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

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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 $\geq$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.