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Changing Surface Conditions at Kilimanjaro Indicated from Multiscale Imagery

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The shrinking glacier atop Kilimanjaro has received much attention as it is one of the few remaining tropical glaciers in the world. Physical drivers ranging from changes in temperature and humidity to shifts in cloud coverage and radiation have been attributed to reducing the ice mass. Studies have utilized varying methods and often use point data sources that tend to be spatially and temporally poor in the region. The objective of this study was to use complementing remote sensing data sets with systematic measurements to delineate ice cap fluctuations and land surface phenology on Kilimanjaro over the past two decades. Multitemporal, fine-scale Landsat imagery (30 m) showed approximately a 70% reduction in ice coverage since 1976. High-frequency (bimonthly) image analysis conducted along a human activity–elevation ecocline showed that the entire mountain, including the subalpine and alpine regions, has undergone an increase in vegetative signal indicating a "greening up" of Kilimanjaro over the past two decades. In addition, upper elevations of Kilimanjaro have undergone a temporal shift, or lengthening, in dry season phenology on the order of one month over the past two decades. The shift in dry season timing is concordant with maximum ablation periods. Overall, this study provides insight into land surface trends at resolutions that are currently lacking in Kilimanjaro climate change analyses.

Keywords: *Climate change; remote sensing; phenological shift; Kilimanjaro; East Africa.*

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Introduction

The ice cap on Kilimanjaro has frequently been used as an indicator of global and regional climate change. Lying 300 km south of the equator in Tanzania, Kilimanjaro has one of the few remaining tropical glaciers in the world. Studies of Kilimanjaro have suggested causes for the fluctuating ice cap. A wide range of methods have been used in an attempt to answer questions related to climate change and Kilimanjaro ice loss. Data sources utilized in these studies include satellite measurements, lake and ice cores (Thompson et al 2002; Stager et al 2003; Thompson et al 2003), station data, precipitation model reconstructions (Nicholson and Yin 2001), and field visits and mapping records (Hastenrath 1984; Hastenrath and Greischar 1997), among others.

Complex interactions between climate forcings are often suggested as contributing to glacial retreat. Global warming, induced from the greenhouse effect, has been attributed to driving the reduction of glaciers worldwide (Oerlemans 2001). However, in East Africa, data are often spatially and temporally inconsistent, with large gaps, creating challenges when addressing regional climate change. For example, from station data in the Amboseli basin, Altmann et al (2002) found an increase of more than 2°K/decade in mean daily maximum temperature since the mid-1970s. Other studies have found no significant changes or highly variable regional temperature (Hay et al 2002).

Kaser et al (2004) provide a thorough review of Kilimanjaro glacial retreat, detail several theories, and attribute a decrease in atmospheric moisture around the end of the 19th century and drier climatic conditions as primary reasons for the shrinking ice cap. For example, precipitation trends inferred from data gathered at stations located on Kilimanjaro have shown decreases in the past few decades (Hemp 2005). Lake-level reconstructions show large decadal fluctuations and wetter conditions for the latter half of the 19th century, with an abrupt change in the last few decades of that century (Nicholson and Yin 2001) followed by generally drier and warmer conditions in East Africa in the 20th century (Nicholson 2001; Thompson et al 2003). Noted changes in lake levels covering this time period have been tied to decreased precipitation and decreased cloud coverage, all concordant with glacial retreat (Hastenrath 2001). Molg et al (2003) attributed increases in incoming shortwave radiation, resulting from changes in humidity and the diurnal cycle of convective cloudiness, as a reason for glacial retreat for the Rwenzori range in Uganda.

A few studies have used airborne and mapping data at discrete points in time for quantifying the ice extent on

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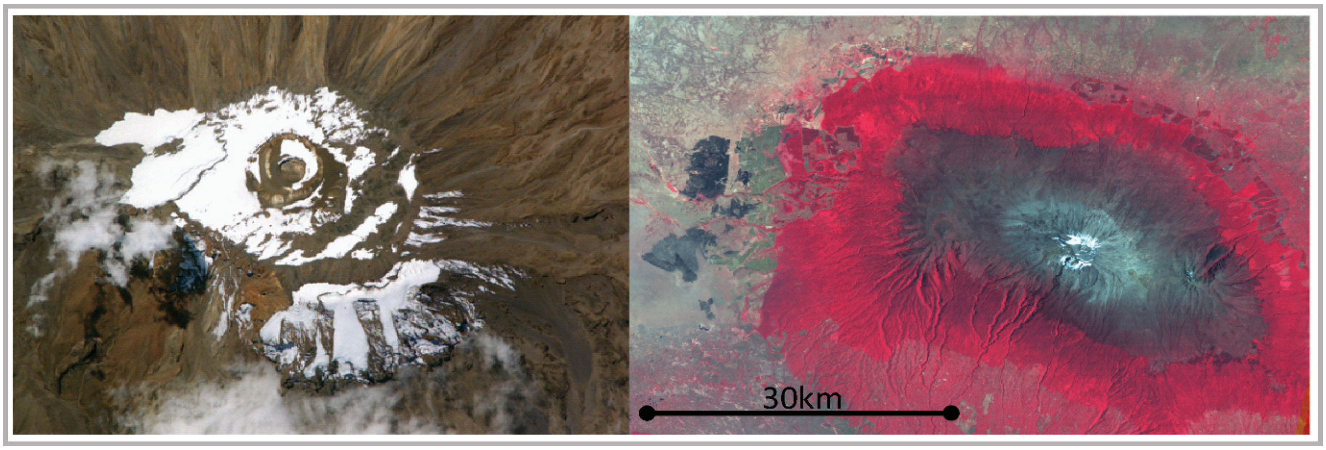
FIGURE 1 Kilimanjaro peak image (left) taken from the International Space Station on 28 June 2004. (Source: Earth Observations Laboratory, Johnson Space Center, NASA); false color (4:3:2) Landsat-7 ETM+ image (right) of Kilimanjaro area taken on 21 February 2000. Red indicates vegetated surfaces with darkening tone representing greater biomass.



Kilimanjaro to show considerable retreat (Hastenrath and Greischar 1997) over the past several decades. However, analyses from historical maps, occasional remote sensing imagery, or air photos only provide snapshots or discrete intervals (time periods) of ice extent. Due to the substantial seasonal dynamics of the ice cap, quantifying the spatial extent and rate of change with snapshot intervals relies on generalities. Furthermore, Kaser et al (2004) concluded that decadal analysis is lacking and insufficient for complete understanding of the dynamics of climate change in the tropics. Finer time scales are advantageous for contributions to climate change science and for improved understanding of change (eg Olson et al 2008).

The overall goal of this study was to provide deeper insight into the change process on Kilimanjaro using complementing long-term and well-calibrated satellite observations. The objectives were to delineate the extent and rate of ice cap extinction and characterize land surface phenology at a high frequency along the Kilimanjaro human activity–elevation ecocline.

Approach

Satellite imagery background

Three satellite-based sensors were used in this study. The delineation approach used fine spatial resolution decadal satellite observations from Landsat and the advanced spaceborne thermal emission and reflection radiometer (ASTER) instruments. The second approach to assess phenology used the advanced very high resolution radiometer (AVHRR) sensor, which records reflected solar radiation in the red (0.55–0.68 μm) and near-infrared (0.73–1.1 μm) spectral regions. Data from these portions of the spectrum have long been used in the form of the Normalized Difference Vegetation Index (NDVI) (Equation 1).

$$\text{NDVI} = \frac{\text{near-infrared} - \text{red}}{\text{near-infrared} + \text{red}} \qquad (1)$$

The NDVI indicator is primarily sensitive to vegetation amount, particularly green vegetation, and its vigor. Therefore, an increase in this indicator suggests an increase in the total amount of vegetation. For bare soil, the NDVI is just above zero while for snow and ice this indicator is zero. For a mixed snow and bare soil pixel, an increase in NDVI would mean that the proportion of the snow is reduced because of nonzero values for bare soil.

Numerous studies have utilized NDVI to assess land surface changes and possible impacts of climatic trends. Applications range from examining extreme climatic events to analyzing vegetation dynamics to developing coupled vegetation–precipitation records (Davenport and Nicholson 1993; Myneni et al 1998; Anyamba et al 2001; Tucker et al 2001; Bogaert et al 2002; Lotsch et al 2003; Slayback et al 2003; Zhou et al 2003). For example, Myneni et al (1998) analyzed a long-term NDVI time series and concluded that the growing season in the northern high latitudes (>45°N) expanded approximately 12 growing degree days during the 1980s, with the greatest increases linked where warming occurred simultaneously with carbon dioxide increases. Davenport and Nicholson (1993) previously found strong spatial and temporal correspondence between the NDVI and rainfall in East Africa. Therefore, by examining the temporal and spatial dynamics of the NDVI, ice–vegetation dynamics on Kilimanjaro can be inferred. Although limited by spatial resolution, a high temporal frequency analysis of land surface conditions on Kilimanjaro allows for quantification of vegetation–climate patterns.

Kilimanjaro description

The mountain has three main peaks, with the highest, Kibo, reaching 5895 m above sea level (masl) (Figure 1).

The climate is primarily controlled by the equatorial location along the coast. The Intertropical Convergence Zone (ITCZ) influences the long rainy season from March to May and the short rainy season occurring around November. A recent study (Schefuss et al 2005) suggested that central Africa's climate was not solely related to the change in the position of the ITCZ but was also controlled by the sea surface temperature difference between the tropics and subtropics of the South Atlantic Ocean.

On the mountain, rainfall varies by location, ranging from 800 mm/y to approximately 2700 mm/y at 2200 masl, and gradually decreases as elevation increases (Hemp 2005). In the alpine region, precipitation decreases to approximately 200 mm annually (Hemp 2002). Depending on the mountain's directional face, forest systems cover the altitudinal zone beginning around 1300–1800 m and extending to approximately 2700–3200 m. Above the tree line in the alpine system at altitudes of approximately 3750 m, vegetation becomes dwarfed, with upper montane forest shifting toward subapline conditions around 2800 m. The alpine region extending between 3500–4000 m is controlled by nighttime frosts and high daytime sunshine (Hemp 2005). Generally, at around 3000 m the vegetation cover can be described as the broad classes of open to very open shrubs, transitioning into sparse vegetation, stony soil, bare rock, and ice and snow as the elevation increases to the peak.

Lambrechts et al (2002) detail the numerous human activities taking place on and around Kilimanjaro. Activities range from deforestation to agriculture at lower elevations and around the Kilimanjaro foothills. Human-related activities gradually diminish with increases in elevation. Land uses on the foothills include wildlife, herding, forestry, and farming. Crops include maize, beans, bananas, coffee, and pasture, and scattered villages reach population densities of 500 people per km^2. Kilimanjaro National Park, approximately 75,000 hectares, covers the mountain at elevations above 2700 m, and generally little or no direct human impact occurs above this elevation except for climbing activities. At lower elevations of 700 m, savanna and grasslands are used for seasonal crops and cattle pasture. Persistent agricultural activity exists in the form of coffee and banana plantations at elevations between 1000 masl and 1800 masl largely due to the suitable climate conditions. On the northern, northeastern, and western slopes, large forest plantations exist in the montane zone. In the montane zone on the southern and eastern slopes, forest strips reside between the plantation areas, where timber harvest and firewood collection occur.

Methods

Ice extent delineation

To quantify the rate of ice cap retreat and to discern the impacts of regional climate from potential human impacts, two primary data sets were used in this study. The first data set consists of fine spatial resolution infrequent satellite observations from Landsat and ASTER. The second data set consists of a bimonthly NDVI time series from July 1981 to December 2003 observed by the AVHRR sensor. The fine spatial resolution snapshot measurements from Landsat and ASTER satellite sensors were used to assess ice extent for time periods over the past three decades. These included 30 m image data from Landsat-2 on 24 January 1976, from Landsat-5 on 25 February 1987, from Landsat-7 on 21 February 2000, and from ASTER on 31 March 2005 at 15 m spatial resolution. These images provide snapshots of the ice cap and allow the mapping of areal extent of the ice cap very accurately (Figure 2).

The ice extent at each particular date was calculated by classifying the mountain into a binary scheme of ice versus non-ice (Figure 2). The images are from approximately the same seasonal period occurring before the long rainy season and after the short rainy season. A 27.5% increase occurred between 1976 and 1987 in total surface ice. Between 1987 and 2000 a sharp decline occurred, nearly reducing the glacial coverage to one third its size in 13 years. From the ASTER data in 2005, ice at the peak of Kilimanjaro was nearly bare, with 2 main ice masses and scattered remnants totaling 294 hectares, suggesting a shrinking rate of approximately 30 hectares per year.

Trend analysis

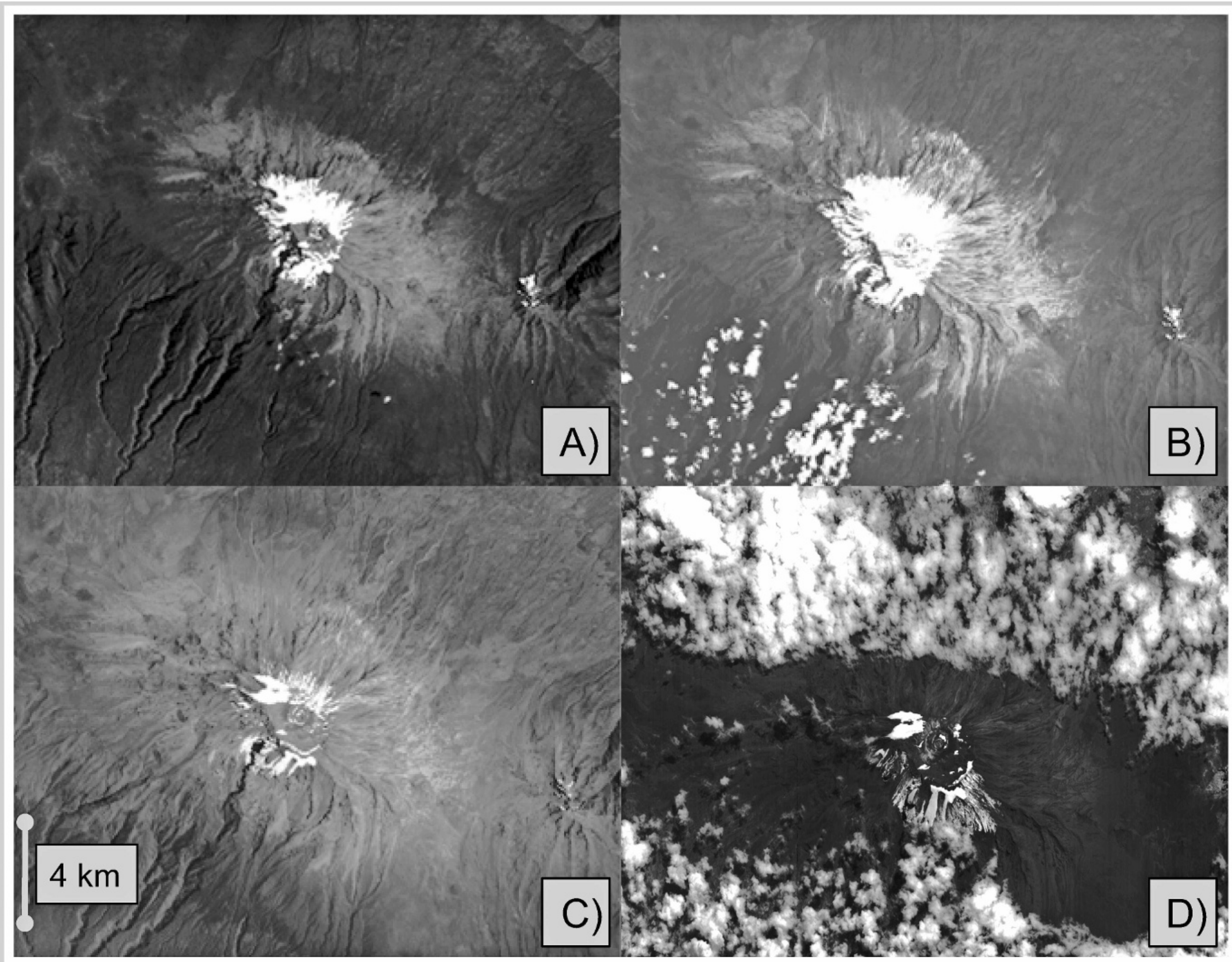
To characterize the land surface conditions and investigate the seasonal variability, frequent coarser resolution satellite data were analyzed by elevation zones. The NDVI time series used is part of the Global Inventory Modeling and Mapping Studies (GIMMS) data set that has been corrected for orbital shifting, atmospheric and aerosol variation, change in solar and sensor viewing angles, and sensor radiometric degradations (Tucker et al 2004). GIMMS is a highly calibrated, 22-year record from five different Nation Oceanic & Atmospheric Administration satellites. Maximum NDVI values, generally over 9–10 day periods, were composited to formulate 15-day time intervals at 8 km spatial resolution. A resampling procedure for the upper peak of Kilimanjaro was used to evenly break each pixel into 250 m subpixels by elevation gradients (Figure 3). The resampled data were then divided by different elevation zones that were derived from a 90 m resolution digital elevation model acquired by the Shuttle Radar Topography Mission. The elevation zones encompass the different land covers/uses and human activities (Table 1).

Results

Trends

The GIMMS NDVI data provide a two-decade high-frequency time series of land surface conditions. Figure 4

FIGURE 2 Imagery subsets detailing ice extent changes on Kilimanjaro for four time periods: (A) 24 January 1976; (B) 25 February 1987; (C) 21 February 2000; (D) 3 March 2005. (Source data from US Geological Survey Earth Resources Observation and Science Center)



illustrates average NDVI for elevation zone 3, 4000 m to the peak of Kilimanjaro, from 1982 to 2003. Large variation is evident, with several considerable NDVI peaks and valleys occurring over the past two decades. Generally, the peaks suggest an increase in green vegetation while the valleys suggest a reduction in green materials. In the case of Kilimanjaro, at an elevation above human activities, each pixel consists of radiometric contributions from vegetation, bare rocks/soil, and snow. Given the fact that the elevation above 4000 m generally consists of either bare soil/rock or snow, an increase in NDVI would suggest a reduction in snow/ice cover and/or an increase in vegetation. At 5000 m to the peak, an increase in NDVI suggests a reduction in snow/ice cover. Therefore, the peaks of NDVI in the time series for the highest elevation zones correspond to the lowest ice/snow cover while the low periods correspond to the highest cover. The linear trend for this particular elevation band has a slope of 0.19, showing an overall slight increase during the two-decade time span (Figure 4).

The trend lines from the elevation zones provide an indication of changes in the surface characteristics. Figure 5 displays the linear trend lines based on the NDVI time series. The lowest slope value calculated was for elevation zone 5 (2000–3000 m), showing a small increase. The dominant vegetation cover in this elevation zone is submontane/montane forest cover, and it has moderate human activity including deforestation and land use conversion. It is believed that human impacts on the landscape within this zone resulted in a net loss in tree cover due to deforestation (Lambrechts et al 2002). Net forest loss could lead to a decrease in NDVI, but new growth and possibly an increase in favorable conditions may have counterbalanced the decrease. The highest slope value was for elevation zone 1 (2000 m to the peak). Generally, lower elevations have higher NDVI values, as expected with the given ecocline on Kilimanjaro.

The trends in the NDVI show that Kilimanjaro is "greening up," reflected by the increasing green vegetative signal from 1982 to 2003. In all elevation zones NDVI

FIGURE 3 Trends analysis using high-frequency AVHRR measurements and the derived NDVI metric quantifying vegetation signal. The grid details the spatial resolution of the data set used for the trend analysis.

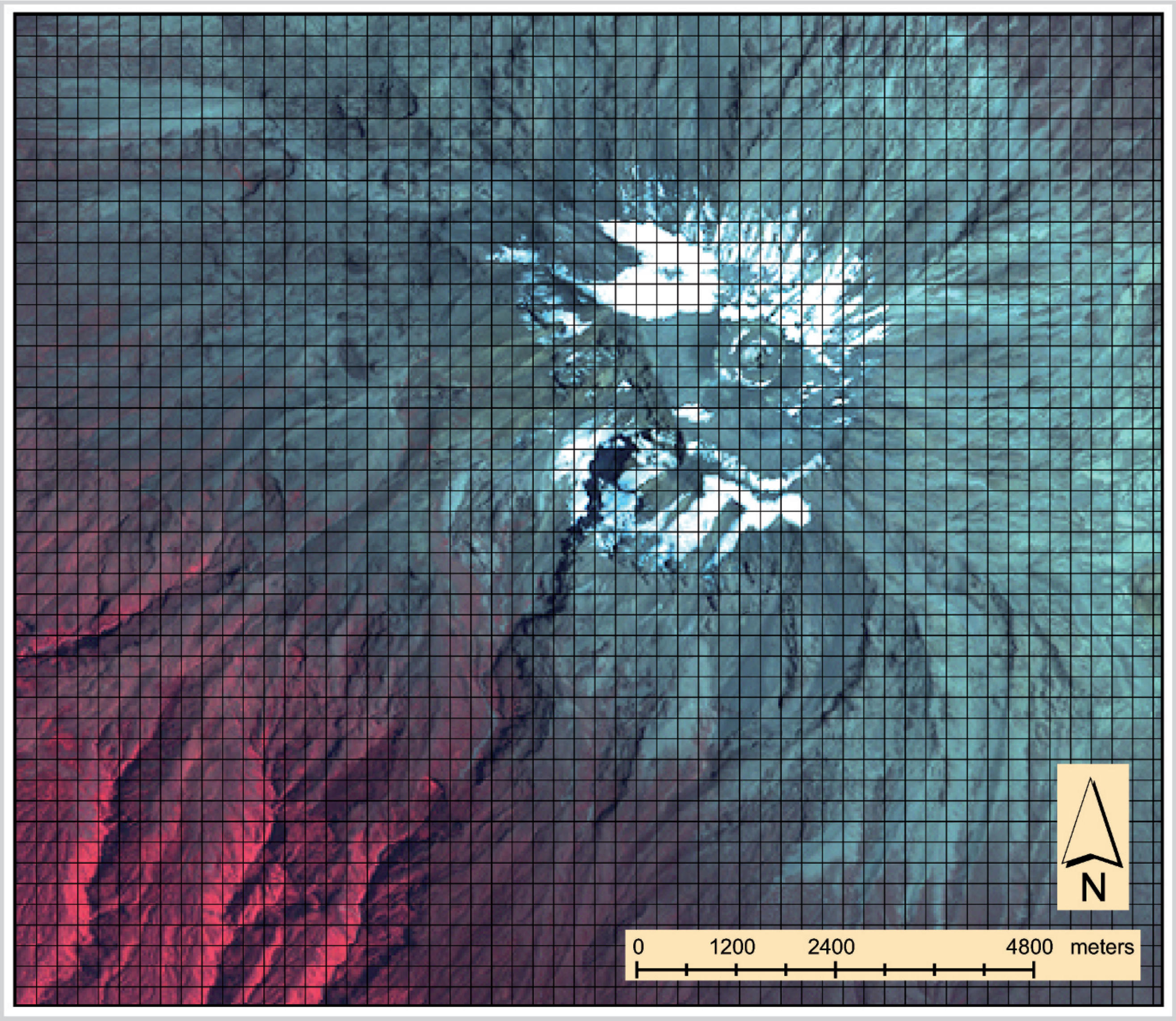
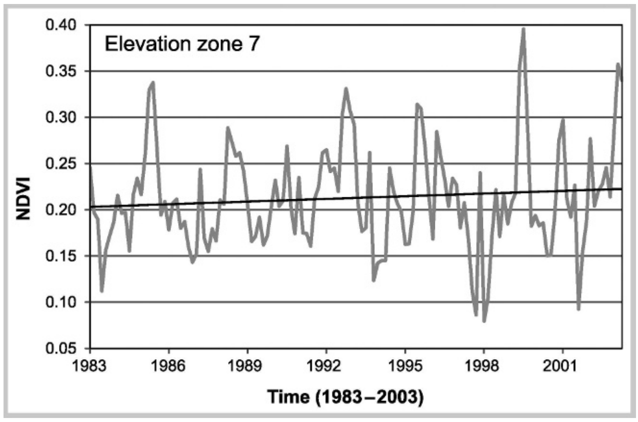


TABLE 1 Human activities and elevation zones on Kilimanjaro. (Based on author data)

Zones	Elevation	Description
Zone 1	>2000 m	Savanna, rain-fed agriculture, settlements to ice cap
Zone 2	>3000 m	Forest to ice cap
Zone 3	>4000 m	Alpine, ice cap
Zone 4	>5000 m	Bare rock, ice cap
Zone 5	2000 m–3000 m	Montane/submontane, agroforestry
Zone 6	3000 m–4000 m	Subalpine, dwarfed shrub, minimal human impact
Zone 7	4000 m–peak	Alpine fringe, bare rock, ice, no human impact

FIGURE 4 NDVI trend spanning 1982 to 2003 for the elevation zone from 4000 m to the peak.



signal has increased over the past two decades. The ecocline that exists along Kilimanjaro elevation gradients gained in green signal, indicating increases in biomass and vigor and/or decreases in ice cover. Hemp (2005) found that climate change at Kilimanjaro was responsible for shifting fire regimes, altering the vegetation structure of the mountain, and causing some downward vegetation migration. The changing fire regimes impacting vegetation structure could in fact result in new, more vigorous biomass growing at locations where fire cleared out woody debris. In this study, increasing green signal was indicative of increasing green biomass across all elevation zones. With alpine vegetation beginning around 3000 m, this phenomenon was noteworthy, with the alpine zones being particularly sensitive to climatic conditions.

The linear trends displayed in Figure 5 show the relationship between vegetation and elevation gradients. Lower (higher) elevations have higher (lower) NDVI values. The sharpest trend occurred for elevation zone 1 (0.30), with elevation zones 2 (0.21), 6 (0.21), and 7 (0.19) having similar slope values. Lower elevations closer to the human land use activity fringe possess smaller increases in slope values. This equates to the higher elevations of the mountain gaining the most in green signal. With minimal human land use activity occurring at these upper mountain elevation zones, the increasing slopes can be interpreted as a proxy for changing conditions.

As expected, NDVI values have lower minimums with increasing elevation zones. The alpine system transitions from sparse vegetation cover to bare ground by approximately 4000 masl. Generally, in this zone the NDVI values were relatively low compared with lower elevation zones. NDVI values approaching zero are the equivalent of bare ground or rock. With an increasing NDVI trend, plant biomass and vigor have been rising and/or encroaching into the bare ground areas approaching the peak. In order for these green signal increases to occur, ample resources and tolerable conditions are required. With numerous studies illustrating the relationship between NDVI increases and warmer temperatures (Myneni et al 1998; Tucker et al 2001; Slayback et al 2003), the increase in vegetation signal in the alpine region is concordant with those studies linking increased NDVI with increasing temperatures.

To provide regional context, a map illustrating NDVI trends for the region was developed (Figure 6). The region has undergone substantial changes in green vegetative signal that varies over time and space. Visible sharp decline in NDVI is apparent to the west of Kilimanjaro in central Tanzania, likely due to a combination of drier conditions and landscape

FIGURE 5 Linear NDVI trends for selected elevation zones. All zones indicate an increase in green vegetative signal over the past few decades.

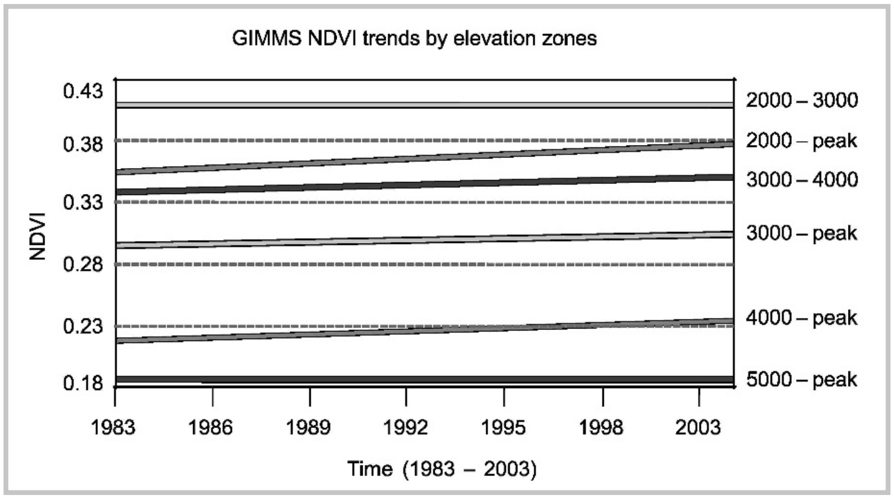
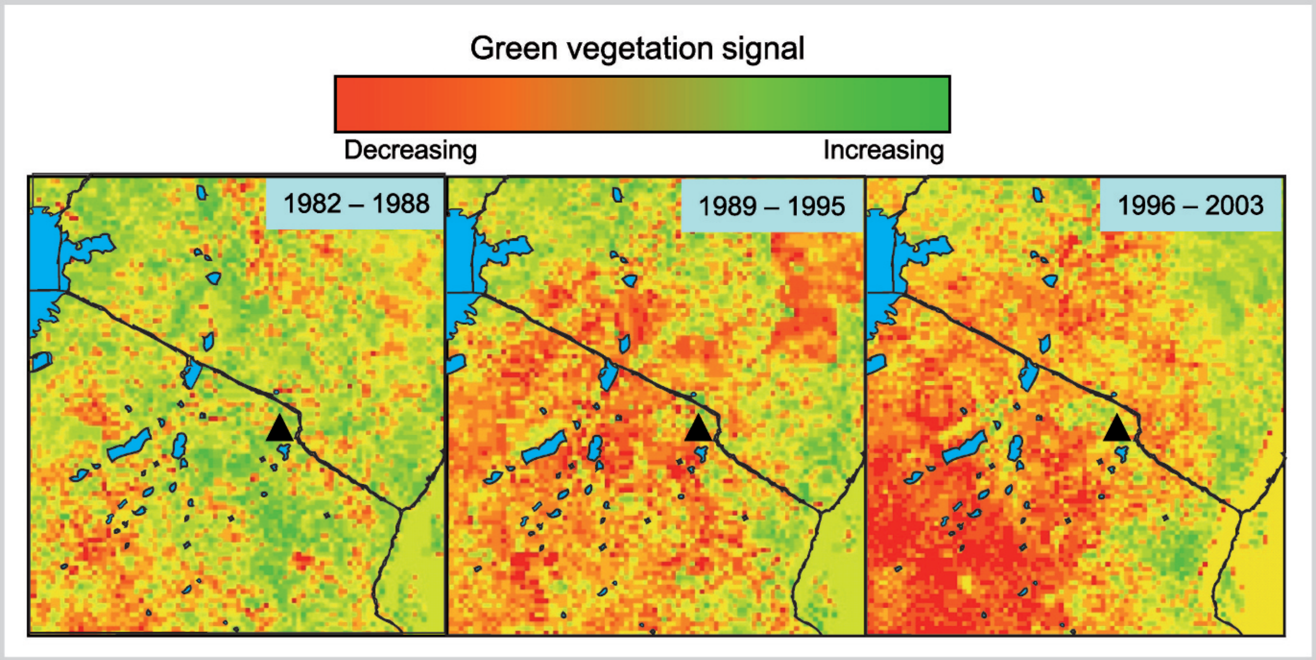


FIGURE 6 Change in NDVI for the Kenya–Tanzania border region. Three time periods show shifts in green vegetation signal with larger magnitude decreases occurring during more recent time periods (1996–2003).



modifications (Olson et al 2008). With a substantial decrease in green vegetation signal in the region, the opposite trends occurring at Kilimanjaro are likely a characteristic of the environment. The trend analysis on Kilimanjaro suggests that shifting climate is enhancing green signal upward along the ecocline at the expense of ice accumulation.

Seasonal dynamics

Evidence has shown that Kilimanjaro's glaciers are very responsive to seasonal dynamics and surface conditions (Molg et al 2003; Kaser et al 2004). Therefore, the dynamics in NDVI on Kilimanjaro can provide insight into the regional climatic variability. An objective of the seasonal pattern trend analysis was to examine the phenological occurrence of the dry season. The dry season is associated with low glacial ice mass conditions, or maximum ablation period. Third-order polynomial curves were fitted to capture seasonal trends for each year by elevation zone from 1982 to 2003. Figure 7 illustrates the year 1993 for elevation zone 6 (3000–4000 m). The dormancy season midpoint occurs approximately during the latter half of August (16.5) for 1993 in this elevation zone.

The annual dormancy period was identified for an individual year and plotted over time. The elevation zones all show temporal shifts (later in the year) in the occurrence of the driest period. The length in the shift of the driest time period increases by elevation zone. Elevation zone 7 (4000 m to the peak) has the greatest shift, with approximately a one-month time shift in the occurrence of the driest period, while elevation zones 5 and 6 have minimal shifts over the two-decade period. The large shift in the upper elevation zone suggests not only a change in timing of the maximum dry period but also a lengthening of the primary ablation period (Figure 8). Furthermore, this implies that the peak of the mountain was where the largest, and really only, shift in dry-period conditions occurred.

Conclusions

The approach used in this study adds insight into the changing land surface conditions and climate taking place at Kilimanjaro. At the rate of decrease as measured in this analysis the ice cap atop Kilimanjaro

FIGURE 7 Seasonal phenology displayed for 1993 fitted with third-order polynomial to identify the dry period. For the year 1993, the driest time of year occurred in the latter half of August.

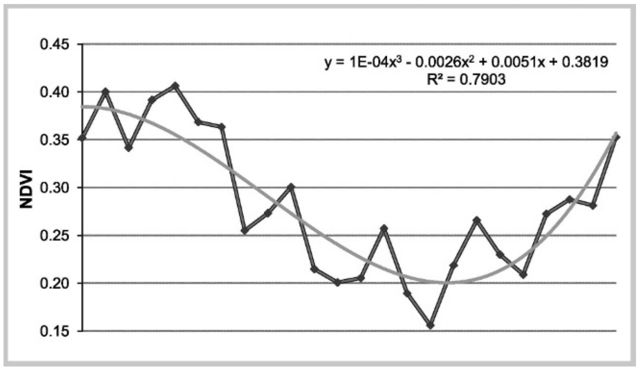
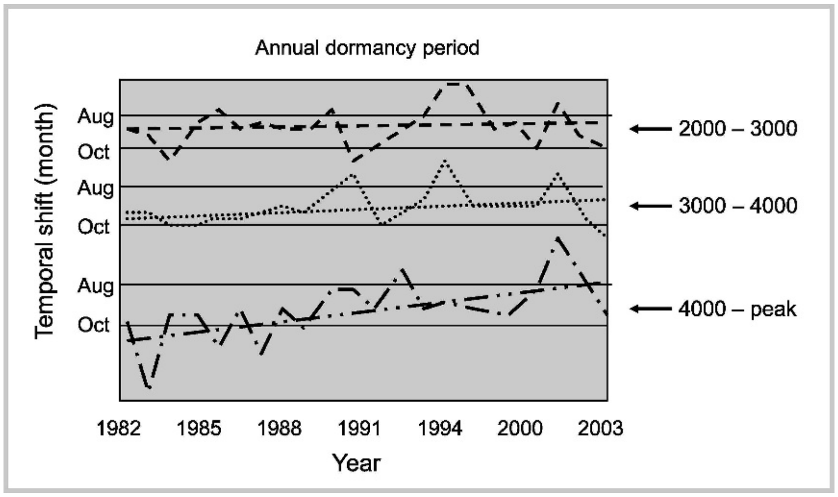


FIGURE 8 Annual dry season phenology for selected elevation zones showing temporal shifts from 1982 to 2003. The larger temporal shifts occurred at the higher elevation zones.



will be completely gone by 2010. All the upper elevation zones (above 2000 m) of Kilimanjaro have increased in green signal over the past two decades. In the sensitive alpine regions, increases can be an indicator of changing climate. The seasonal analysis shows a shift in the timing of the driest period, which coincides with maximum glacial ablation on the order of one month, with increasing elevation showing increasing temporal shifts. The lengthening of the dry period that happens primarily at the peak is suggestive of longer ablation seasons. Tremendous annual variability was present, with large shifts in maximum and minimum NDVI signal. We believe this is an indicator of variability in climate patterns. The seasonal shift in dormancy is a reflection of the general timing of the rainy seasons. This analysis shows that NDVI green signal increases have occurred on Kilimanjaro that are likely due to shrinking ice that causes more exposure of bare rock/soil. These changes took place where no direct human activity was present, and therefore, we believe, the variability and change in seasonality are impacts of regional climate change.

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