Investigating glacial change in East Africa

Environmental Science Undergraduate Dissertation

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Contents

1.0 Abstract

Climate change is the leading human and environmental crisis of the 21st century causing shifts in temperature and weather patterns which are having alarming effects on the environment. Climate change is triggering glacial shrinkage globally which could create severe implications for the human population. This study focused on the affect climate change has on East Africa's last remaining tropical glaciers found on Kilimanjaro, Mount Kenya, and the Rwenzori Mountains (Mount Stanley, Speke, and Baker). A remote sensing approach was implemented using Landsat images to document glacial change on all mountain tops. Four images were used in each study site ranging from 1986 to 2022 in a decadal format, with temperature data derived from Jomo Kenyatta weather station situated in Kenya. The analysis found that 81.2% of the glaciated area had disappeared between 1986 and 2022, with a 1.2°C temperature increase in the same period. Mount Kenya experienced the largest glacial loss of 88.8% followed by the Rwenzori at 85.8% and 76.9% at Kilimanjaro with most of the glacial retreat occurring between 2009 and 2022. The literature suggested that glacial retreat in Eastern Africa is predominantly due to warming air temperatures, which correlates with the data collected but other local factors such as changes in land use and bush fires do affect glacial survival. Glacial extinction may create extreme issues for local communities such as water scarcity and tourism as well as have a negative effect on ecosystems that rely on glacial meltwater. If the current trends of temperature rise continue with the unpredictability of weather patterns, these mountain glaciers will likely disappear within the next couple of decades.

2.0 Introduction

2.1 Background

Glaciers cover roughly 10% of the land area in the world storing around 69% of the fresh water (NSIDC, 2020). Glaciers can be defined as, "any large mass of perennial ice that originates on land by the recrystallization of snow or other forms of solid precipitation and that shows evidence of past or present flow" (Meier, 2021, p. 1). Meier (2021) continues to classify glaciers into three groups: ice sheets/caps, ice shelves and alpine glaciers. Although most of the world's glaciers reside in polar regions, less than 0.1% are located in tropical countries (U.S Geological Survey, n.d). Due to these tropical countries having low latitudes, glaciers can only survive in high altitude areas above the snowline. Tropical countries experience periods of drought with warm temperatures which can make glaciers like these a vital source of water during the dry seasons for local communities shadowing the mountain and a great indicator of climate change as they are mainly controlled by temperature and precipitation (Jackson et.al, 2020).

The global air temperature has risen around 1.1°C since 1880 with 9 of the 10 hottest years ever recorded arising in the past decade (NASA earth observatory, n.d). Because tropical glaciers are highly sensitive to climatic variations, with the warming air temperature, they will eventually completely melt. These glaciers are important freshwater reservoirs, supplying water to communities during the dry season where the level of precipitation is significantly less. They supply water to local rivers and lakes, however once the glacier has fully disappeared this supply will be cut (Seehaus. et.al, 2019). This may create water scarcity issues for countries which will affect agriculture activities, fresh drinking water for rural and urban populations and tourist activities (Urama & Ozor, 2010). This project will be focusing on the tropical alpine glaciers found on Mount Kenya, Kilimanjaro, and the Rwenzori Mountains in Africa. These glaciers are found at high altitudes and purely restricted by the surrounding topography.

2.2 Study Area

This study focuses on tropical glaciers found in Tanzania, Kenya and in Uganda situated in East Africa. These three countries contain the only remaining glaciers found in Africa that are situated on the tallest equatorial mountains on the continent (Figure 1).

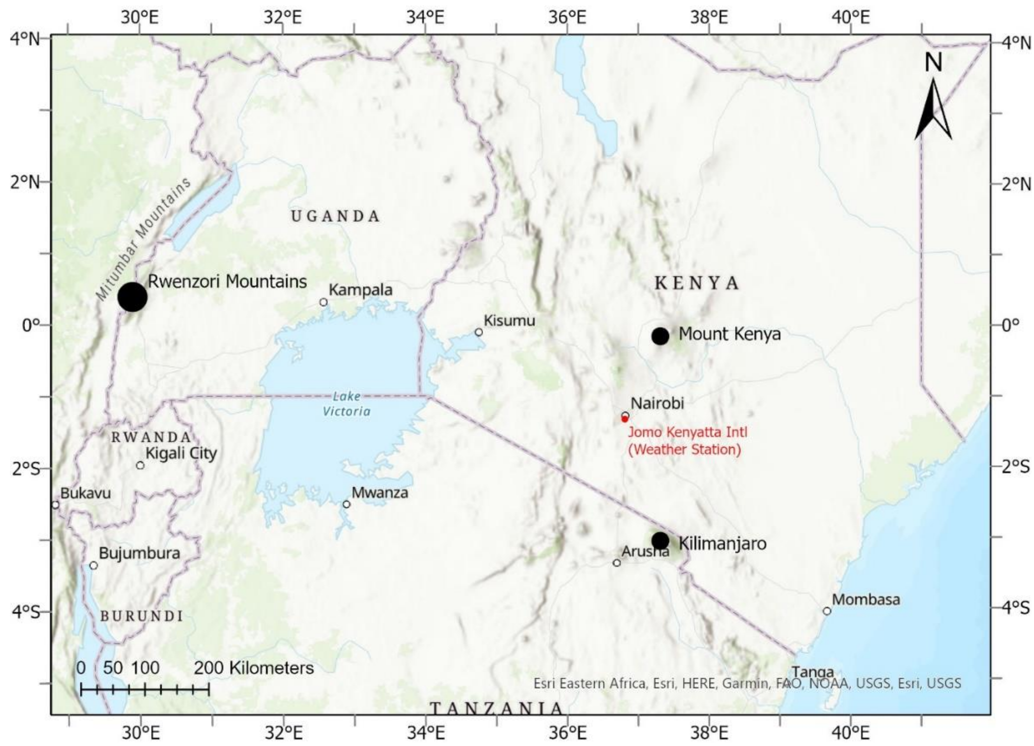


Figure 1: Topographic map of Eastern Africa, with the three mountains that contain the last remaining glaciers. The weather station situated at Jomo Kenyatta International Airport highlighted in red.

Mount Kilimanjaro is the first study area. It is the tallest mountain in Africa reaching a height of 5894m, situated 3°04 South, 37°21 East, in Tanzania. This dormant stratovolcano has three peaks, Shira, Mawenzi and Kibo, in which Kibo (5893m) is the only one of the three to have glaciers (Kaser et.al, 2004). The exploration of Kilimanjaro began in 1887 however the first photograph of the glaciers was taken in 1912, when compared to recent images the total area appears to have been decreasing since this time. Porter (2001) predicts the glacial cover on the mountain is <5km^2 however Kaser et.al, (2004) states that the coverage is even less than this at 2.6km^2 which was based on satellite imagines taken in the 2000s.

Mount Kenya is the second site. This extinct volcano is 5194m in height and situated 0.15° South, 37.31° East. It is the second highest peak in Africa, consisting of two tall, steep peaks which have hanging and valley receding glaciers attached to them. The first expeditions up Mt Kenya were in the late 19th and early 20th century from which sketches and photographs of the glaciers were took. Historically, Mt. Kenya contained 15 glaciers but in recent years it has roughly 10 (Spink, 1949**).** Porter, (2001) reports that these receding glaciers only cover less than 1km^2, however in recent years the expected area is to cover less.

Finally, the Rwenzori mountains are situated in Western Uganda, 0.39° North, 29.87° East. The tallest of these non-volcanic peaks sit at 5109m, making it the third highest peak in Africa. The glaciers in this mountain range are larger compared to Mt. Kenya and Kilimanjaro due to snowfall and cover from clouds. These mountains are rarely examined due to their poor accessibility and poor image quality. This mountain range is a vital source to the river Nile, which supplies water throughout the continent (UNESCO, n.d). The glaciers at this site are found on three peaks situated on Mount Stanley, Baker and Speke in which Mount Stanley has the most glacial coverage.

2.3 Climate

To understand the dynamics of Africa’s glaciers, getting a good overview of the climate can make it possible to create links between glacial retreat and climate change. The climate in Uganda, Tanzania and some areas in Kenya is a tropical savanna. Kenya consists of hot desserts in the North of the country with mostly arid steppe hot areas elsewhere which are also present in Tanzania. These countries experience high temperatures with little variation between the seasons compared to the highlands that have considerably lower temperatures.

East Africa is influenced by various climate systems such as monsoonal systems, coastal influences, Rif Valley lakes, and several convergence zones. Its seasons follow a bimodal rainfall regime. March to May (MAM) is the long-wet season followed by a long dry season from June to September (JJAS). The short-wet season is from October to December (OND) and finally a moderately dry season is in January and February (JF) (Molg et.al, 2009). Most of East Africa’s precipitation originates from the Indian Ocean which is driven by the Indian Ocean Dipole (IOD), as a result the weather can vary every wet season (Blau & Ha, 2020). The Indian Ocean Dipole is the difference in temperature at each side of the Indian ocean. A positive dipole is when the west coast of the Indian ocean is warm and causes severe flooding in eastern Africa. A negative Dipole causes severe drought in Africa due to the west coast of the Indian ocean being cold and a neutral Dipole is when ocean temperatures are the same across the ocean (Uchoa, 2019).

Lake shore processes can also dictate rain fall. Lake Victoria is the largest freshwater lake in Africa, laying in Tanzania, Uganda, and Kenya (Britannica, 2021). Due to its area, it creates a mesoscale circulation system which produces large rainfall, with rain falling in the west at night and in the east mid-afternoon. This can also affect the precipitation level in the highlands in Kenya. The sea breeze interacts with the monsoon flow resulting in rainfall that affects the rainfall regime further inland (Nicholson, 2017). Several studies reported a decrease in precipitation since 1999 (Ayugi et.al, 2018, 2022, Mumo et.al, 2019, Ngoma et.al, 2021), however the prediction for future rainfall intensities remains unclear. Some studies suggest that the region will experience more frequent, very extreme wet days before the end of the 21st century however this is not known for sure due to the unpredictability of East Africa’s weather (USAID, 2020 & Ayugi et.al, 2022).

2.4 Aims and Objectives

Aim

To investigate the relationship between climate change and glacial retreat on Mount Kenya, Kilimanjaro and the Rwenzori mountains, and the complications this has on the environment and local communities. The hypothesis for this project is that due to climate change, all the glaciers in the East African Mountain ranges have retreated.

Objectives

- Download Landsat data dating from the 1980s to 2022.
- Use a remote GIS sensing approach to map the glacial boundaries of the three study areas and compare patterns of change over time.
- Study historical weather records to determine decadal climate trends in temperature
- Use the climate data with the mapped glacier outlines to determine the impacts of climate change on the region’s glaciers

3.0 Methodology

3.1 Data Collection

Most glaciers are found in remote mountain regions which makes them hard to access and reliably map (Ewertowski & Rzeszewski, 2007). Although, they have been manually measured for 100s of years, it is only in recent times that with the use of satellite images, glacial behaviour is measured using GIS systems. Landsat one was the first launched earth observing satellite which was only used to monitor the earths landmasses. Since Landsat ones launch in 1972, other satellites like it have since been launched such as Landsat 9, it launched in 2021 to join Landsat 8 (Table 1). Both satellites have an ‘improved calibration, signal to noise characteristics, higher 12-bit radiometric resolution, and spectrally narrower wavebands’ (Roy et.al, 2016, pp. 58), compared to previous Landsat satellites. This makes them more useful for monitoring environmental change on earth (Nasa Landsat Science, n.d).

Table 1: Characteristics of Landsat Sensors (STARS Project, n.d)
*Did not achieve orbit. $^{\beta}$Addition of a coastal and a cirrus band

Satellite	Sensor	Launch Year	No. of MS bands [nominal resolution]	Panchromatic resolution (nominal) (m)	Thermal bands [resolution]	Altitude (km)
Landsat 1	MSS/RBV	1972	4 [80 m]	-	-	920
Landsat 2	MSS/RBV	1975	4 [80 m]	-	-	920
Landsat 3	MSS/RBV	1978	4 [80 m]	-	-	920
Landsat 4	MSS/TM	1982	6 [30 m]	-	1 [120 m]	705
Landsat 5	MSS/TM	1984	6 [30 m]	-	1 [120 m]	705
Landsat 6*	ETM+	1993	-	-	-	-
Landsat 7	ETM+	1999	6 [30 m]	1 [15 m]	1 [60 m]	705
Landsat 8	OLI/TIRS	2013	8^{β} [30 m]	1 [15 m]	2 [100 m]	705

To identify the glacial boundaries in three areas in East Africa, this study used Landsat images within a 36-year period which begun in 1986. These images were accessed through the United States Geological Survey (USGS) who store Landsat data and provide an online system called Earth Explorer, which was used to download Landsat imagery of the glaciers on Kilimanjaro, Mount Kenya, and Rwenzori. Before image download could begin, sufficient literature on the study area was read thoroughly to identify what times of the year would be best to source the images.

Nie et.al, (2017) suggests that by using images from similar seasons will reduce the effect of season variability and gathering images that has the sun directly overhead will prevent shadowing. Because of this, images were sourced at the end of the dry season/ ablation season, in Autumn/ September and January/February to minimize the coverage of snow and cloud**.** When finding images, Loibl et.al, (2014) methods were implemented in sourcing images that have minimal cloud cover, no snow cover and found in late summer or after a dry season which ensures that the images obtained were clear and showed the outline of the glaciers.

A filter of less than 10% cloud cover was added to aid in finding the right images. The images were selected from various times, in a decadal form, and downloaded as GeoTiff data to be unzipped (Table 2). The 2012 image of the Rwenzori mountains contains scan error lines which is the result of the Scan line Corrector failing in 2003 (USGS, n.d). But having said that the Landsat 7 image contains the scan error lines outside of the area of study for this image, which did not directly affect the mapping of glacier outlines.

Table 2: The Satellite number and year each image was downloaded covering Kilimanjaro, Mount Kenya, and the Rwenzori Mountains.

Kilimanjaro		**Mount Kenya**		**Rwenzori Mountains**	
Satellite	Year	Satellite	Year	Satellite	Year
1-5 MSS	1986	1-5 MSS	1987	4-5 TM	1987
4-5 TM	1996	7 ETM+	2000	7 ETM+	2012
7 ETM+	2009	7 ETM+	2009	8 OLI/TIRS	2017
8 OLI/TIRS	2019	8 OLI/TIRS	2022		

Each image contains 7-8 colour multispectral bands. These were stacked to create a multispectral image on Erdas Imagine 16.6.0 with all colour composite bands layered in the image. The Visible Near Infra-Red (VNIR) band reflects snow and ice which makes it easier to view the glacial outlines. As Racoviteanu et.al (2009) explains that by using false colour combinations, it makes the glaciers visible to the surrounding environment which will be shown as light blue/ green. Global Land Ice Measurements from space (GLIMs) and Google Earth helped identify where the glaciers were situated which was difficult to establish through viewing 2D images. GLIMs is an initiative which monitors the worlds glaciers using satellites imagery (Earth Data, n.d). Due to Mount Kenya's glaciers having a small area, the Landsat images were highly pixelated which made it hard to identify what areas of the mountain was glacial ice or snow. GLIMS data from 2015 was used to aid mapping glacial boundaries. The data in this project will be used to update the GLIMs database to more recent imagery of mapped glacial boundaries in East Africa once this project has ceased.

3.2 Data Processing

All images downloaded spanned over a large area however, only a small section of the image was required. Any cloud in the images reflect a large amount of light making the glacial ice darker and harder to view. Because of this all images were sub-set using the sub-set and chip tool which zooms into the study area and crops the rest of the image causing more contrast on the screen due to the smaller amount of data displayed (Figure 2A and 2B).

Bands, 4, 3 & 1 (infra-red) were used to identify the glacial outline, and for Landsat 8 band 5, 4 & 2 were used. To begin the mapping process, vector layers were created on Erdas and labelled the year of their corresponding glacial image. In the vector layer, using the draw tool, polygons were created mapping the glacier outlines. This was repeated for every glacier, each year, in all three study sites. The vector layers were made transparent, and every layer was given a different outline colour to distinguish the different glacier sizes throughout the years (Figure 2C and 2D). The Landsat images and Vector layers were then added to ArcGIS Pro 2.7.0.

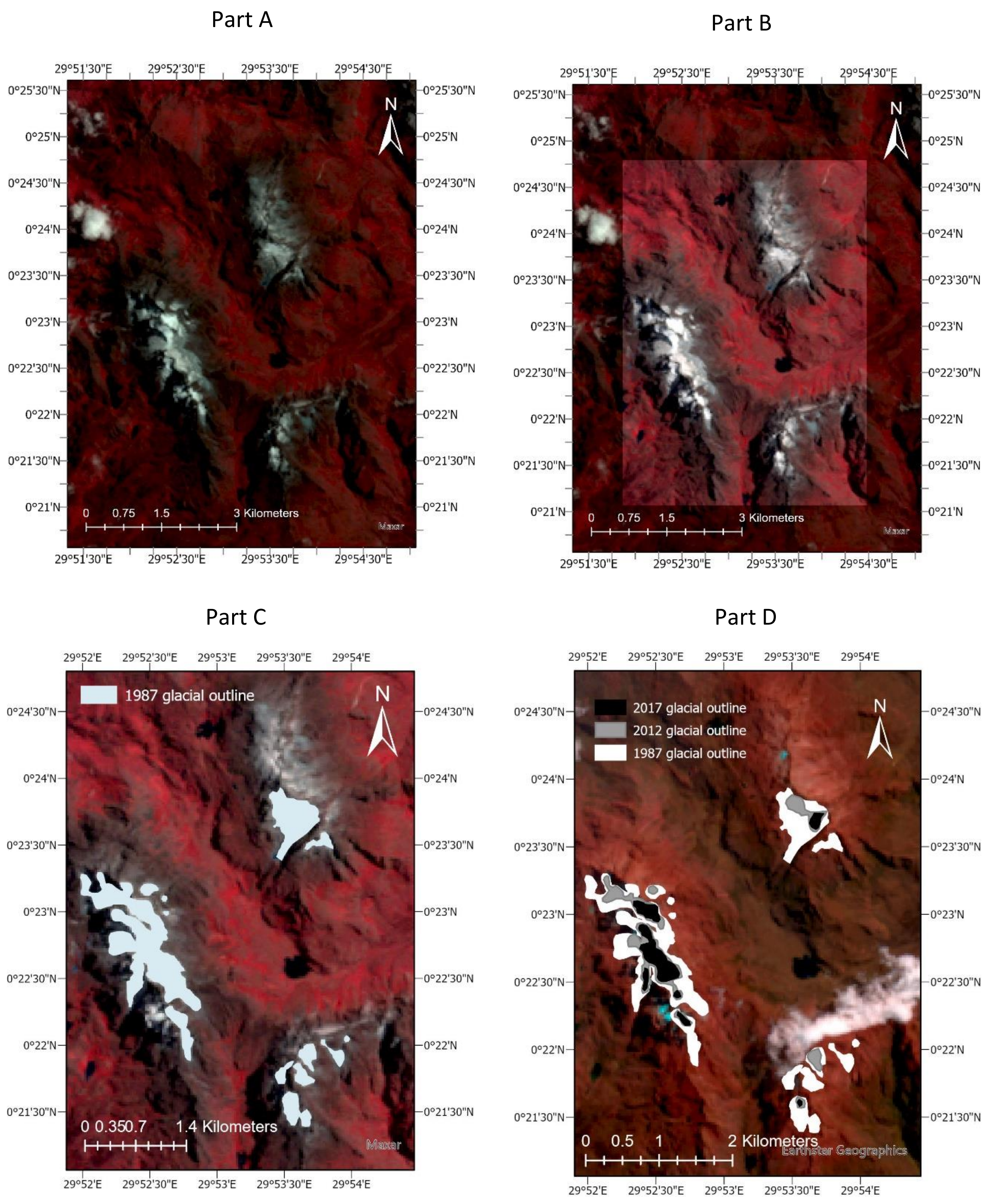


Figure 2: Part A) A 1987 Landsat 4-5 image of the Rwenzori Mountains prior to processing. Part B) A 1987 sub-set Landsat image of the Rwenzori Mountains. Part C) The digitised 1987 glacial outline displayed on the 1987 sub-set Landsat image of the Rwenzori Mountains. Part D) All glacier outlines from 1987, 2012 and 2017 displayed on the most recent 2017 sub-set Landsat 8 image of the Rwenzori mountains.

3.3 Quantifying Change

Initially, it was easy to point out that the glaciers have been receding by turning on all shapefile (vector) layers to display the glacial boundaries for each year. Maps were made displaying the shapefiles and the newest Landsat image as the background. Using the calculate geometry tool, the area for each glacial boundary was calculated. The Geodesic Area was selected due to its higher accuracy using an area unit of Km^2 (ESRI, n.d). The areas for every glacier in each shapefile was calculated. Due to the high snow cover and the difficulty of distinguishing between each alpine glacier, for the Rwenzori mountains in particular, all ice cover was mapped as one glacier. In recent years as the ice began to melt, individual glaciers became easier to find. When calculating the percentage of change, all individual glacial areas were subtracted from the whole ice cover mapped, which were then tabulated.

Finally, temperature data between 1957-2021, was found from a local weather station situated in Jomo Kenyatta Intl airport in Kenya. Using Microsoft 365 Excel a line graph was created with a linear line inserted to display the general data trend. Temperature change is a product of climate change, which can be defined as the 'long-term shift in temperature and weather patterns', (United Nations, n.d). After assessing climate data and glacial behaviour, the link between climate change influencing glacial retreat was generated.

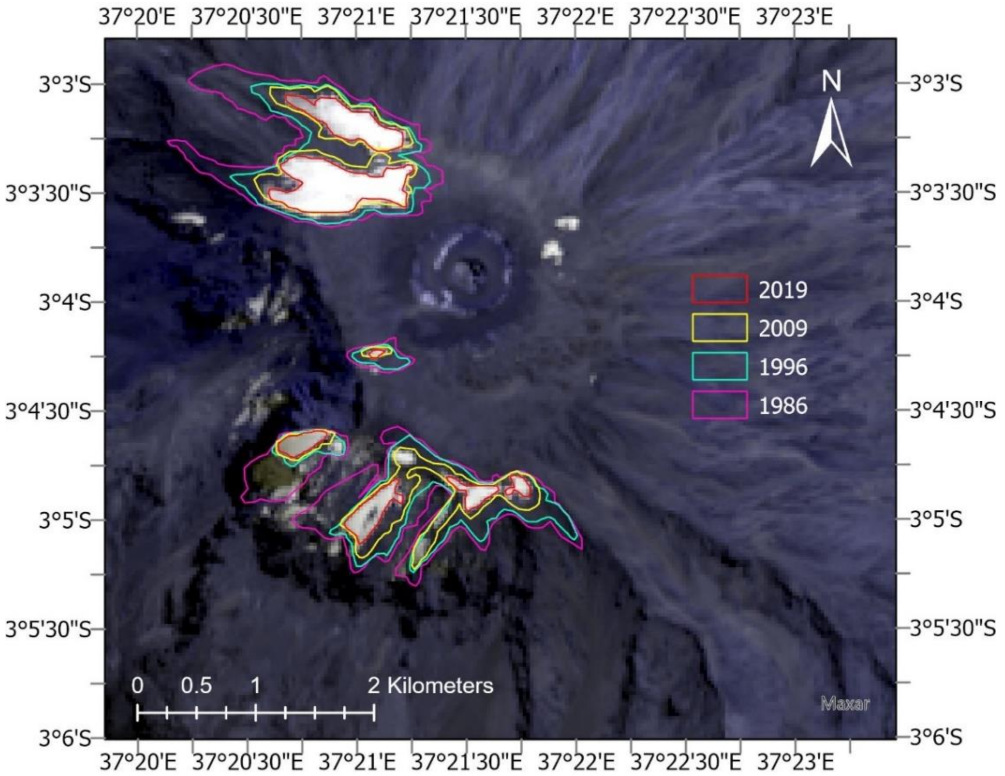
4.0 Results

Kilimanjaro and Mount Kenya contained some overlap of glaciers due to having no distinct glacial boundary between adjacent glaciers. Because of this they were mapped as one glaciated system. In the Rwenzori mountains, each glacier system for each mountain top was took as a total glaciated area. All glaciated areas mapped showed a recession in every decade, with some glaciers completely disappearing. It was assumed that the glaciers with the larger areas will have more glacial ice compared to smaller glaciers.

4.1 Mount Kilimanjaro

Mapping in Kilimanjaro confirmed that all glaciers here are receding shown in Figure 3A. The total area of the glacier retreat from 1986 to 2019 is 2.6Km^2 (Table 3). Every glacier showed evidence of continuous retreat with the overall fastest retreat happening between 1986 and 1996 with a total loss of 1.1Km^2. Figure 3B displays the area change of each glacier situated on Kilimanjaro. The glacial system that lost the most glacial ice was Heim-Kersten-Decken-Rebman (Southern Icefield) which retreated at the fastest rate between 2009 and 2019, however this was to be expected due to its size. The Furtwangler is a small glacier measuring at 0.094Km^2 in 1986 although, 93.6% of its glacial ice has melted leaving it with an area of 0.006Km^2 in 2019, so it can be assumed that this glacier has been melting faster than the Southern Icefield.

Part A



Part B

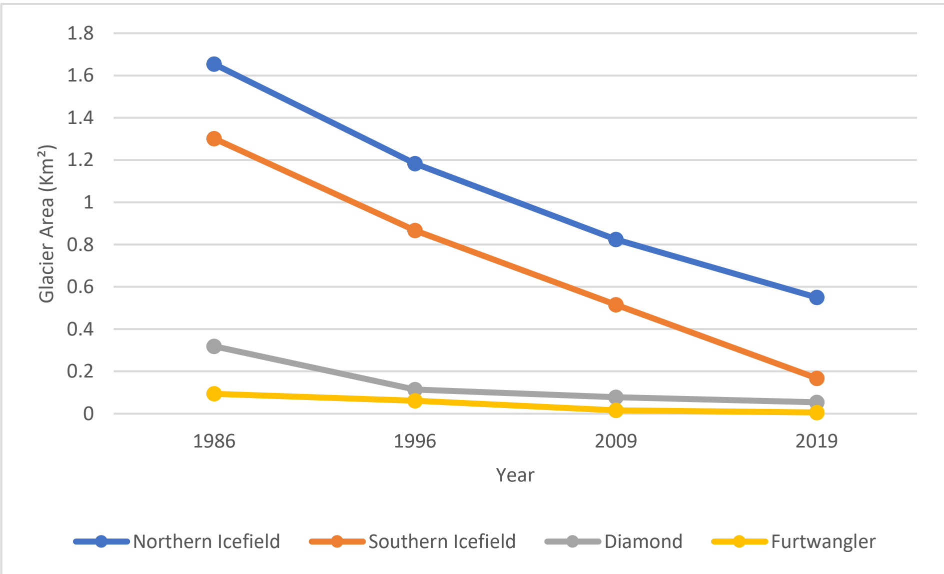
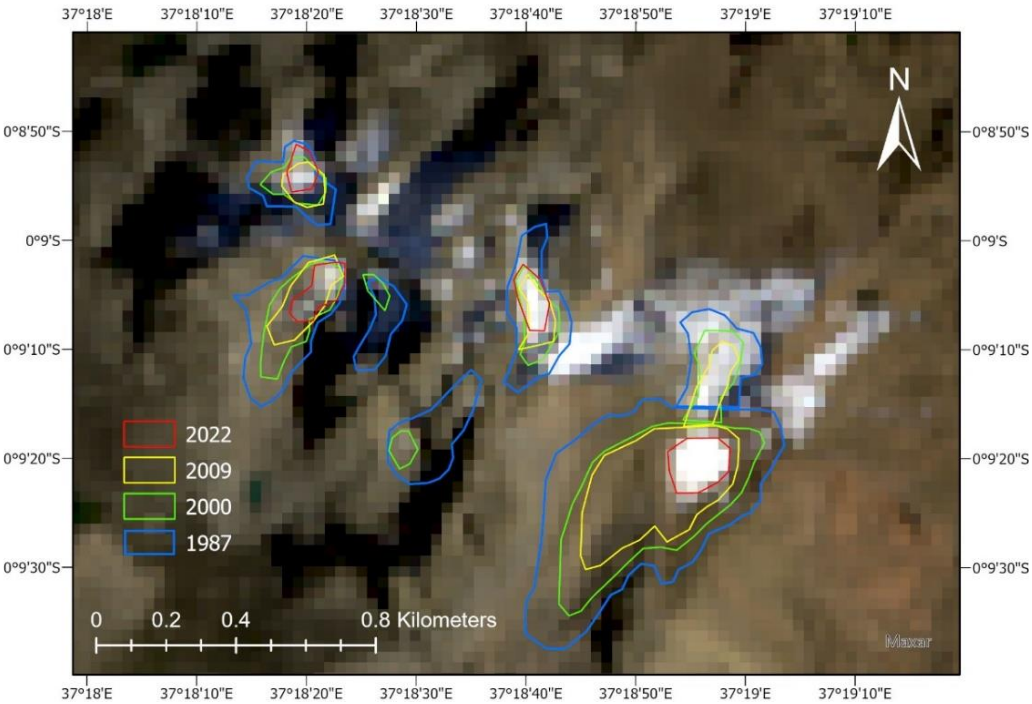


Figure 3: Part A) A 2019 Landsat image, using natural colour of Kilimanjaro displaying the various glacier outlines for each decadal year starting in 1986 to 2019. Part B) The total glaciated area every decadal year in Km² on Kilimanjaro.

4.2 Mount Kenya

Mapping in Mount Kenya shows that all glaciers on this mountain have retreated (Figure 4A). From 1987 to 2022 the total glacial retreat was 0.505Km², which is an 89.9% difference in the whole glaciated area (Table 3). Like Kilimanjaro, the fastest time of glacial retreat was between 2009 and 2022. Figure 4B displays the glacier areas throughout each decadal year. It is found that the Lewis glacier lost the most glacial ice (0.272Km²) and the fastest rate of melting was between 1987 and 2000, again this was to be expected due to its size compared to the remaining glaciers. The Tyndall glacier had an area of 0.071Km² in 1987, however since then 78.9% of its ice has melted resulting in it only having an area of 0.015Km². The GLIMs data was used to aid the mapping (Figure 5) which displayed the glacier boundaries mapped in 2015. The Darwin and Forel glacier have only been mapped in 1987 and 2000, whether these glacial systems have completely melted or shadowed by the high cliffs will need to be discussed. 2022 image of Mount Kenya contained more snow cover compared to other images. The Gregory glacier was not mapped for 2022 due to no clear glaciated boundary between the Lewis Glacier and due to the large pixilation, it was difficult to identify whether it is snow cover or glacier ice even with the use of GLIMS (Figure 5).

Part A



Part B

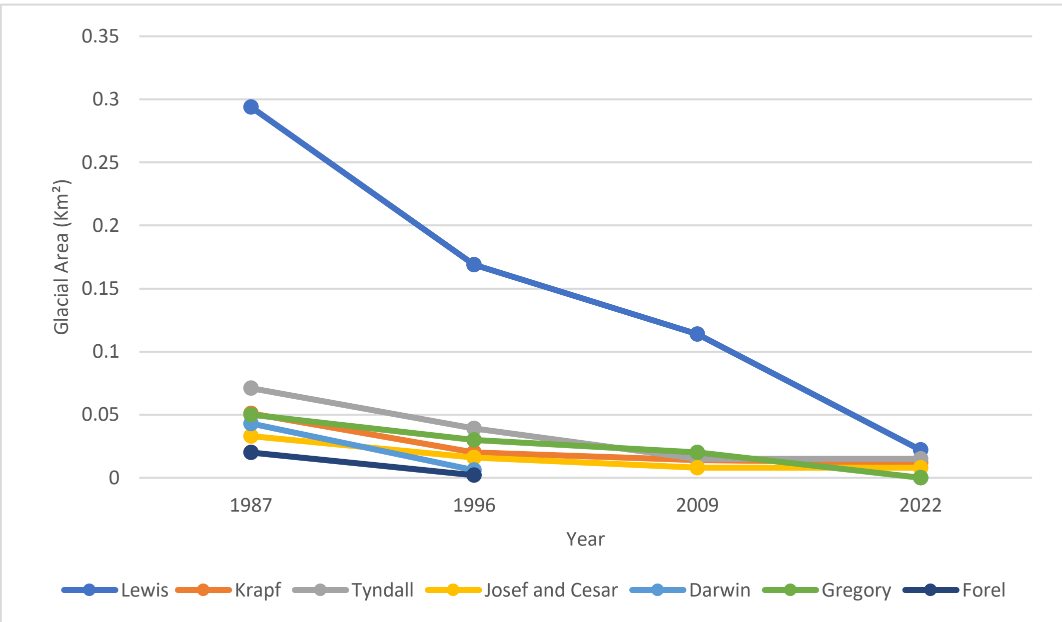


Figure 4: Part A) A 2022 Landsat image, using natural colour of Mount Kenya displaying the various glacier outlines for each decadal year starting in 1987 to 2022. Part B) The total glaciated area every decadal year in Km² in Mount Kenya.

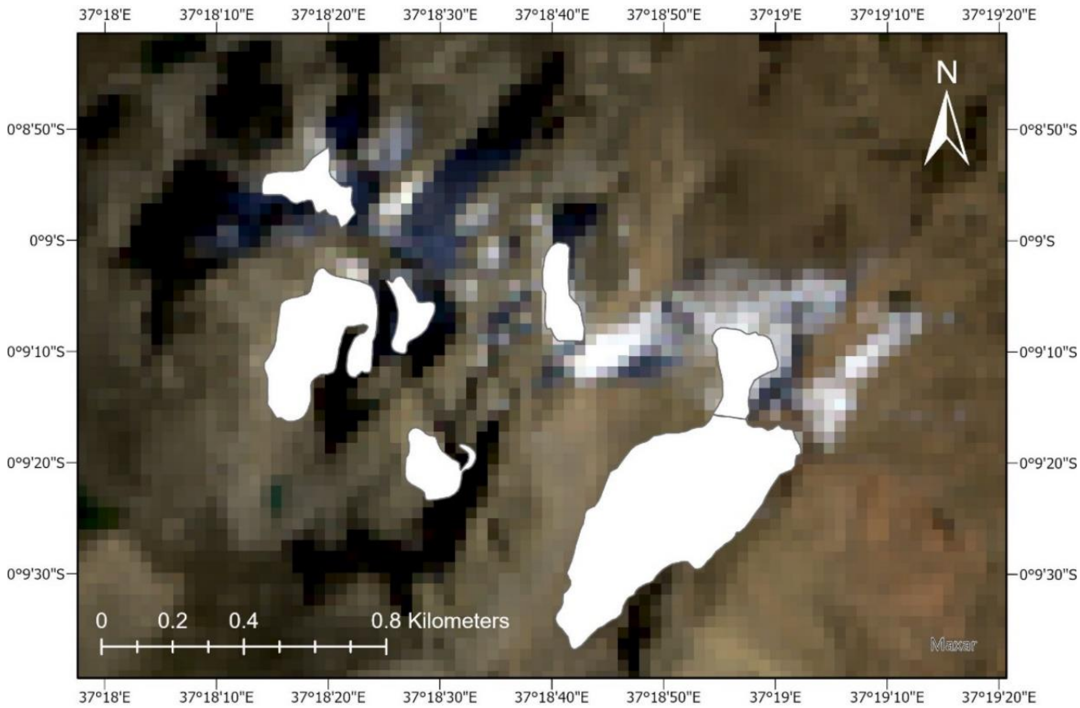
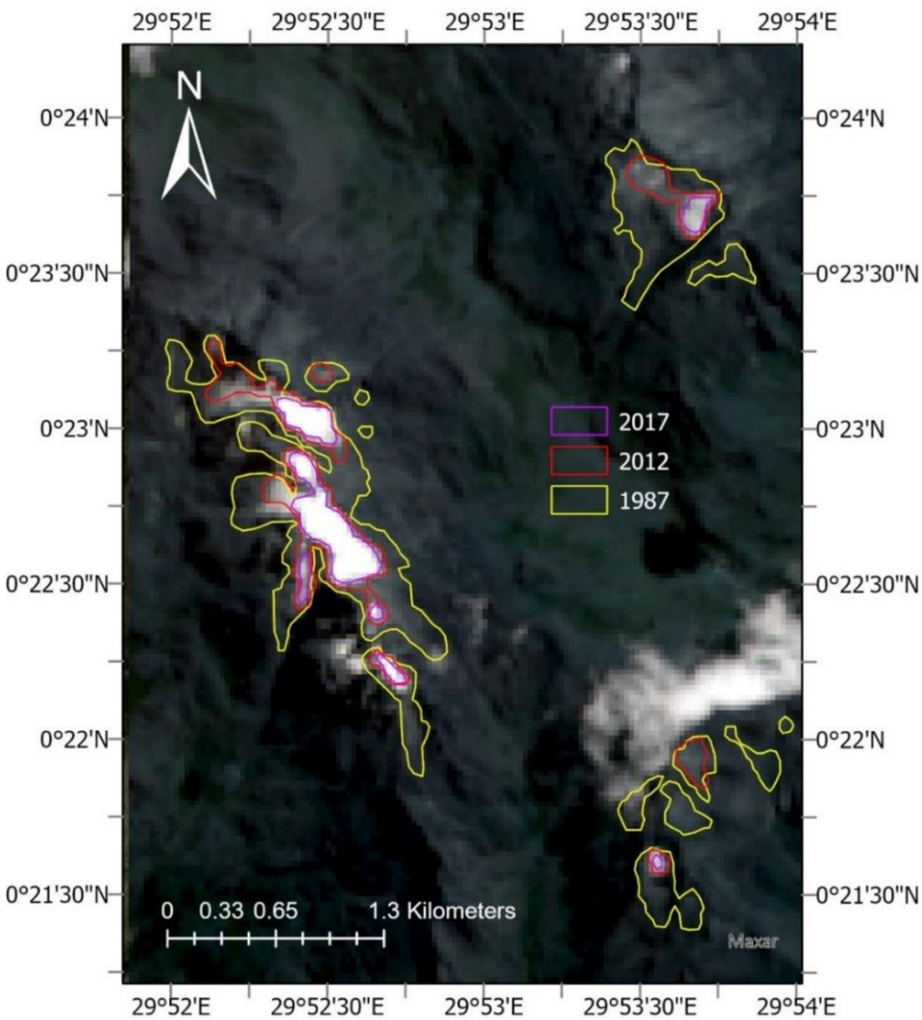


Figure 5: GLIMS image of Mount Kenya from 2015 to help identify where the glaciers are situated on the mountain to aid mapping.

4.3 The Rwenzori Mountains

Like Mount Kenya and Kilimanjaro, all the mountain peaks in the Rwenzori mountains have shown glacial retreat, shown in Figure 6A. The total glaciated area for all three mountain tops was 1.86Km². Between 1987 and 2017 the total area change for all three peaks was 1.6Km² which is an 85.8% area change on the mountain range. The largest glacial retreat in the Rwenzori mountains was between 1987 and 2012 which saw a total retreat of 1.24Km² (Table 4). However, it is noted that this is spanned over a 25-year period compared to a 5-year period between 2012 and 2017. Over the 25-year period, on average per year, an area of 0.05Km² was lost compared to 0.07Km² per year from 2012 to 2017. This results in 2012 to 2017 having the fastest rate of retreat with a total area of 0.36Km² lost. Mount Baker experienced most of its glaciers vanishing. The Y glacier, Wollaston, Moore and West baker have all melted between 1987 and 2012. East Baker had completely melted by 2017 and the Edward glacier is the only remaining one on this mountain top with a total area of 0.003Km² in 2017.

Part A



Part B

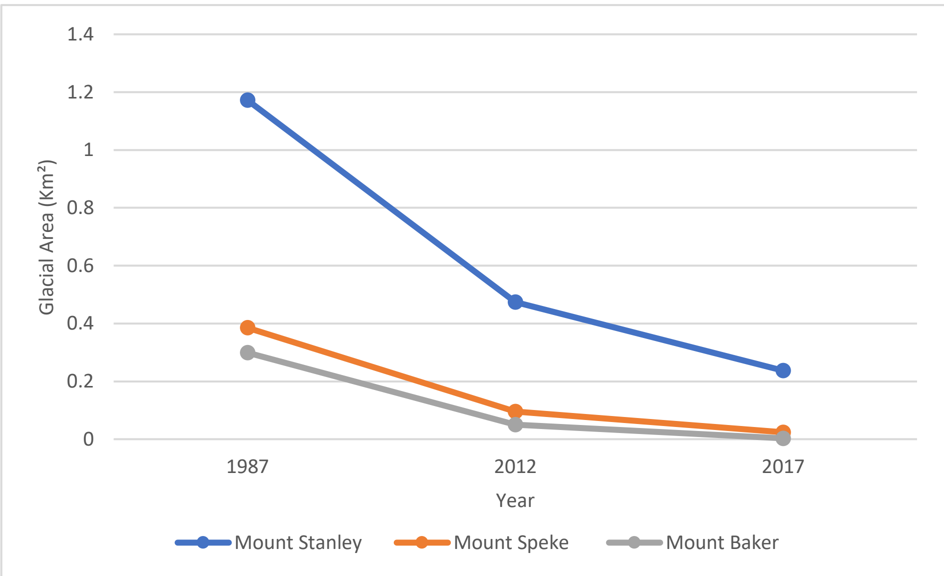


Figure 6: Part A) A 2017 Landsat image, using natural colour of the Rwenzori Mountains displaying the various glacier outlines for each decadal year starting in 1987 to 2022 on Mount Stanley, Baker, and Speke. Part B) The total glaciated area every decadal year in Km² on the Rwenzori Mountains.

Table 3: The area changes and percentage change of the glacier outlines from 1986 and 2019 in Mount Kilimanjaro, the area changes from 1987 to 2022 in Mount Kenya.

Mount Kilimanjaro				
Glacier Name	Area 1986 (km²)	Area 2019 (km²)	Area change (km²)	% Change
Northern Icefield	1.654	0.55	1.104	66.7
Furtwangler	0.094	0.006	0.088	93.6
Diamond	0.319	0.054	0.265	83.1
Southern Icefield	1.302	0.168	1.134	87.1
Mount Kenya				
Glacier Name	Area 1987 (km²)	Area 2022 (km²)	Area change (km²)	% Change
Lewis	0.294	0.022	0.272	92.5
Darwin	0.043	0	0.043	100
Krapf	0.051	0.012	0.039	76.7
Tyndall	0.071	0.015	0.056	78.9
Josef and Cesar	0.033	0.008	0.025	75.8
Gregory	0.05	0	0.05	100
Forel	0.02	0	0.02	100

A combined total area for glaciers Heim, Kersten, Decken and Rebman were used as one glacial total area due to the proximity of the glacial boundaries, this glacial system can also be known as the Southern Icefield. Josef and Cesar are a part of the same glacial system but have two separate terminal ends on them. Due to no clear line between the two glaciers, the area of these glaciers was also recorded as one.

Table 4: The area changes and percentage change in ice cover from 1987 to 2017 in the Rwenzori Mountains for Mount Stanley, Baker and Speke.

Rwenzori Mountains				
Mountain Ranges	Area 1987 (km²)	Area 2017 (km²)	Area change (km²)	% Change
Mount Stanley	1.172	0.237	0.935	79.8
Mount Baker	0.299	0.003	0.296	98.9
Mount Speke	0.385	0.024	0.361	93.8

Due to large glacial and snow cover, the combined total glaciated area of all three mountains was mapped. Mount Stanley contains the largest glacial cover of 1.172km². All the percentage area changes remain large however, Mount Stanley has the least change of 79.8%. Compared to Mount Speke (93.8%) and Mount Baker with a 98.99% change, meaning that most of the glaciers on this mountain top have almost completely melted. The average area change for the Rwenzori mountains is 85.8% compared to Mount Kenya at 89.9% and least average area of change is Kilimanjaro with a 76.9% change.

4.4 Temperature change

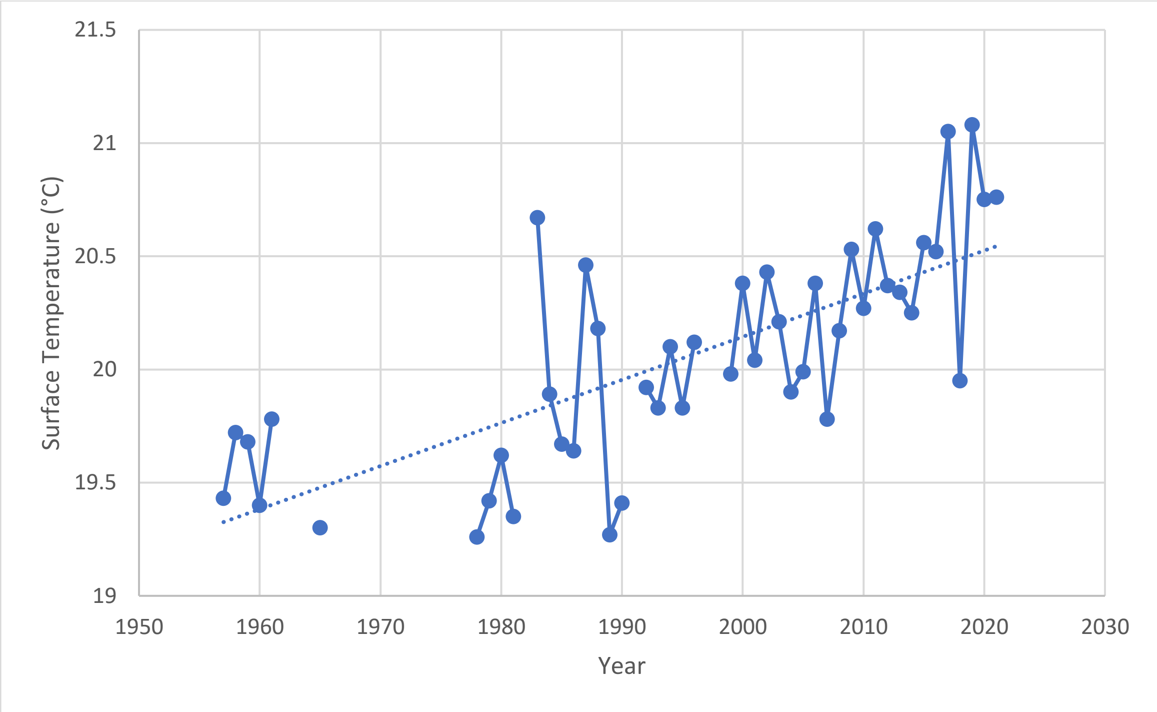


Figure 7: Annual mean temperature in Jomo Kenyatta Airport, Kenya, between the years of 1958-2021.

All glaciers have retreated rapidly from the late 80s to the present day (Table 3 and 4), which could be linked to annual temperature rise. The annual mean temperature fluctuates between every year; however, the general trend shows that the temperature has steadily increased from 19.4°C in 1957 to around 20.8°C in 2021 with the highest annual temperature of 21°C, recorded in 2019. There are gaps in the data, the largest from 1961 to 1983. The airport went through construction to have a new terminal built, the gap in data could be a result of this construction (Place and See, 2022). The earliest year of the Landsat data collected is from 1986 so the gap in data poses no issue for the study. In future, the temperature will likely continue to rise and with the unpredictable rain patterns, the glaciers on Kilimanjaro, Mount Kenya and the Rwenzori mountains are likely to completely disappear.

5.0 Discussion

This study aimed to identify if there is a link between rising temperature and the continuous retreat of tropical glaciers in Africa. From the data collected, alpine glaciers in East Africa were shown to be retreating at an alarming rate, which is largely the result of rising temperatures, but there are other local factors that have been found to impact on glacier mass balance in the region that are discussed below. In total all three study sites experienced an 81% reduction in glacial area between 1986 and 2022. The weather station in this area recorded an annual temperature increase of 1.2°C since 1986 to 2021. It is predicted that the annual temperature in Eastern Africa will increase to 4.3°C by the end of this century (UNDP, 2022) which will further accelerate the retreat of Africa's only remaining glaciers.

As the remote sensing mapping showed, Kilimanjaro, Mount Kenya, and Rwenzori Mountains all experienced glacial retreat. The reoccurring pattern of all glaciers melting at the fastest rate between 2009 to the present day coincides with the temperature data collected (Figure 7). From the 2000s the annual temperature increased at a fast, steady rate compared to previous years. Glaciers in low latitudes are extremely sensitive to climate change due to being in a climatic region with warmer annual temperatures that keep glaciers close to melting point. Because of this they are much thinner, smaller and melt at a faster rate than larger glaciers (Yao-Jun LI, et.al, 2019). Due to their mass being less, they also have a lower heat capacity resulting in smaller glaciers taking a shorter time to shrink in warmer and drier conditions (Thompson et.al, 2011). This is shown in evidence for this study area, Kilimanjaro had the largest area covered by glacial ice and is melting at a slower rate compared to Rwenzori and an even slower rate than Mount Kenya which has the least glacial coverage. This makes small mountain glaciers important indicators of climate change due to their fast response time, sensitivity to the climate and the clear visibility whether they are growing or shrinking in response to the climate (Vuille et.al, 2008).

5.1 General Trends

Kilimanjaro seen the largest area of ice lost in the Southern Icefield between 1986 and 2019 however the Furtwangler glacier appears to be retreating at a faster rate. This supports the result of Thompson et.al (2011) who took ice-volume changes between 2000 and 2007 and found that the Furtwangler and Northern Icefield are losing their ice volumes at nearly equivalent levels of 54% and 46%. Table 3 shows that the southern end of the mountain contains a higher ice extent compared to the north. Young and Hastenrath (1987) also note this difference and further explain that rainfall is more abundant in the south due to the south-easterly wind flow in the lower troposphere during the rainy season which would be the cause of a greater accumulation of ice. The Southern Icefield is distinguished by the grouping of four glaciers, Rebmann, Decken, Kersten and Heim glaciers. From 2009 to 2019 they experienced a wide state of fragmentation and became separated making it easier to identify the glacier boundaries. Global changes in temperature and precipitation are affecting the behaviour of the glaciers however, it could also be linked to more regional variations such as deforestation and bush fires (McKenzie et.al, 2010). Around Kilimanjaro, the locals maximize the use of the land cover and plant dense Banana forests that shadow the surrounding land, which provides fodder, medicines, firewood and under the banana trees coffee plants are grown. However, in recent years plantation owners are changing their coffee varieties to ones that are less shade demanding resulting in the little need for tree canopy to produce shade. Since this, hundreds of trees have been removed (Rechkemmer & Litre, 2009). Rasetter (2010) explains that the trees create moisture through transpiration which flows up the mountain and helps to maintain the glacial ice. An increase in deforestation may be speeding up glacial retreat due to less moisture around the mountain and it is believed that the recession on Furtwangler is strongly linked to tree removal (Pepin et.al, 2014). This has affects for water availability and regional/local climate. An increase in deforestation has already seen an increase in fires due to the area being drier and replacing forests which filter and store water, with bush vegetation that have a limited role in water balance (Mölg, 2008).

Mount Kenya in total had a glacial area of 0.057Km² in 2022, compared to 0.562Km² in 1987 (Table 3). This was much higher back in 1948, as Nilsson (1949) calculated that the total glaciated area to be 1.2Km², which the Lewis glacier accounted for 0.36Km² of this (Young & Hastenrath, 1987). Figure 4A shows that the glaciers in the west and southern slopes are best developed. These are the 'most favourable areas for accumulation and the survival of snow' which could be due to the large shade cover in this area (Young & Hastenrath, 1987, pp. 55). This study found that the Lewis glacier had the largest loss of ice from 1987-2022 with a total loss of 0.272Km². It is observed that the glacier did not only retreat at its terminus but retreated from all sides. Prinz et.al, (2018) supports this by identifying shrinkage from all sides and a separation from the lower and upper half of the Lewis glacier, which was divided by a rock outcrop. The glaciers on the North side of the mountain are usually covered by snow whereas the west-facing glaciers are in the shade which posed a problem for mapping especially in mapping the Gregory glacier in 2022 on the north side. Six glaciers were identified in this study however at the start of the century there were 18 which decreased to 11 in 1986 (Young & Hastenrath, 1987). Due to poor visibility on the Landsat images, more than half of the glaciers were not mapped. Prinz et.al (2011) found that the Lewis glacier had the highest rates of glacial ice loss throughout the decades compared to other tropical glaciers. At the start of the 1900s, East Africa's glaciers were likely affected by a decrease in rainfall and reduced cloudiness due to regional aridity changes influenced by the Indian ocean (Hemp, 2005). However, in recent years the main driver for glacial change at Mount Kenya and the Rwenzori Mountains is climate change in particular a rise of temperature (McKenzie et.al, 2010.)

In total the Rwenzori mountains had a glacial area covering around 1.9Km² in 1987 which has decreased to 0.26Km² in 2017. Unlike, Kilimanjaro and Mount Kenya the most glacial retreat occurred between 1986 and 2012. This is backed by Klein (2007) who explains that significant glacial retreat occurred between the late 1980s and early 2000s in the Rwenzori. Muhati et.al, (2018); Torbick et.al, (2009); Alsop, (2007) and O'Loughlin et.al, (2014) all describe a decline in precipitation but a sharp increase in air temperature since the 1980s which coincides with Figure 7, that displays an initial increase in temperature between 1989 and 2000. Comparing temperature data (Figure 7) to the pattern of glacial retreat (Table 4), it can be assumed that in this area the rising temperature highly influences glacial retreat. In more recent times, the glacial area cover is expected to be less. Klaus Thymann's 2020 expedition to the Rwenzori mountains revealed that Mount Speke and Mount Baker no longer have any glacial coverage (Thymann, 2020). This is a drastic change compared to the first glacial area estimations in 1907 by the Duke of the Abruzzi, approximating a coverage of 6.5Km² (Taylor et.al, 2006). Mölg et.al, (2003) also states that glaciers on the western side of the mountains experienced more retreat due to being exposed to the morning sun therefore having an increase in shortwave radiation. However, no link between glacier positioning and retreat was identified in this study, as the whole mountain range is experiencing large glacial retreat no matter of glacial orientation in relation to the sun position. Due to the large cloud cover in this area, recent clear images could only be sourced dating back to 2017. Mölg et.al, (2003) explained that the large percentage of cloud cover is due to air circulation caused by surface heating from the sun, which causes convective cloudiness and precipitation over the peaks of the mountains.

5.2 Impacts on water availability

Glacial extinction will likely have severe consequences on terrestrial and aquatic ecosystems, hydrology, and human systems in this region. Because Kenya, Tanzania, and Uganda are water scarce countries, tropical glaciers in these areas are crucial freshwater reserves that supply fresh water to surrounding communities during the dry seasons. In Kenya, between 1986 and 1999, 73% of the dry season flow in rivers originated from the Mount Kenya and 8% was the product of glacial melting (Rechkemmer & Litre, 2009). Millions of people surrounding these mountains rely on glacier-fed watersheds for a source of water whether it be used as drinking water or for crop irrigation. The Rwenzori mountains receive more precipitation than the other sites however, glacial runoff is a vital source for various lakes in western Uganda with 50% of the water in Lake George originating from the mountains (Eggermont et.al, 2009). Having said that, Molg et.al (2013) states that Kilimanjaro has no effect on water supplies for communities surrounding the mountain, but this is argued by Rastetter (2010) who explains that the Kilimanjaro's surrounding population rely on glacial meltwater and precipitation to fill their springs to be used for drinking water and crop irrigation. Although where most of this water is derived from has not been investigated in detail (Rastetter, 2010).

If the current trend of glacial recession continues, it will eventually mean that all glaciers on Kilimanjaro, Mount Kenya, and the Rwenzori mountains will disappear having a negative effect on the local hydrology. In due course, streams will flow slower with less water in them, and the gradual rise in air temperatures will increase the evaporation in streams which are fed by glacier melt. As a consequence of these factors and the added irregular precipitation patterns in Eastern Africa, the region will experience severe water scarcity (Buytaert, n.d). If surrounding communities are not supplied with fresh pumped water from other sources, it could increase the spread of water borne diseases. Joubert (2011. p. 64) expresses their worries on how flooding and droughts lead to an increase in diseases like Cholera due to the declining water quality and the over extraction of water due to the population demand. With the formation of glacial meltwater ponds and warming air temperatures, it is a breeding ground for mosquito and other disease-carrying insects which could increase the rate of diseases such as malaria (Veettil & Kamp, 2019).

Humans will not only be directly affected by glacial recession but the ecosystems that surround the ice will also suffer. Glaciers are natural water reserves storing water as ice daily, seasonally or throughout the centuries. Glacial ice traps in atmospheric chemicals such a nitrogen, dissolved organic matter and organic pesticides as well as trapping toxins such as bacteria, fungi, and viruses. These have the potential to alter the water clarity due to glacial meltwater moving suspended solids, affecting the distribution of light dependent organisms such as phytoplankton and zooplankton (Slemmons et.al, 2013). Slemmons et.al, (2013) further states that the hydrology and temperature can affect the biodiversity of species. Less biodiversity and biomass are present in low temperatures with increased sediment input which is found closer to the glacier. With all the added material in the water course from melting alpine glaciers, it could alter food-web dynamics, eliminate cold-water tolerant species, and reduce habitat heterogeneity. Having said that, Losapio et.al, (2021) explains that the biodiversity increases with glacial retreat but that only remains true if the glacier is still present.

Glacial extinction will rise the water temperature downstream. As a result of no glacial run off, there is no supply of cold water into streams, causing little sediment transport. This will decrease the turbidity of the water which will create problems for primary producers due to the increased light penetration in the water column. Because of the quick timescale of these processes, not all species will have time or the ability to migrate and colonize elsewhere, which will be the result of high-altitude plants not surviving after glacial extinction (Losapio et.al, 2021). It is to be noted that the outcome of glacial extinction is only a prediction of what may happen. Few studies have been carried out on this topic but that is set to increase in the future because of the high rates of global deglaciation.

5.3 Consequences of glacial change

Glaciers are not only important as water source, but they attract tourists from over the globe to view their beauty. The Rwenzori mountains are an important source to the economy due to its national park which contributes 13% to the country's gross domestic income (Thompson et.al, 2021). Each year thousands of people are attracted to visit the mountain glaciers in this region, especially Kilimanjaro. Tanzania relies heavily on tourism. A study by Minja (2014), found that the largest source of tourism income derived from mountain climbing and mountain equipment hire. On Kilimanjaro alone, 60,000 people travel annually to view or climb the mountain in which Minja (2014) also stated that the ice loss is already having a negative effect on the tourism sector which is only set to worsen due to climate change increasing the rate of glacial retreat.

These glaciers are perfect time capsules that can produce 'long, high quality records of climatic and environmental variation' (Thompson & Davis, 2013). Physical and chemical tests are preformed to identify past concentrations of greenhouses gases. Ice cores from Kilimanjaro identified that no major eruptions have occurred in the region in the last 500 ka, as well as this the region has experienced severe droughts and flooding events in history (Thompson & David, 2013). Ice cores are required to identify what may have caused these past events and what could be done to potentially stop or slow them down. Without glacial ice, future generations have less scientific evidence of past events and could be at a disadvantage understanding, preventing, or predicting such disasters.

Finally, glacial loss can have profound impacts on spiritual and cultural identity which is less discussed in the literature. Around the world some groups believe that mountains are sacred for their extreme height, and they are seen as natural temples, a place of worship. Like mountains, glaciers have been seen as 'malevolent forces', sources of inspiration and living beings. Allison (2015) describes tribes at the base of Kilimanjaro view the glaciers as the 'house of god', due to the movements and sounds they make, they are perceived as animate forces that will only be respected. The Rwenzori mountains are seen by locals as the 'Mountains of the Moon' due to their height and the white snow-caps on the top of the mountains.

5.4 Limitations of the study

Each study site had their own limitations. Mount Kenya and Kilimanjaro had four images ranging from 1986-2022. The USGS database had the poorest spread of data for the Rwenzori mountains and only contained images from 1998, 2012 and 2017, due to the large amount of cloud cover in this region in the other years. The Rwenzori mountains have an extensive area of tropical montane cloud forests. Ray (2013) describes these forests as areas with ‘persistent cloud cover/fog at vegetation or ground level that ensures that the tree crowns are regularly in contact with cloud water’ (2013, p. 79). This justifies the lack of Landsat images at this site due to the large cloud cover, the glaciated area could not be identified and mapped effectively.

The spatial resolution for the images is 30m however, due to the small area of glaciation on each mountain especially Mount Kenya, some of the glaciated area might not have been mapped as accurate as it could have been if higher spatial resolution data was available. However, in future other studies could improve on the mapped data as it becomes accessible. Mount Kenya was difficult to distinguish between glacial ice and snow due to large pixelization of images. Prinz et.al, (2018) explains that some very small glaciers are shadowed by the steep walls that surround them. To map the site accurately, high resolution images and expert knowledge of the site would be required. With the coarse resolution and high degree of shadowing, GLIMS was used as an aid to help identify glacial boundaries for mapping. At Kilimanjaro, Thompson et.al, (2011) explains that ground observations are essential for refining the extent of glacial change as using Landsat images alone could be underestimating ice loss by up to 50% this could be assumed for Mount Kenya as the glaciers are smaller.

All sites had poor historical weather data. Temperature and precipitation data contained large gaps which could lead to problems in understanding how climate change will affect East Africa directly. This made it hard to obtain reliable temperature data for this study. Lombrana (2021) also states that Africa has the world’s least developed land-based weather observation network however weather stations are being installed in schools to educate young people on the importance of weather stations which will establish plentiful weather data for future generations.

6.0 Conclusion

Kilimanjaro, Mount Kenya, and the Rwenzori Mountains are the three remaining sites that have glaciated peaks in the whole African continent and all three mountain ranges are rapidly losing glacial ice. Some of this is due to local drivers such as deforestation, although the main driver is climate change. Weather data obtained from Jomo Kenyatta International airport, displayed gradual warming trends in the annual mean temperature from 1986 to 2021, with some of the largest mean surface temperatures occurring in the last 10 years. This correlates to the fastest glacial retreat happening from 2009 to recent. The consequences of glacial retreat include water scarcity, scientific loss, increase in water borne diseases, loss of habitat and the spiritual connection of locals to glacial ice. The mapping in this report provides a clear picture of the impacts of climate change has on African glaciers. If society fails to react swiftly to reduce greenhouse gas emissions, Africa is highly likely to lose these important landscape features within the next decade.

7.0 References

A. Ahmed, (2018) The Atlantic [Online] Available at: Climate Science Can't Help Some Poor Countries in the Global South - The Atlantic (Accessed 23/03/2022)

A. G. Klein and J. L. Kincaid (2007) 'A Reassessment of the Satellite Record of Glacier Change in the Rwenzori Mountains, East Africa' *64th Eastern Snow Conference,* Canada, 2007, Texas A&M University [Online] Available at: Eastern Snow Conference Proceedings (researchgate.net) (Accessed 05/03/2022)

A. Hemp (2005) 'Climate change-driven forest fires marginalize the impact of ice cap wasting on Kilimanjaro', *Climate change Biology,* Vol. 11, pp. 1013–1023 [Online] DOI: https://doi.org/10.1111/j.1365-2486.2005.00968.x (Accessed 11/04/2022)

A. Rechkemmer and G. Litre (2009) 'Mountainous Regions: Laboratories for Adaptation' *7th International Science Conference on the Human Dimensions of Global Environmental Change,* Germany, 26-30th April, IHDP [Online] Available at: 7916_IHDPUpdate20082.pdf (unisdr.org) (Accessed 05/02/2022)

A.E. Racoviteanu, F. Paul, B. Raup, S. J. S. Kgalsa, R. Armstrong, (2009), 'Challenges and recommendations in mapping of glacier parameters from space: results of the 2008 Global Land Ice Measurements from Space (GLIMS) workshop, Boulder, Colorado, USA', *Annals of Glaciology,* Vol. 50, No. 53, pp. 53-69 [Online] DOI: https://doi.org/10.3189/172756410790595804 (Accessed 12/02/2022)

B. Ayugi, Z. Jiang, V. Lyakaremy, H. Ngoma, H. Babaousmail, C. Onyutha, V. N. Dike, R. Mumo and V. Ongoma (2022) 'East African population exposure to precipitation extremes under 1.5 ◦C and 2.0 ◦C warming levels based on CMIP6 models', *Environmental Research Letters,* Vol. 17 [Online] DOI: https://doi.org/10.1088/1748-9326/ac5d9d (Accessed 27/04/2022)

B. K. Veettil and U. Kamp (2019) 'Global Disappearance of Tropical Mountain Glaciers: Observations, Causes, and Challenges', *Geosciences,* Vol. 9, No. 196 [Online] DOI: http://dx.doi.org/10.3390/geosciences9050196 (Accessed 22/03/2022)

Britannica (2021) *Lake Victoria,* [Online] Available at: Lake Victoria | Size, Map, Countries, & Facts | Britannica (04/04/2022)

C. Rastetter (2010) 'Deforestation may lead to Kilimanjaro Glacial Melt, Study', *Circle of Blue* [Online] Available at: Deforestation May Lead to Kilimanjaro Glacial Melt, Study - Circle of Blue (Accessed 06/04/2022)

D. K. Ray (2013) 'Tropical Montane cloud Forests' *Climate Vulnerability,* Vol. 5, pp. 79-85 [Online] DOI: https://doi.org/10.1016/B978-0-12-384703-4.00519-0 (Accessed 22/03/2022)

D. Loibl, F. Lehmkuhl, J. Grießinger, (2014), 'Reconstructing glacier retreat since the Little Ice Age in SE Tibet by glacier mapping and equilibrium line altitude calculation', *Geomorphology,* Vol. 214, pp. 22-39 [Online] DOI: http://dx.doi.org/10.1016/j.geomorph.2014.03.018 (Accessed 17/02/2022)

D. P. Roy, V. Kovalskyy, H. K. Zhang, E. F. Vermote, L. Yan, S.S. Kumar, A. Egorov (2016), 'Characterization of Landsat-7 to Landsat-8 reflective wavelength and normalized difference vegetation index continuity', *Remote Sensing of Environment,* Vol. 185, pp. 57-70 [Online] DOI: http://dx.doi.org/10.1016/j.rse.2015.12.024 (Accessed 05/04/2022)

E. A. Allison, (2015) 'The spiritual significance of glaciers in an age of climate change', *Wire's Climate change,* Vol. 6, No. 5, pp. 493–508 [Online] DOI: https://doi.org/10.1002/wcc.354 (Accessed 06/03/2022)

Earth Data (n.d) *GLIMS: Global Land Ice Measurements from Space – Monitoring the World's changing Glaciers* [Online] Available at: GLIMS: About GLIMS (Accessed 22/04/2022)

ESRI (n.d) *Geodesic versus planar distance,* [Online] Available at: Geodesic versus planar distance—ArcGIS Pro | Documentation (Accessed 28/02/2022)

G. Kaser, D. R, Hardy, T. Molg, R. S. Bradley, T. M. Hyera, (2004), 'Modern glacier retreat on Kilimanjaro as evidence of climate change: observations and facts', *International journal of climatology,* Vol. 24, No. 3, pp. 329-339, [Online] DOI: https://doi.org/10.1002/joc.1008 (Accessed 07/02/2022)

G. L. Muhati, D. Olago and L. Olaka (2018) 'Past and projected rainfall and temperature trends in a sub-humid Montane Forest in Northern Kenya based on the CMIP5 model ensemble', *Global Ecology and Conservation,* Vol. 16 [Online] DOI: https://doi.org/10.1016/j.gecco.2018.e00469 (Accessed 26/04/2022)

G. Losapio, B. E. L. Cerabolini, C. Maffioletti, D. Tampucci, M. Gobbi and M. Caccianiga (2021) 'The Consequences of Glacial Retreat are uneven between Plant Species', *Frontiers and Ecology and Evolution,* Vol. 8, pp. 1-11 [Online] DOI: https://doi.org/10.3389/fevo.2020.616562 (Accessed 11/04/2022)

G. Minja (2014) 'Vulnerability of tourism in Kilimanjaro national park and the livelihoods of adjacent communities to the impacts of climate change and variability', *European Scientific Journal,* Vol. 10, No. 26, pp. 217-230 [Online] Available at: https://www.academia.edu/download/42586916/MINJA_PUBLICATION_ESJ_.pdf (Accessed 20/03/2022)

H. Eggermont, K. V. Damme, and J. M. Russell (2009) 'Rwenzori Mountains (Mountains of the Moon): Headwaters of the White Nile', *The Nile: Origin, environments, limnology and human use,* [Online] DOI: http://dx.doi.org/10.1007/978-1-4020-9726-3_13 (Accessed 06/03/2022)

J. A. T. Young and S. Hastenrath (1987) 'Glaciers of Middle and East Africa – Glaciers of Africa', *U.S. Geological Survey Professional Paper,* Vol. 1386, No. 3, pp. 49-69 [Online] Available at: africa.pdf (usgs.gov) (Accessed 04/03/2022)

J. M. Mckenzie, B. G. Mark, L. G. Thompson, U. Schotterer, P-N. Lin (2010) 'A hydrogeochemical survey of Kilimanjaro (Tanzania): implications for water sources and ages', *Hydrogeology Journal,* Vol. 18, pp. 985-995 [Online] DOI: https://doi.org/10.1007/s10040-009-0558-4 (Accessed 11/04/2022)

J. O'Loughlin, A. M. Linke, and F. D. W. Witmer (2014) 'Effects of temperature and precipitation variability on the risk of violence in sub-Saharan Africa 1980-2012', *Institute of Behavioural Science,* Vol. 111, No. 27, pp. 16712 – 16717 [Online] DOI: https://doi.org/10.1073/pnas.1411899111 (Accessed 26/04/2022)

K. E. H. Slemmons, J. E. Sarosa and K. Simon, (2013) 'The influence of glacial meltwater on alpine aquatic ecosystems: A review', *Environmental science, Processes & Impacts,* Vol. 15, No. 10 [Online] DOI: http://dx.doi.org/10.1039/c3em00243h (Accessed 21/03/2022)

K. Thymann (2020), *Africa's first Mountains to loose their Glaciers,* [Online] Available at: Africa's first mountains to lose their glaciers — the Story INSTITUTE Accessed 15/02/2022)

L. G. Thompson and M. E. Davis 'Ice core records: Africa', *Encyclopedia of Quaternary Science (Second Edition),* pp. 373-378 [Online] DOI: https://doi.org/10.1016/B978-0-444-53643-3.00319-8 (Accessed 23/03/2022)

L. G. Thompson, E. Mosley-Thompson, M. E. Davis, H. H. Brecher (2011) 'Tropical glaciers, recorders and indicators of climate change, are disappearing globally', *Annals of Glaciology,* Vol. 52, pp. 59, pp. 23-34 [Online] DOI: https://doi.org/10.3189/172756411799096231 (Accessed 06/03/2022)

L. G. Thompson, M. E. Davis, E. Mosley-Thompson, S. E. Porter, G. V. Corrales, C. A. Shuman, C. J. Tucker, (2021) 'The impacts of warming on rapidly retreating high-altitude, low-latitude glaciers and ice core-derived climate records', *Global and Planetary Change,* Vol. 203 [Online] DOI: https://doi.org/10.1016/j.gloplacha.2021.103538 (Accessed 06/03/2022)

L. Joubert (2011) 'South Africa's changing climate', *Current Allergy & Clinical Immunology,* Vol. 24, No. 2, pp. 62-64 [Online] Available at: South Africa's changing climate : review article (journals.co.za) (Accessed 22/03/2022)

L. M. Lombrana (2021) Bloomberg [Online] Available at: Africa's Climate Data Has Gaps. Can Old Books Help? - Bloomberg (Accessed 23/03/2022)

M. Ewertowski and M. Rzeszewski (2007) 'Changes Of Glacier Extent: Using Gis To Integration Maps, Remote Sensing Material And Field Surveying. Petuaniabukta, Central Spitsbergen Case Study', *10th AGILE International Conference on Geographic Information Science,* Aalborg Denmark, 2007, [Online] Available at: https://agile-online.org/conference_paper/cds/agile_2007/proc/pdf/163_pdf.pdf (Accessed 23/02/2022)

M. F. Meier, (2021) *Encyclopedia Britannica [Online] Available at:* glacier | Definition, Formation, Types, Examples, & Facts | Britannica (Accessed 04/02/2022)

M. T. Blau & K. J. Ha (2020) 'The Indian Ocean dipole and its impact on East African short rains in two CMIP5 historical scenarios with and without anthropogenic influence', *Journal of Geophysical Research: Atmospheres*, Vol. 125, No. 16 [Online] DOI: https://doi.org/10.1029/2020JD033121 (Accessed 06/02/2022)

M.S. Jackson, M.A. Kelly, J.M. Russell, A.M. Doughty, J.A. Howley, J.W. Chipman, D.A. Cavagnaro, M.B. Baber, S.R.H. Zimmerman, B. Nakileza (2020), 'Glacial fluctuations in tropical Africa during the last glacial termination and implications for tropical climate following the Last Glacial Maximum', *Quaternary Science Reviews,* vol. 243, [Online] DOI: https://doi.org/10.1016/j.quascirev.2020.106455 (Accessed 04/02/2022)

N. C. Pepin, W. J. Duane, M. Schaefer, G. Pike and D. R. Hardy (2014) 'Measuring and modelling the retreat of the ice fields on Kilimanjaro, East Africa', *Artic, Antartic and Alpine Research,* Vol. 46, No. 4, pp. 905-917 [Online] DOI: http://dx.doi.org/10.1657/1938-4246-46.4.905 (Accessed 22/04/2022)

N. Torbick, J, Ge and J. Oi (2009) 'Changing surface conditions and Kilimanjaro Indicated from Multiscale Imagery', *Mountain Research and Development,* Vol. 29, No. 1, pp. 5-13 [Online] Available at: https://www.jstor.org/stable/mounresedeve.29.1.5 (Accessed 26/04/2022)

NASA earth observatory, (n.d) *World of Change: Global Temperatures* [Online] Available at: World of Change: Global Temperatures (nasa.gov) (Accessed 06/02/2022)

Nasa Landsat Science (n.d) *Landsat 9,* [Online] Available at: Landsat 9 | Landsat Science (nasa.gov) (Accessed 15/02/2022)

National Snow and Ice Data Center (2020) *All about Glaciers* [Online] Available at: Facts about glaciers | National Snow and Ice Data Center (nsidc.org) (Accessed 04/02/2022)

P. Uchoa (2019) ‘Indian Ocean Dipole: What is it and why is it linked to floods and bushfired?’, *BBC News,* 7th December [Online], Available at: Indian Ocean Dipole: What is it and why is it linked to floods and bushfires? - BBC News (Accessed 07/02/2022)

Place and See (2022) *Jomo Kenyatta International Airport,* [Online] Available at: Jomo Kenyatta International Airport (placeandsee.com) (Accessed 01/03/2022)

R. G. Taylor, L. Mileham, C. Tindimugaya, A. Majugu, A. Muwanga, and B. Nakileza (2006) ‘Recent glacial recession in the Rwenzori Mountains of East Africa due to rising air temperature’, *Geophysical research letters,* Vol. 33, No. 10 [Online] DOI: https://doi.org/10.1029/2006GL025962 (Accessed 28/02/2022)

R. Prinz, A. Fischer, L. Nicholson and G. Kaser (2011) ‘Seventy-six years of mean mass balance rates derived from recent and re-evaluated ice volume measurements on tropical Lewis Glacier, Mount Kenya’, *Geophysical Research Letters,* Vol. 38, [Online] DOI: http://dx.doi.org/10.1029/2011GL049208 (Accessed 06/03/2022)

R. Prinz, A. Heller, M. Ladner, L. I. Nicholson and G. Kaser (2018) ‘Mapping the Loss of Mt. Kenya’s Glaciers: An Example of the Challenges of Satellite Monitoring of Very Small Glaciers’, *Geosciences,* Vol. 8, No. 174 [Online] DOI: http://dx.doi.org/10.3390/geosciences8050174 (Accessed 06/03/2022)

S. C. Porter (2001), ‘Snowline depression in the tropics during the Last Glaciation’, *Quaternary Science Reviews,* Vol. 20, No. 10, pp. 1067-1091 [Online] DOI: https://doi.org/10.1016/S0277-3791(00)00178-5 (Accessed 07/02/2022)

S. E. Nicholson (2017) ‘Climate and climatic variability of rainfall over eastern Africa’, *Reviews of Geophysics,* Vol. 55, No. 3 [Online] DOI: https://doi.org/10.1002/2016RG000544 (Accessed 07/02/2022)

Seehaus. T, Malz. P, Sommer. C, Lippl. S, Cochachin. A, Braun. M (2019) ‘Changes of the tropical glaciers throughout Peru between 2000 and 2016 – mass balance and area fluctuations’, *The Cryosphere,* vol. 13, no. 10, pp. 2537–2556 [Online] DOI: https://doi.org/10.5194/tc-13-2537-2019 (Accessed 07/02/2022)

Spink, P. (1949), ‘The Equatorial Glaciers of East Africa’, *Journal of Glaciology,* Vol. *1, No.* 5, pp. 277-282, [Online] DOI: https://doi.org/10.3189/002214349793702584 (Accessed 07/02/2022)

STARS Project (n.d), *Remote Sensing Technology – Landsat,* [Online] Available at: Landsat - STARS Project (stars-project.org) (Accessed 20/04/2022)

T. Mölg, C. Georges and G. Kaser (2003) ‘The contribution of increased incoming shortwave radiation to the retreat of the Rwenzori Glaciers, East Africa, during the 20th Century’, *International Journal of*

Climatology, Vol. 23, No. 3, pp. 291-303 [Online] DOI: https://doi.org/10.1002/joc.877 (Accessed 05/03/2022)

T. Mölg, D. R. Hardy, N. J. Cullen, and G. Kaser (2008) 'Tropical Glaciers, Climate Change, and Society – focus on Kilimanjaro (East Africa), *Trends in Natural Landscapes,* pp. 168-182 [Online] Available at: (PDF) Tropical Glaciers, climate change, and society: Focus on Kilimanjaro (East Africa) (researchgate.net) (Accessed 06/03/2022)

T. Molg, N. J. Cullen, D. R. Hardy, M. Winkler, G. Kaser, (2009) 'Quantifying Climate Change in the Tropical Midtroposphere over East Africa from Glacier Shrinkage on Kilimanjaro', *Journal of Climate,* Vol. 22, No. 15, pp. 4162-4181, [Online] DOI: https://doi.org/10.1175/2009JCLI2954.1 (Accessed 07/02/2022)

USAID (2020) *'Climate risk profile – East Africa'* [Online Fact Sheet] Available at: Template (climatelinks.org) (Accessed 20/04/2022)

U.S Geological Survey (n.d) *What is a Glacier?* [Online] Available at: What is a glacier? | U.S. Geological Survey (usgs.gov) (Accessed 04/02/2022)

U.S. Geological Survey (n.d) *Climate and Land Use Change* [Online] Available at: Climate and Land Use Change | USGS.gov (Accessed 24/10/2021)

United Nations (n.d) *Climate Action,* [Online] Available at: What Is Climate Change? | United Nations (Accessed 28/02/2022)

United Nations Development Programme/UNDP, (2022) *Climate Change Adaptation – Africa,* [Online] Available at: Africa | UNDP Climate Change Adaptation (adaptation-undp.org) (Accessed 03/03/2022)

United Nations Educational, Scientific and Cultural Organization (n.d) *Rwenzori Mountains National Park* [Online] Available at: Rwenzori Mountains National Park - UNESCO World Heritage Centre (Accessed 07/02/2022)

Urama, K.C. and Ozor, N (2010) 'Impacts of climate change on water resources in Africa: the role of adaptation', *African Technology Policy Studies Network*, vol. *29*, pp.1-29 [Online] Available at: https://www.researchgate.net/publication/267218899_Impacts_of_climate_change_on_water_resources_in_Africa_the_role_of_adaptation (Accessed 06/02/2022)

USGS (n.d) *Landsat 7,* [Online] Available at: Landsat 7 | U.S. Geological Survey (usgs.gov) (Accessed 12/02/2022)

Vuille. M, Francou. B, Wagnon. P, Juen. I, Kaser. G, Mark. B. G, Bradley. R. S, (2008) *Earth Science Reviews,* Vol. 89, pp. 79-96 [Online] DOI: http://dx.doi.org/10.1016/j.earscirev.2008.04.002 (Accessed 04/03/2022)

W. Buytaert (n.d) *Glacial melt and water scarcity,* [Online] Available at: Glacier melt and water security | Grantham Institute – Climate Change and the Environment | Imperial College London (Accessed 10/04/2022)

Yao-Jun LI, Yong-Jian Ding, Dong-Hui Shangguan, Rong-Jun Wang (2019) 'Regional differences in global glacier retreat from 1980 to 2015', *Advances in Climate change research,* Vol. 10, No. 4, pp. 203-113 [Online] DOI: https://doi.org/10.1016/j.accre.2020.03.003 (Accessed 04/03/2022)

Zoe Alsop (2007) 'Malaria returns to Kenya's highlands as temperatures rise', *World Report,* Vol. 370, pp. 925-926 [Online] DOI: doi:10.1016/S0140-6736(07)61428-7 (thelancet.com) (Accessed 26/04/2022)