that to continuously operate the machine, it would be important to undertake schemes for environmental conservation and protection of the river basin.

When the machine was completed in May 2002, a nursery for raising seedlings and planting was established beside the mill house. This was run by the villagers, who distributed the seedlings to individuals and farmer groups for planting around the households and the river basin. As time progressed, however, peoples' enthusiasm for raising seedlings and planting began to dissipate. The issue of environmental conservation arose again at the beginning of the micro-hydropower generation project, and tree planting efforts were relaunched, primarily by the members of the *Sengu* Committee. In addition, the Mbinga District office provided support to the village for planting trees on Environment Day in 2011. However, these efforts required the cooperation of the surrounding villages as well. Consequently, when construction of the hydro-milling machine began in around 2000, efforts were made to visit other villages for the purpose of explaining the situation and seeking their understanding (Araki 2016). However, it was not easy for the *Sengu* Committee to connect different villages together in a cooperative way, whereby the external actors who addressed the issue of water resource utilization played the key role. In this case, a District Community Development officer visited the neighboring villages several times to explain the importance of tree planting for the preservation of environment in the river basin, and to facilitate coordination among the residents of different villages in the area. In 2018, a district coordinator with specialization in this field was newly appointed.

5 Conclusion

Local people in the Matengo Highlands of Tanzania took an initiative to harness water resources and created a common resource with a hydro-milling machine, a micro-hydroelectric generation, and water supply facilities, which have shown great potential. For example, the hydro-mill machine has helped reduced labor and household expenditures, the micro-hydropower generation system has enriched everyday life by providing electricity, and water supply facilities have opened up access to safe drinking water and reduced the need to draw water from rivers and springs. Despite of importance of such initiatives, however, sustainable use of the above-mentioned facilities was not easily achievable. This case study shows that local participation and the community-based organizations played significant roles in their sustainable use and management. At the very beginning of the construction of a hydro-milling machine, the *Sengu* Committee was formed, and this committee has remained devoted in supervising and managing the hydro-milling machine. The continuous usage and management of the machine was highly evaluated by a German NGO, which resulted in scaling up to the micro-hydroelectric generation project. In terms of water supply schemes, factors such as leadership and water users' association functioned as key factors during the period of construction, and have influenced sustainable use and management of the water supply facilities.

In view of the importance to access energy without jeopardizing climate stability, the generation of renewable energy, such as that derived from micro-hydroelectric system, is of considerable potential for rural Africa. Despite the promising advancements, however, such initiatives could also prompt resource-related conflicts and competitions. The case of the Matengo Highlands indicates that the continued use of water resources portends cooperative conflicts both within the village and among the villages along the river basin. In contrast to the social entities such as schools, dispensary, and church in the public sphere, the electrification of the private sphere did not mean that all households received electricity equally. Rather, some households could easily receive electricity while others would take time depending on their financial status. With respect to the long-term sustainable utilization of water resources, determining how cooperation and social relations can be built both within the village and with the villages along the river basin will be the key for future progress.

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Summary and Conclusions: Toward a Multidisciplinary Understanding of Tropical High Mountains in Africa

Kazuharu Mizuno and Yuya Otani

Abstract In this book, the actual situation of glacier shrinkage of Mount Kenya due to global warming, rainfall and snowfall as inputs to the water resources of Mount Kenya and the surrounding areas are studied and discussed. The study also elucidated the impact of changes in the water environment due to glacier shrinkage on the awareness of the people living at the foot of the mountain, which is an arid region, and the wisdom and measures of the local people to cope with such changes. The relationship between soil formation processes and environmental factors on the shrinking glacier front was analyzed. The advance of plant distribution with the retreat of Tyndall glacier was reviewed, and the growth process and distribution of large rosette plants were discussed. In addition, we discussed examples of water resource management in response to climate change in other parts of East Africa, and the factors that influence their sustainable use and management. In summary, the impact of glacier shrinkage on the natural environment and local communities, particularly on the surrounding ecosystem and water environment, is discussed and the challenges for future research on Mount Kenya are presented.

Keywords Glaciers · Climate change · Nature · Society · Water resource · High tropical mountains

This chapter provides a summary of the advancements in our understanding of the impact of global warming-induced glacier shrinkage in Mount Kenya on the natural environment and local society. Chapters 1–9 focus on the results of research conducted to understand environmental changes of the ecosystem and water environment in regions surrounding Mount Kenya. In addition, the probable future issues

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estimated from the respective empirical analyses are presented for the purpose of the development of research on Mount Kenya in the future.

To understand the natural and local society, it is first necessary to grasp the actual state of glacier shrinkage. To that end, an image analysis of Mount Kenya acquired by aerial photography was undertaken, and it was demonstrated that the number of glaciers, which stood at 17 in 1929, had decreased to only 10 in 2004 and 9 in 2016 (detailed in Chap. 1). In this study, the Pleiades image that was acquired on February 17, 2016 and the digital surface model (DSM) that was created based on aerial photography acquired from a Cessna aircraft on August 19, 2018 were compared, and the presence of eight glaciers was confirmed. On the other hand, the surficial changes in the terrain of the Northey Glacier, which was included in the glacier ledger in 2016, could not be confirmed. The mass of the eight glaciers was found to have reduced, and it is believed that the snowline altitude in the observation period was at a higher position than the eight glaciers. Among the eight glaciers, the mean mass balance of six glaciers in a 30-year period was found to be −36 m (water equivalent). In addition, it was demonstrated that the Darwin Glacier (0.00034 km^2), Heim Glacier (0.00039 km^2), and Diamond Glacier (0.00025 km^2) were considerably smaller. It was found that these glaciers do not have an extensive ice thickness, and the glacier flows due to internal deformation. It is believed that they are in a stage that occurs immediately before the disappearance when a glacier transitions to stagnant ice.

The issues associated with glacial shrinkage were also extracted. It was reported in a 2010 survey that the mean ice thickness of the Lewis Glacier, which has the largest glaciated area in Mount Kenya, was 18 m (maximum ice thickness 45 m). However, from 2015 onwards, the glacier started splitting in two, and almost all of the ice body in the downstream part had decreased by 2020. It is necessary to measure the thickness and flow of the Lewis Glacier (the ice body of the upstream part) and to investigate by a field survey whether or not it is a modern glacier. In addition, it is necessary to undertake continuous mass balance observations and investigate the changes in the mass balance of the eight glaciers as reflected by the data analysis of Cessna aerial photography acquired in 2019.

In Chap. 2, research on understanding the formative causes of the climatic environment that result in changes in the pattern of rainfall and snowfall has been detailed. Rainfall and snowfall are the main input of the water resources of Mount Kenya and the surrounding regions. The area around Mount Kenya has both a long rainy season and a short rainy season, and the rainfall peaks in April and November, respectively. Precipitation in these rainy seasons reaches the maximum in the foothills, whose center is the southeastern part of Mount Kenya and in the Aberdare Mountains; that region extends to the south during the long rainy season.

Based on the relationship between these rainy seasons and the intrusion of easterly wind into the interior of the mountain at altitudes where the pressure of 700 hPa prevails, we concluded that the intrusion from the Indian Ocean occurs along the ridges that extend eastward along the continental eastern shore from the southern hemisphere in the rainy season. It is manifested by the strengthening of the easterly wind, which is related to the depth of the low-pressure part of Congo basin in the short rainy season. The rainy seasons in areas around Mount Kenya are believed to be the result of not only the north–south movement of the intertropical convergence zone but also the intrusion of the easterly wind from the Indian Ocean inland, and it was suggested that this is related to the position of the east–west divergence that forms between equatorial troughs.

The course of the intrusion of the easterly wind, which is associated with the rainy season in Mount Kenya and the area surrounding it, differs in the long and short rainy seasons. Understanding the course of the development of ridges in the southern hemisphere and the lower pressure part of the Congo basin during these rainy seasons, which are believed to be the respective causes that promote the intrusion of the easterly wind, is an issue worth investigating in the future.

In Chaps. 1 and 2, we have discussed the climatic environment of Mount Kenya and the current state of glacier shrinkage. Accordingly, in Chap. 3, we have discussed a case study, which was implemented for clarifying the kind of impact the glacier shrinkage of Mount Kenya has on the water resources and water environment of the surrounding environment based on field observations, isotope ratio analysis, dating, interview surveys, etc. In the foothill areas (at approximately 2000 m) of Mount Kenya, precipitation is generally low; therefore, the current situation is that agricultural water and domestic water depend on the river water and spring water derived from Mount Kenya. As a result of the investigation and analysis, it was indicated that the average recharge altitude of the river water used by foothill inhabitants was 4650 m. On the other hand, the average altitude of the recharge area for spring water was 4718 m. It was also found that the meltwater in the glacier zone contributes to water resources in the foothills. In addition, based on dating, it was learned that the foothill spring water is yielded over a span of approximately 40–60 years from the time of recharge. It is anticipated that Mount Kenya's glaciers will disappear between the 2020s and 2030s; based on the current results, it was suggested that the future disappearance of the glaciers might have a significant impact on the water resources of the foothills.

In this study, we elucidated the impact of glacier disappearance on water resources based on a grasp of recharge elevation by isotope analysis. Understanding of the extent of the quantitative impact of glacial disappearance on water resources at the foothills in the future remains insufficient. Therefore, it is necessary to observe the input–output of the water resources of the entire basin including the glaciers and to construct and understand a water cycle model that incorporates such information as geological structure.

The relationship between glacier shrinkage and the surrounding water environment has been considered in Chaps. 1–3. Based on that, a study was conducted on the effects of glacier shrinkage in Mount Kenya during the past 40 years on the perspective and awareness of the inhabitants of the foothills, which is a dry region; this has been detailed in Chap. 4. The changes in glacier area were analyzed with satellite images (Landsat) acquired during 1976–2016 with ArcGIS and ENVI. Subsequently, inhabitants along the Naromoru River and Likii River were interviewed about the changes in the glaciers, changes in the direction of river flow, and the effects these changes have had on their lives.

As a result of the survey and analysis of the Landsat images, it was learned that the glacier of Mt. Kenya, which was approximately 1.86 km^2 in 1976, decreased to approximately 0.17 km^2 in 2016. The survey on the awareness of the foothill residents regarding glacier changes indicated that while the inhabitants were aware of the ongoing glacial shrinkage, there were some differences in such awareness in terms of gender, age, and education. Awareness about glacier shrinkage was affected more by a visual perspective, in particular, visual frequency, proximity to distant mountains, topography, meteorological conditions, and obstacles to vegetation. For areas farther from the mountains, the perspectives of the inhabitants did not coincide completely with the actual trends of glacier shrinkage.

However, the inhabitants were aware of the phenomenon of glacier shrinkage, and harbored concerns about water resources such as a decrease in the volume of river flow and an increase in the severity of water shortages. It was found that all inhabitants who were interviewed on this occasion were worried about the probabilistic occurrence of problems and conflicts in the future over the availability of water and the retreat of the glaciers. From the results of this survey, the author believes that the national and regional governments should have a standpoint about glacier shrinkage and water resource management in the future development actions in the said region. Accordingly, a natural resource management plan should be formulated.

In Chaps. 1–4, an empirical analysis was conducted to understand the relationships between glaciers, water environment, and the inhabitants' awareness. When it comes to the unique natural environments of Mount Kenya, it is also necessary to elucidate the impact of glacier shrinkage on those natural environments because they play a key role in not only enhancing the biodiversity but also attract tourism in the region. To this end, an investigation of the glaciers, soil, and vegetation was undertaken from a microscopic perspective in Chaps. 5–7.

In Chap. 5, we examined the relationship between soil formation processes and the environmental factors on the front areas of Tyndall Glacier on Mount Kenya, where the glacier environment has shrunk due to global warming from the Holocene. The glacier front area is one of those places where the soil formation processes can be traced by comparing those soil sections for which the time elapsed since the disappearance of glacier differs. By classifying the moraines that developed on the Tyndall Glacier's front area, seven rows of the Lewis era (Lewis I and II), Tyndall era (Tyndall I-IC), and Likii era III were distinguished. In addition, the age of the formation of each moraine was estimated. Moreover, an examination of the process of soil formation was conducted based on observation of the soil sections. It is likely that the soil layer is composed mostly of aeolian dust supplied from the surrounding bare land. The rate of formation of the soil layer was in the range of 0.03–5 mm/year. It was also found that there was a tendency for a greater soil formation rate during the initial stages of soil formation. It was confirmed that the formation rate during the initial stages of soil formation was larger in Mount Kenya compared to that in other regions; however, the long-term soil formation rate fell within the range of the other regions.

In this study, no direct chronology could be obtained for the moraines of the Tyndall era (Tyndall I-IC) and Likii era III. It is necessary to obtain the chronological data for each moraine, and to estimate the pedogenic rates more accurately. In addition, studying the changes of the mineralogical and chemical characteristics during the course of pedogenesis should be implemented in the future.

In Chap. 6, studies over a period of more than two decades about the advancements of plant distribution accompanying the retreat of Tyndall Glacier in Mount Kenya were considered and examined. Following the glacial retreat due to global warming, four kinds of pioneering plants were seen to have expanded the front line of the respective plant distribution in the upslope direction. In particular, in the case of *Senecio keniophytum*, which grows first in those places where a glacier has melted, the forefront of its distribution was found to have advanced at more or less the same rate as the rate of glacial retreat. In a permanent plot that was placed in contact with the glacier terminus in 1996, the number of individuals and the vegetation coverage rate of *Senecio keniophytum* increased significantly in 2011. Recently, the number of plant individuals and the vegetation coverage rate were found to be significantly increased in the vicinity of the glacier terminus where the glaciers disappeared; however, the rate of such enhancement declined after ≥10 years since glacier disappearance. The growth of *Helichrysum citrispinum*, which was not observed in the area around the glacier terminus to date, was confirmed at the start of 2009; however, the rise of the temperature might have been directly related to the expansion of its distribution. After the passage of several years since the glacier had disappeared, weathering of the gravel progressed and the soil particles became finer, and the humus of the pioneer species accumulated and continued to develop into a nutrient-rich soil. The development of the soil is believed to have been affected by the number of years since it was released from the glacier and the extent of colonization of the plants accompanying the movement of surficial materials. The relationship between the height and age of *Senecio keniodendron*, which is a large woody rosette plant, was unknown to date; however, radiocarbon dating clarified that the growth rates of the two individuals considered were 3 cm/year and 4.5 cm/year, respectively.

It is believed that the rise in temperature is directly related to the expansion in the distribution of *Helichrysum citrispinum*. However, to further clarify that relationship, it is necessary to collect observation data continuously in the future as well, and to analyze the impact of temperature and other environmental factors on vegetation distribution. In addition, it is necessary to collect more data and to clarify the relationships between the height and age of *Senecio keniodendron*.

In Chap. 7, an investigation was conducted on the growth process and distribution of large rosette plants, which are the characteristic plants of Africa's tropical alpine regions. *Senecio keniodendron* and *Lobelia telekii*, two large rosette plants, are distributed in the glacier retreat region that extends to the front area of Mount Kenya's Tyndall Glacier. These plants are key elements that create an attractive landscape for the climbers and tourists, who visit Mount Kenya. Their preservation is sought based on the fact that the mechanism to maintain the vegetation landscape in Africa's tropical alpine regions that are exposed to climate change has been clarified. Field surveys were conducted on these two species of plants in 2016 and 2018, and the changes in that period were recorded. The results of the survey indicated that the death rate and the rate of the appearance of new seedlings were similar for the two species, and the number of individuals was stable in the survey zone. In addition, the spread and growth of the surviving individuals were confirmed during the 2-year period. In addition, when the height of the rosette leaf of *Lobelia telekii* exceeded 20 cm in 2016, the tendency for inflorescences to be formed in 2018 became clearer. It was observed that there is a tendency for the large rosette plants to be distributed in a concentrated manner in places with abundant solar radiation, and it is believed that the amount of solar radiation is related to the initial colonization of larger rosette plants.

In the future, it is necessary to continue to examine the causes of the distribution of large rosette plants by conducting longer-term surveys. In addition, the empirical demonstration should be provided for the relationships between various environmental causes that are directly involved in the plant's distribution, such as soil moisture, ground temperature, snowmelt, and sunlight.

In Chaps. 1–7, Mount Kenya's glaciers, climate and water environment, and the awareness among inhabitants about these ongoing changes are discussed. In addition, the environmental changes peculiar to the region such as the changes in plants and soil, have been clarified. Accordingly, this perspective was broadened in Chaps. 8–9, and an effort was made to grasp the actual situation regarding the kind of efforts the regional inhabitants are undertaking for confronting the changes of the water under climate change.

In Chap. 8, the wisdom and awareness of the inhabitants from the foothill region of Mount Kenya were evaluated based on their responses to queries regarding the glacier shrinkage-induced changes in water resources during a field survey. During the past 50 years, the farmers living at the foot of Mount Kenya have experienced a variety of changes in the water environment. Along with the rapid retreat of glaciers near the peak, the temperature at the peak increased and the snow that fell in the alpine region during rainy seasons melted before the start of dry season. As a result, when a river that flows to the foothills experienced the onset of the dry season, the volume of water decreased abruptly. In addition, the rainfall also became irregular. The precipitation in the major rainy season from March to May decreased, and the amount of rainfall was higher compared to that in the small rainy season from November to December. In addition to such changes in the water environment, the changes in land use and population growth in the foothills also had an impact on agriculture, which caused the water shortage problem to become more severe. The use of irrigation channels that are directly connected to the river was prohibited in order to ensure a water source that could be used continuously and to avoid disputes over water among the farmers. Instead, in the upper and middle regions of the foothills, a water management project was promoted, in which water was drawn from the river with pipelines and distributed to the users. In addition, the farmers themselves also began to address the problem of water shortages using a variety of strategies. For example, they divided the land finely and planted various crops according to the season, selected crop types suited to dryness, undertook crop rotation and mixed cultivation and created ponds for irrigating agricultural lands. However, the lower region of the foothills is most vulnerable to water shortages, and this remains a potential cause of water disputes.

The following three issues can be listed as the research topics of Chap. 8. First, in the upper and middle regions of the foothills, those farmers that did not participate in the water management project accounted for 40% of the entire population, and the actual state of water usage in irrigation by the said inhabitants has not been clarified. To achieve sustainable use of water in the foothill regions, a survey targeting the said inhabitants must be conducted. Second, to avoid potential water disputes, it is necessary to clarify how and what kind of inhabitants' organizations are involved in the management and use of water in the lower foothills, where there are several new settlers. Third, to understand the sustainability and transformations of the livelihoods in the foothills, it is necessary to investigate how the mountain climbing guides and porters, who are deeply involved with Mount Kenya, are affected by the changes in the environment.

In Chap. 9, we provided an example of water resource management associated with climate changes in other regions of East Africa, i.e., the Matengo Highlands of Tanzania, where people are using water resources. We discussed the process of developing facilities for common usages, such as hydro-milling machines, micro-hydroelectric power generation plants, and water supply facilities, from the standpoint of sustainable use and management. The facilities of using water resources in rural African have great potential. For example, hydro-milling machines alleviate the workload of women and reduce household expenditures; micro-hydroelectric generation systems improve the quality of daily life by providing electricity; and water supply facilities provide safe drinking water. In addition, women are freed from the labor of drawing water from rivers and springs. Despite these advantages, it is not easy to sustain and manage facilities that use water resources continuously. As a result of the survey, it became clear that local participation and community-based organizations play a key role in the establishment of facilities and the sustained use and management thereof, and this serves as the motive force that is connected to micro-hydroelectric power generation. Similarly, in water supply schemes, it was found that leadership and the water users' association are indispensable factors in the diffusion of water supply facilities in the village and the sustained operation and management thereof. Energy usage that does not adversely affect climate fluctuations is an urgent issue; however, the use of renewable energy such as micro-hydroelectric power generation holds great potential in rural Africa. While there are such positive aspects, it also harbors the seeds of conflict in relationships within villages and between the villages of the region surrounding the area where water resources are shared. When it comes to long-term sustainable use, the issue is how to continue to build harmonious social relations.

In the future, it is necessary to focus on the changes in the environment and to investigate the long-term usage and management of the facilities that use water resources. In addition, if conflicts or disputes occur, then we should understand the kind of relationships that the villagers share amongst themselves, with inhabitants of other villages along the river basin, and with external agencies, such as the government and NGOs associated with the sustained use and management of water resources. We need to continue to study the causes of the above-mentioned factors, and determine their solutions.

From Chaps. 1 to 9, the relationships between the actual state of the climate and glacier shrinkage surrounding Mount Kenya, the surrounding vegetation, soil, and water environment, and the lives of the foothill region inhabitants have been discussed. It cannot be denied that there is a gap between the fields of natural science (such as parameters associated with snow, ice, and moisture) and human sciences (such as sociology and anthropology) in conventional research on African tropical alpine regions. Given such circumstances, this book, which has cross-sectionally studied the relationship between glacier shrinkage and the regional inhabitants confronting it, might be valuable in the contemporary age, when the assurance of a sustainable relationship between nature and mankind is critical.