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Spatiotemporal analysis of snow cover variations at Mt. Kilimanjaro using multi-temporal Landsat images during 27 years

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ABSTRACT

The Landsat TM and ETM+ images have been acquired for the long period from the 1980s until the present with the temporal resolution of a 16-day repeat cycle from the visible, near infrared (NIR), short wave infrared (SWIR) and thermal infrared (TIR) bands. The Landsat multi-temporal images have been successfully used to monitor variations of the Earth surface during 27 years. In this paper, we observe the variations of (1) the snow cover area, (2) the snowline height and (3) the land surface temperature (LST) lapse rate at Mt. Kilimanjaro using a total number of 15 Landsat-5 TM and Landsat-7 ETM+ images from June 1984–July 2011. Segmentation of normalized difference snow index (NDSI) images with a threshold of 0.6 is used to extract snow cover. Snowline altitude is then determined by combining the snow cover classification maps with a digital elevation model (DEM). And the LST lapse rate is also calculated from the TIR band in the forest area. The results from this study show that (1) the snow cover area largely decreases from 10.1 km^2 to 2.3 km^2 during about 27 years, which corresponds to a 77.2% reduction, (2) the snowline height rose from 4760 m to 5020 m by about 260 m, and (3) the LST lapse rate shifted from −5.2 °C/km to −2.7 °C/km. This study demonstrates that multi-temporal Landsat images can be successfully used for the spatiotemporal analysis of long-term snow cover changes.

1. Introduction

Mt. Kilimanjaro, which is the tallest mountain in Africa, stands on the Kenya-Tanzania border approximately 370 km south of the equator. Kibo is one of the peaks of Mt. Kilimanjaro (5895 m) that has snow cover near the top (Kaser et al., 2004). The snow cover of Mt. Kilimanjaro has frequently been used as an indicator of the global and regional climate because it presents the interaction between snow cover and the climate of the tropics (Kaser, 2001; Torbick et al., 2009). The snow cover of Mt. Kilimanjaro affects approximately 3000 plant species and more than one million local people who depend on it for their livelihoods (Hemp, 2005), as well as water resource of the Pangani River that originate on Mt. Kilimanjaro (Lein, 2004).

It is well known that the snow cover has retreated continuously since the late 19th century at Mt. Kilimanjaro (Kaser et al., 2004; Klute, 1920; Hastenrath and Greischar, 1997; Thompson et al., 2002). The previous studies have reported that its area decreased by 82% from 1912 to 2002 (Klute, 1920; Thompson et al., 2002). Many researchers have argued that variation in the snow cover is one of indicators related with the climate change (Kaser et al., 2004; Hemp, 2005; Thompson et al., 2002; Molg et al., 2009). The Fourth Report of Climate Change Assessment of the Intergovernmental Panel on Climate Change (IPCC) in 2007 predicted that climate change would persist for several more centuries, even though greenhouse gas emissions might be mitigated. Thus, despite the variation in the small area, the snow cover on Mt. Kilimanjaro (especially on Kibo) is recognized as an indicator of climate change in Africa (Thompson et al., 2002; IPCC, 2007; Oerlemans, 2005). It is important to monitor the snow cover variations on Mt. Kilimanjaro.

According to previous studies, small scale circumstances could affect a strong ablation and melting, which known eight times more efficient than sublimation (Kaser et al., 2004). The mass balance is the product of changes in meteorological parameters depending on air temperature, solar radiation and precipitation (Oerlemans, 2005). The snow cover repeats cycles of accumulating in the wet season and ablation and melting in the dry season (Hastenrath and Greischar, 1997). Thus the snow cover area and the snowline height on the mountain slope have slowly been changing every year. During the dry seasons, enough energy are provided for substantial ablation at snow covers despite negative air temperature due to the small incidence angle of sun. The lack

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of turbulent air flow along the vertical surfaces prevent sublimation and allows the snow cover to melt. The melt water immediately evaporated without flowing downward. Therefore, melt water has been of little importance to the lowlands directly, only small rivers discharge from the slope glaciers (Kaser et al., 2004).

The observation of snow cover changes from remote-sensed images has been widely used because we can identify snow cover areas from images, and get the Earth surface information of the past through the images as well (Thompson et al., 2002; Nolin, 1998; Paul et al., 2004; Silverio and Jaquet, 2005; Bolch, 2007). Most of all, the Landsat satellites have acquired visible and near infrared (VNIR), short wavelength infrared (SWIR) and thermal infrared (TIR) images for the long period from the 1980s until the present, and hence we can monitor the snow cover changes on Mt. Kilimanjaro using the Landsat TM and ETM+ images during about 30 years. It means that the Landsat data have the remarkable capability that we can monitor the last 30 year's Earth snow cover from the data.

The previous studies are as follows: Nolin (1998) conducted mapping of snow cover using the normalized difference snow index (NDSI). The NDSI is used to identify snow from the reflectance difference between snow and clouds in the short wavelength infrared (SWIR) and near infrared (NIR) wavelength regions. This is because both clouds and snow have similar reflectance in the visible and NIR regions whereas the reflectance of a cloud is typically much greater than that of snow in the SWIR region (Riggs et al., 1994; Hall et al., 1995). In addition, Krajci et al. (2014) estimated snowline height from MODIS images for seasonally snow covered Jalovecky basins, Slovakia. In generally, the snowline defined as the lowest elevation of perennial snow, which is equivalent to the lower limit of snow cover at the end of summer (Porter, 2001). The snowline used to estimate equilibrium line and glacier mass balance (Rabatel et al., 2012; Shea et al., 2013). The snowline height variation on a tall mountain is strongly correlated with the land surface temperature (LST) variation. That is, the snowline height increases when the LST increases, while the snowline height decreases when the LST decreases. For this reason, it is possible to derive the variation of the LST from that of the snowline height and to estimate the variations in the snow cover in the near future as well. Moreover, Sun-Mack et al. (2014) and Maeda and Hurskainen (2014) studied LST lapse rate from MODIS data. The LST lapse rate is defined as the rate of decrease with height for the LST (Minder et al., 2010). It has been used: (1) to investigate the potential impacts of climate change, (2) to identify climatic controls on snowpack trends, (3) to diagnose human influences on regional climates and (4) to create models of mountain glaciers (Hamlet et al., 2005; Bonfils et al., 2008; Roe and O'Neal, 2010).

The objective of this study is to monitor the snow cover variations at Mt. Kilimanjaro using a total number of 15 Landsat-5 TM and Landsat-7 ETM+ images spanning the 27 years from June 1984 to July 2011. For the spatiotemporal analysis of the snow cover variations, we observe the variations of (1) the snow cover area, (2) the snowline height and (3) the LST lapse rate. For this, the NDSI is calculated from the each image after an atmospheric correction, and then the snow cover area and snowline height are estimated and analyzed from NDSI and the Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM). In addition, the LST lapse rate is calculated and interpreted from the TIR band in the forest area. The estimations show how much the snow cover area of Mt. Kilimanjaro has decreased, as well as how much the snowline height increased. Additionally, we show how much the LST lapse rate is reduced over time.

2. Study area and data

2.1. Study area

Mt. Kilimanjaro is located approximately 370 km south of the equator on the Kenya-Tanzania border between 2°45' and 3°25' South and 3°70' and 37°43' East (Fig. 1). Mt. Kilimanjaro consists of three single peaks: Shira (4005 m), Mawenzi (5140 m) and Kibo (5893 m) (Kaser et al., 2004; Hemp, 2005; Thompson et al., 2002). Kibo has two craters in the middle of the caldera, the one has diameter of 750 and the other has 300 m, respectively. There were a continuous glacier cover all around the crater rim and the large snow free areas in the approximately horizontal surfaces of the caldera. Glaciers are more extensive on the south and west than on the north and east because more abundant precipitation rainfall on the southern side (Hastenrath and Greischar, 1997). The summit glaciers around the crater have vertical walls of less than 25 m along north and south margins and ice bodies show a strong east-west side (Kaser et al., 2004). According to the nomenclature of glacier entities, glaciers of Mt. Kilimanjaro was composed of 20 patch in the 1970s (Hastenrath and Greischar, 1997). On the other hand, Cullen et al. (2006) divided into two glaciers by elevation: plateau ($\geq$ 5700 m) and slope ($<$ 5700 m) glaciers. In addition, Mt. Kilimanjaro has various plants and vegetation belts around the mountain. Most of plants and vegetation exist at altitudes until 4000 m, but there is still vegetation over 4000 m at least lichen, moss and grasses (Klute, 1920; Hemp, 2005).

Because Mt. Kilimanjaro is located East Africa, it is characterized by Equatorial trough and two distinct rainy seasons: the long rains from March to May and the short, but heavy rains concentrated in the period from October to December, accounting for about 18, 42, 15, and 25% of the mean annual rainfall, respectively (Klute, 1920; Indeje et al., 2000). Some 70–80% of precipitation rained when the Intertropical Convergence Zone (ITCZ) moves across the Kilimanjaro region (Camberlin and Philippon, 2002). The maximum precipitation of approximately 2700 mm occurs at 2200 m, reaching 80%, 70%, 50% and 20% of the maximum at 2400, 2700, 3000 and 4000 m, respectively (Hemp, 2001). The snowfall events of Mt. Kilimanjaro shows a similar trend with the annual precipitation cycle, showing the long rains and short rains seasons separated by two dry seasons in the 2000–2005. The seasonal distribution of the 70 significant snowfall events include: 14, 32, 6 and 18 events in the short dry (January to February), long rain (March to May), long dry (July to September) and short rain (October to December) season, respectively (Chan et al., 2008). The monthly snowfall was recorded more than 10 cm in wet season, but less than 5 cm in dry season (Hardy, 2003).

2.2. Data

A total number of 15 Landsat-5 TM and Landsat-7 ETM+ images were used for the measurements of the snow cover area and the snowline height of the Mt. Kilimanjaro over a period of 27 years from 1984 to 2011. To avoid uncertainties associated with seasonal changes of snow cover, we only used dry-season observations (see Table 1). The SRTM DEM was used to estimate the snowline height and the LST lapse rate. The air temperature data were acquired by the website TuTiempo.net (http://www.tutiempo.net). The Landsat images used for this study were concentrated in the 1984–1987, 1999–2002 and 2009–2011, because Mt. Kilimanjaro was covered by heavy clouds in most of the Landsat images. Thus, a statistical analysis was conducted by the division of the Landsat data into three groups (1984–1987, 1999–2002, and 2009–2011). The estimation of the LST lapse rate was performed using 8 Landsat images because the other images included heavy clouds in the vegetation area (Table 1).