remote sensing

Article

Snow Extent Variability in Lesotho Derived from MODIS Data (2000–2014)

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Abstract: In Lesotho, snow cover is not only highly relevant to the climate system, but also affects socio-economic factors such as water storage for irrigation or hydro-electricity. However, while sound knowledge of annual and inter-annual snow dynamics is strongly required by local stakeholders, *in-situ* snow information remains limited. In this study, satellite data are used to generate a time series of snow cover and to provide the missing information on a national scale. A snow retrieval method, which is based on MODIS data and considers the concept of a normalized difference snow index (NDSI), has been implemented. Monitoring gaps due to cloud cover are filled by temporal and spatial post-processing. The comparison is based on the use of clear sky reference images from Landsat-TM and ENVISAT-MERIS. While the snow product is considered to be of good quality (mean accuracy: 68%), a slight bias towards snow underestimation is observed. Based on the daily product, a consistent time series of snow cover for Lesotho from 2000–2014 was generated for the first time. Analysis of the time series showed that the high annual variability of snow coverage and the short duration of single snow events require daily monitoring with a gap-filling procedure.

Keywords: snow cover; MODIS; NDSI; Lesotho; temporal and spatial gap-filling

1. Introduction

The economy of the Kingdom of Lesotho, located in southern Africa, strongly depends on its water resources for hydro-electricity production, the export of water to South Africa, and for the irrigation of farmland. The mean annual precipitation is 600–800 mm in the lowlands and about 1200 mm in the mountainous areas [1]. Unfortunately, the rain gauge network is sparse, with only about 30 operational, long-term stations, and most of them are located in accessible areas. Consequently, the precipitation rate in the highest mountains (>3000 m above mean sea level (amsl)) is only an approximation. While winter precipitation is much lower, snowfall at higher altitudes can be frequently observed, and the snow remains on the ground for several days or even weeks. The snow water equivalent is not precisely known due to missing measurements in the Highlands, but it is assumed to total more than 100 mm per year [2].

The government of Lesotho has some concern related to climate change influencing on the amount and variability of precipitation in the future. The uncertainty associated with model predictions of precipitation change in southern Africa including Lesotho was presented in the latest IPCC Assessment Report (AR5) [3]. Independently of the selected scenario (*i.e.*, RCP 2.6 or even RCP 8.5), a slight trend towards reduced annual precipitation volumes was projected for the period between now and 2050. Irrespective of the changes to snowfall in the future, AR5 (2013) reported that air temperature is expected to increase. Depending on the scenario that is being considered, air temperature is projected to rise about 1–2 °C from now until 2050 during the winter months (*i.e.*, June–August). With the consideration of this approximated increase in temperature, the frequency of snowfall events is expected to decrease or snowmelt will begin earlier. This is attributed to the mean winter temperature at Sani Pass (2850 m), which was −2.9 °C in 2003 and −2.1 °C in 2004 [4]. Consequently, a slight increase in temperature effectively reduces the number of snowfall days, as well as the duration of snow cover in the highlands of Lesotho. The resulting impact on snow cover is unknown due to missing information about snow cover distribution and its dynamic, because only five measurement stations report sporadic information about snowfall and they are only located in accessible valleys [5].

However, local stakeholders have indicated that there is a strong need to have information about the spatial distribution of snow; this information is used to locate areas with sufficient water availability to initiate crop production but also to get information about the year-to-year variability. Only satellite remote sensing can help provide some of the missing data.

In particular, snow extent is a parameter that is commonly retrieved by optical satellite data [6–9]. During the last years, many studies showed the benefit of remote sensing derived snow maps [10,11] for mountainous areas with ephemeral snow dynamic. Unfortunately, in this regions prevailing cloud cover limits monitoring of the ground but post-processing considering temporal and spatial characteristics of the snow cover minimizes these gaps [12,13]. Especially the MODIS sensor with 36 spectral bands and a reasonable resolution of 250 m–1000 m is an appropriate tool to monitor snow cover in mountains [14]. The MODIS snow product (MOD10A1) [15] was used by [16] to monitor the snow dynamic of the Moroccan Atlas mountain range. They improved the original snow mapping applying a spatio-temporal filter algorithm to reduce cloud-affected pixels considering three days in backward direction. A recent study by [17] analyzed the MODIS snow maps for the area of Arizona, USA to retrieve snow covered days (SCD) for different catchments. A comparison with *in situ* SNOTEL measurements resulted in a correlation (R^2 = 0.62) for the whole 12-year period. The spatial comparison with Landsat-TM data (NDSI > 0.4) showed an overall accuracy of 77% to 91% for the MODIS product but they noted that thin snow cover was with both sensors not always properly detected. Zhang *et al.* [18] and more recently Yu *et al.* [19] considered MODIS data for their studies on the Tibetan Plateau. Zhang *et al.* [18] combined Terra/Aqua snow products and aggregated it to multi-day snow maps to further reduce cloud cover for improved retrieval of SCD and other metrics for different drainage basins on the Tibetan Plateau. Yu *et al.* [19] combined not only Terra/Aqua snow products but also included the daily snow map of the Interactive Multisensor Snow and Ice Mapping System (IMS) [20] to improve snow mapping significantly due to reduced cloud coverage. A study of Gafurov *et al.* [21] applied an improved method to reduce cloud cover in the MODIS snow product. They developed a six-step procedure considering also temporal and spatial aggregation to get cloud free information for one catchment in Afghanistan. These examples show the usability of the MODIS sensor for snow monitoring in different regions of the world and the need for a gap filling procedure to overcome the cloud problem.

For Lesotho, some studies also showed the usability of satellite remote sensing to monitor the snow cover. Mulder and Grab [22] used Landsat-5 and Landsat-7 low resolution data (360 m) between 1989–2004 to generate snow maps of the Drakensberg mountains, Lesotho. However, the frequent cloud cover combined with Landsat's 16 days imaging repeat cycle [23] resulted in only one to three useable images during the winter periods 1989–2001. Only during winter 2002 were eight images available. Altogether, a supervised classification technique was applied to 41 images, which only covered areas with elevations above 2600 m. The low temporal resolution of Landsat limits the detection of thin snow layers that last only for several days because melting may occur before the next overpass of Landsat. In a subsequent study [24], MODIS rapid response data from 2003–2010 was used to monitor snow cover for Lesotho based on NDSI (NDSI $\geqslant$ 0.4) and a defined threshold (reflectance of Band 4 > 11%) as published for the SNOWMAP algorithm [15]. The retrieved snowfall frequency has high variability (SD = 2.56 number of snowfalls per month), with only one detected snowfall event in 2003 (August), but eight events in 2007 (May–August). The mean extent per snowfall event that occurred between 2003 and 2010 also varies from 355 km^2 (2005) to 4379 km^2 (2006); a larger extent based on a single event was only observed in 2003 [24]. Snowfall was also occasionally detected in October/November, but only lasted for one day [25]. Grab and Linde [24] presented a study on snow cover distribution in Lesotho, which was based on an 8-year long MODIS data series but without any gap-filling techniques to reduce cloud cover as shown by [13,16,18,19]. The high snowfall variability and its spatial distribution require a time series that should be as long as possible to support more reliable analyses. Very often after a snowfall event, persistent cloud covers over the area of interest limits the ability of optical sensors to detect snow on the ground; this information is required for the calculation of mean snow cover durations. Most of the cited references related to Lesotho used only one sensor for snow retrieval without any gap-filling post-processing. Furthermore, accuracy of the retrieved snow cover data has yet to be conducted.

The uncertainty, missing knowledge about snow cover distribution in Lesotho, and the data needs of both the government of Lesotho and the National Weather Service have led to the initiation of a project on snow monitoring. The project is based on the application of satellite data within the eoworld2 framework, which is the result of a collaborative initiative between the World Bank and European Space Agency (ESA). The aim of the study was to generate a homogenous time series of snow cover for an extended time period, and to retrieve the snow cover variability for the highlands of Lesotho. Some requirements concerning both spatial and temporal resolutions need to be fulfilled to meet the aforementioned objectives. Due to the high variability of snow cover, only satellite data with high temporal resolution (*i.e.*, at least one day revisits) can provide the necessary information for snow monitoring [17,18,21]. The tradeoff between temporal and spatial resolution resulted in the selection of MODIS data (MODIS Surface Reflectance Product MOD09GA) for the aforementioned purposes. The MODIS snow product (MOD10A1) was not used for the generation of the time series because snow is often classified as cloud. However, the MOD10A1 snow product and our own retrieval based on MOD09GA were considered for comparison with ENVISAT-MERIS (270 m) and Landsat-TM (30 m) imagery because ground data are not available. Section 2 provides further information on the satellite data and auxiliary products (e.g., elevation model) that were used in this study. The generation of snow maps is based on the Normalized Difference Snow Index (NDSI) and on the definition of additional thresholds for spectral channels in the VIS and NIR range [6,26]. Data gaps attributed to persistent cloud cover are filled with temporal-spatial interpolation techniques to generate a product with daily snow cover information [13,18,21]. Details about the snow retrieval process will be presented in greater detail in Section 2.2. For the first time, a daily snow extent product (2000–2014) is available for Lesotho.

2. Data and Methods

2.1. Study Area

The Kingdom of Lesotho is located in southern Africa (Figure 1). It is 30,355 km^2 and is the only state in the world where its lowest point is located above 1400 m amsl. Approximately 80% of the country has an elevation that is greater than 1800 m and the highest mountain reaches 3482 m (Figure 1). Due to the high altitudes, its climate is cooler than in other regions located at the same southern latitude. While most of the precipitation falls during the summer months, snow in the winter is also common. Trade winds transport humid air masses to the eastern part of South Africa, which result in orographic induced rain events at the Drakensberg Mountains in Lesotho. During the summer period (*i.e.*, December–February), tropical temperate troughs contribute substantially to the precipitation rate in this area, where more than 7 days per months receive >10 mm of rain [27]. During the winter period, cold fronts dominate at the Drakensberg Mountains in Lesotho and along the eastern slopes of KwaZulu-Natal in South Africa [4] leading to frequent snowfalls.

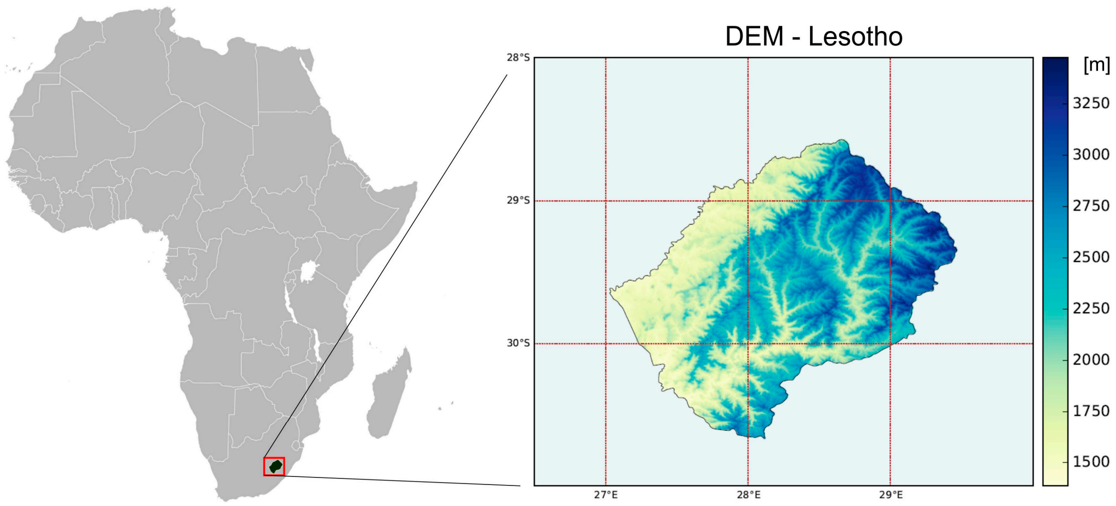

Figure 1. Lesotho in southern Africa (**left**) and digital elevation model of Lesotho (ASTER GDEM) (**right**).

Dominating land cover in Lesotho is cropland (below 1800 m) and grassland/shrubland in higher elevations. Only a few square kilometers are covered by natural forests (0.2% of Lesotho) in the low lands [28].

2.2. Data

We use data acquired by the MODIS sensor, higher resolution satellite data from MERIS onboard ENVISAT, and Thematic Mapper (TM) data from Landsat-7 to compare the snow product derived from MOD09GA. For post-processing of the snow cover maps, an elevation model (Figure 1) derived from ASTER data was employed to delineate the snow line. Details about the data sets are presented in the following sections.

2.2.1. MODIS

The MODIS sensor onboard of Terra was used. While there is also a MODIS sensor on Aqua, the combination of both data sets showed no notable improvement. Hence, Aqua was not considered any further. The use of MODIS data is considered to be one of the best possible choices for snow data retrieval, due to its high spectral and temporal resolution, and data availability since 2000 [29,30]. Imagery over Lesotho is available on a daily or twice daily basis with spatial resolutions between 250 m and 1000 m, depending on the spectral channel. In general, the MODIS snow product is widely accepted and has already been validated for many regions around the world [14,18,29,30]. However, an initial visual inspection of the snow common product (MOD/MYD10A1; [31]) revealed that the cloud detection mask erroneously eliminates too many snow-covered areas. These findings were also reported by [32,33]. Even between morning and afternoon overpasses, a remarkable difference is observed, which is caused by the dominating cloud mask in each of the distributed snow products. The authors of this study implemented an independent snow data processor, based on the MODIS Surface-Reflectance Product MOD09GA, to address the aforementioned limitations associated with directly applying the MODIS cloud mask over Lesotho.

The MODIS Surface-Reflectance Product (MOD09GA) is calculated from MODIS Level 1B land Bands 1–7 (centered at 0.648 µm, 0.858 µm, 0.470 µm, 0.555 µm, 1.240 µm, 1.640 µm, and 2.130 µm, respectively). It has a spatial resolution of 500 m. The product represents an estimate of the surface spectral reflectance for each band.

The product is available in tiles with a sinusoidal projection (MOD/MYD09GA). The tiles are approximately 1200 × 1200 km^2 in area. Within this project, the sinusoidal tiles h20v11 and h20v12 were used to account for the full extent of Lesotho and downloaded from [34].

2.2.2. Landsat-Thematic Mapper (TM)

Snow retrieval data derived from Landsat imagery were defined as the reference data set, as in previous algorithm development studies [35,36]. This is particularly advantageous due to the high spatial resolution of the product and due to the fact that ground truth measurements are unavailable.

The Landsat TM and ETM+ sensors are whiskbroom scanners that capture multispectral images in seven spectral bands (plus one panchromatic band), most of which have a spatial resolution of 30 m. In this study, the most relevant bands are Band 2 (centered at 0.56 μm), Band 3 (0.66 μm), Band 4 (0.83 μm), and Band 5 (1.65 μm). In general, thermal Band 6 (11.45 μm) and SWIR Band 7 (2.21 μm) are used to mask clouds. However, to mitigate against cloud over-detection, this comparison was mostly restricted to clear-sky scenes (17 scenes from 2000 until 2003; downloaded from [37]. Unfortunately, most of the selected scenes were acquired during seasons with reduced snow cover. Consequently, a second reference data set based on the MERIS imagery was also used in this study.

2.2.3. ENVISAT-MERIS

The MERIS sensor, flown on the ENVISAT mission, is a pushbroom spectrometer that gathers data in 15 spectral bands within the visible and near infrared range. With spatial resolution of 260–290 m (at nadir), this sensor can serve as validation reference data to assess the accuracy of the MODIS snow covered extent (SCE) product over the highlands of Lesotho. ENVISAT monitors in a 35-day repeat cycle; however, MERIS' swath width of 1150 km enables global coverage of the Earth in three days. Hence, more clear-sky reference data covering different snow extents in Lesotho could be acquired and used as validation references.

Even though the primary mission of MERIS is to monitor oceans and coastal areas, it offers some opportunities for mapping snow cover at regional/catchment scales over Lesotho. Channel 13 (0.865 μm) and Channel 14 (0.885 μm) are used for further processing. While the high spectral resolution of 15 bands across the 0.4–1.05 μm range is suitable for snow detection, the MERIS sensor lacks short wave infrared and thermal channels that would otherwise support the discrimination of snow from clouds. Therefore, only scenes over Lesotho that likely represent clear-sky conditions were manually selected as a part of the MERIS reference data set. A set of 59 scenes found between the years 2003–2011 that met the aforementioned criteria were included in the reference data set. The MERIS L1b data for all of the carefully selected clear-sky days were downloaded from the ESA MERIS merci service [38] (http://merisfrs-merci-ds.eo.esa.int/merci/welcome.do) and archived at the University of Bern.

2.2.4. Auxiliary Data

Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data on NASA's Terra spacecraft were the basis for the Global Digital Elevation Model (GDEM) V2. The GDEM relies on the along-track stereoscopic capability of the ASTER sensor. It has a spatial resolution of 30 m and covers regions between 83°N and 83°S [39]. The mean absolute elevation error is −0.2 m, with a standard deviation of 8.68 m compared to US elevation (CONUS) data [40]. The accuracy of the GDEM depends on land cover and the steepness of an area of interest. The elevation model was first used to allocate every snow covered pixel at a given altitude to retrieve the snow line altitude. Additionally, all land pixel elevations were considered for plausibility tests that were conducted during the post-processing stage of Lesotho's snow cover.

2.3. Methods

The use of optical satellite to monitor snow cover has been mainly based on the Normalized Difference Snow Index (NDSI) for many years. This is considered to be one of the most reliable methods for snow masking and has also been applied for the MODIS snow product [41–43]. However, the following challenges associated with this method need to be considered. Firstly, clouds and snow both reflect incoming sunlight in VIS in a similar way. Secondly, reflectance values are modified by the slope and aspect of the underlying terrain. Furthermore, sub-pixel snow cover values alter the pixel's reflectance, as well as partly snow covered forests. Since forests in Lesotho are sparse, the modified process described by [44] is unnecessary.

2.3.1. MODIS Processing

The NDSI concept capitalizes on the fact that snow and ice are considerably more reflective in the visible part (MOD09 Band 4: 0.555 µm) than in the short-wave IR (MOD09 Band 6: 1.640 µm) part of the spectrum. On the contrary, the reflectance of most clouds remains high in the short-wave IR portion of the spectrum. The calculated NDSI is located between −1 and +1, where values above 0.4 represent pixels that are at least 50% snow covered. Lin *et al.* [45] analyzed different snow indices using MODIS and Landsat-TM data to show the relation between snow cover fraction (SCF) and indices (*i.e.*, NDSI). Strong scattering of SCF *versus* NDSI is shown depending on the area. For SCF of 50% the NDSI values range between −0.2 and 0.7 but the retrieved equation of the regression results in a snow cover fraction of 0.557 with a NDSI of 0.4. In addition, Mishra *et al.* [46] elaborated in detail the relation between snow cover fraction and NDSI to be compared with different classifiers. They showed a strong relation between NDSI and SCF. A NDSI of 0.4 represents a snow-covered area of 40%–60%. Therefore, the widely used threshold of 0.4 was used to process all of MODIS Terra data from 2000–2014.

$$\mathrm{NDSI} = (\mathrm{MOD09\_B4} - \mathrm{MOD09\_B6})/(\mathrm{MOD09\_B4} + \mathrm{MOD09\_B6}) \quad (1)$$

Most of the clouds were eliminated for NDSI values ⩾ 0.4, although some semi-transparent or sub-pixel clouds remained. In particular, low lying clouds or fog sometimes resulted in the misclassified of clouds as snow. The generated snow maps were visual validated to eliminate erroneous snow classifications. In addition, we have used the cloud flag "potentially cloudy" of the MOD10A1 snow product to facilitate spatial and temporal post-processing. Furthermore, thresholds for B2, B4 and B6 were included to remove dark targets that have similar NDSI values as snow. A pixel is classified as "snow" if NDSI ⩾ 0.4, MOD09GA_B2 > 11%, MOD09GA_B4 > 10% and MOD09GA_B6 > 10%. Otherwise, the pixel is classified as "not snow".

2.3.2. Processing of Landsat-TM

The Landsat-TM data were calibrated with respect to the meta layer and Top-of-atmosphere Reflectance (TOA) data using Geomatica 2014.

The generation of snow data with Landsat imagery follows the same process as with the MODIS imager, and is based on the derivation of a Normalized Difference Snow Index. Channels 2 and 5 were used for the calculation. Klein *et al.* [44] also take the Normalized Difference Vegetation Index (NDVI) into consideration to prevent misclassifications in forested areas. Due to the fact that only 0.2%–1.4% of Lesotho's landscape is covered by forests [28,47], NDVI thresholds were not included.

$$\mathrm{NDSI} = (\mathrm{B2} - \mathrm{B5})/(\mathrm{B2} + \mathrm{B5}) \quad (2)$$

According to [44], a pixel is classified as "snow" if NDSI ⩾ 0.4, B2 > 0.10 and B4 > 0.11; otherwise, the pixel is classified "not snow".

Due to the use of clear-sky Landsat images, misclassification due to clouds was not an issue. Eight Landsat-TM images were supervised classified (Maximum Likelihood classification method) to proof the quality of the NDSI-product. The retrieved snow extent is of reasonable quality with a slight underestimation (mean difference: −10.6%) but with improved accuracy (difference: −8.4%) for days with extended snow cover. Worth noting is that only clear-sky Landsat data were available for days with minor snow cover of the country (0.4%–1.2% of the area of Lesotho). On these days, snow is distributed as widely scattered patches located at the highest mountains making a precise retrieval challenging [30,33]. The quality of snow mapping is improved for days with more homogenous distributed snow cover [46,48].

NDSI-pixel values were aggregated and resampled to identify fractional snow cover (FSC) within a given MODIS pixel. An aggregated sum >50% snow cover of a MODIS pixel transfers FSC into a binary information indicating snow.

2.3.3. Processing of MERIS

Snow processing was carried out using BEAM (*i.e.*, a processing software for sensors on board of ENVISAT, developed by Brockmann Consult on behalf of ESA) and a range of scripts developed for standard analysis (*i.e.*, IDL/R/Python). The following steps are applied to each reference scene: firstly, the radiometric correction and reprojection from swath to geographic projection (Lat-Long) was performed using the BEAM MERIS Level 1 Radiometric Processor and Reprojection Tool; secondly, snow classification using the MERIS Normalized Differential Snow Index (MNDSI), considering MERIS bands at 865 nm (Channel 13) and 885 nm (Channel 14) to simulate the NDSI, which exploits the decrease of reflectance from VIS to red or from NIR to SWIR. This is commonly applied to AATSR, AVHRR or MODIS data, where SWIR bands are available. The MNDSI concept was developed by [49] within the MERIS AlbedoMap project framework, and is calculated as follows

$$\text{MNDSI} = (\text{MERIS\_13} - \text{MERIS\_14})/(\text{MERIS\_13} + \text{MERIS\_14}) \quad (3)$$

Originally, a threshold (*i.e.*, MNDSI > 0.02) was defined by [49], but our investigation based in Lesotho showed that results improved with an application of a threshold of 0.01. Therefore, if a pixel was flagged as bright beforehand, and has a MDSI value that is greater than 0.01, it is classified as snow or ice.

2.3.4. Post-Processing

Post-processing was applied to support further analysis of snow cover dynamics in Lesotho. The primary objective is to reduce cloud cover (*i.e.*, by making assumptions about the surface condition beneath the cloud cover). The following post-processing procedure is based on the application of a combination of spatial and temporal filters [12].

Spatial filtering: In the first step, a straightforward spatial filter is applied using the regional snow line estimation (SNOWL) method proposed by [13]. Every snow-covered pixel is associated with an elevation value based on the ASTER-derived GDEM. The snow line is delineated starting with the highest elevations in a frequency distribution of snow cover (%; y-axes) with respect to altitude (m; x-axes). Due to the dependence of snow development and persistence on temperature, which is linked to altitude, the reclassification of all cloud covered pixels located above the snow line as snow is considered to be valid. Pixels located below the snow line are reclassified to snow-free land. The accuracy of this method was assessed by [13] with data from 754 climate stations over Austria; the SNOWL method was found to produce robust snow cover maps, even under abundant cloud cover (*i.e.*, 90% coverage). This method was also successfully applied by [12] to the European Alps using medium resolution AVHRR sensor data.

Temporal filtering: In a second step, a forward (pixel value of the closest clear-sky observation in the forward time direction) and a backward (pixel value of closest clear-sky observation in the backward time direction) gap-filling procedure [16,17,50] is carried out. Foppa and Seiz [50] used a period of 7 days in both directions for the European Alps. Generally, the time period for filtering needs to be as short as possible, but long enough to obtain cloud-free composites. Hence, it is a trade-off between remaining clouds and the blurring of snow information that result when filtering periods are overextended. Since the single snow events in Lesotho were followed by rapid melting, a maximum filter period of three days in both time directions was chosen for this study.

Figure 2 shows two examples of MODIS RGB images of Lesotho (upper row: 5 August 2006; lower row: 15 August 2012), where the national border is represented by a thin black line, and the resulting snow maps (right). The dark blue indicates the snow cover retrieved by NDSI based on MOD09GA and the light blue areas are filled by post-processing.

The image obtained on 15 August 2012 (lower row) shows some low lying clouds covering parts of southeastern and western Lesotho. The snow retrieval worked well and only some gaps at the southern tip of the country were filled with the post-processing procedure.

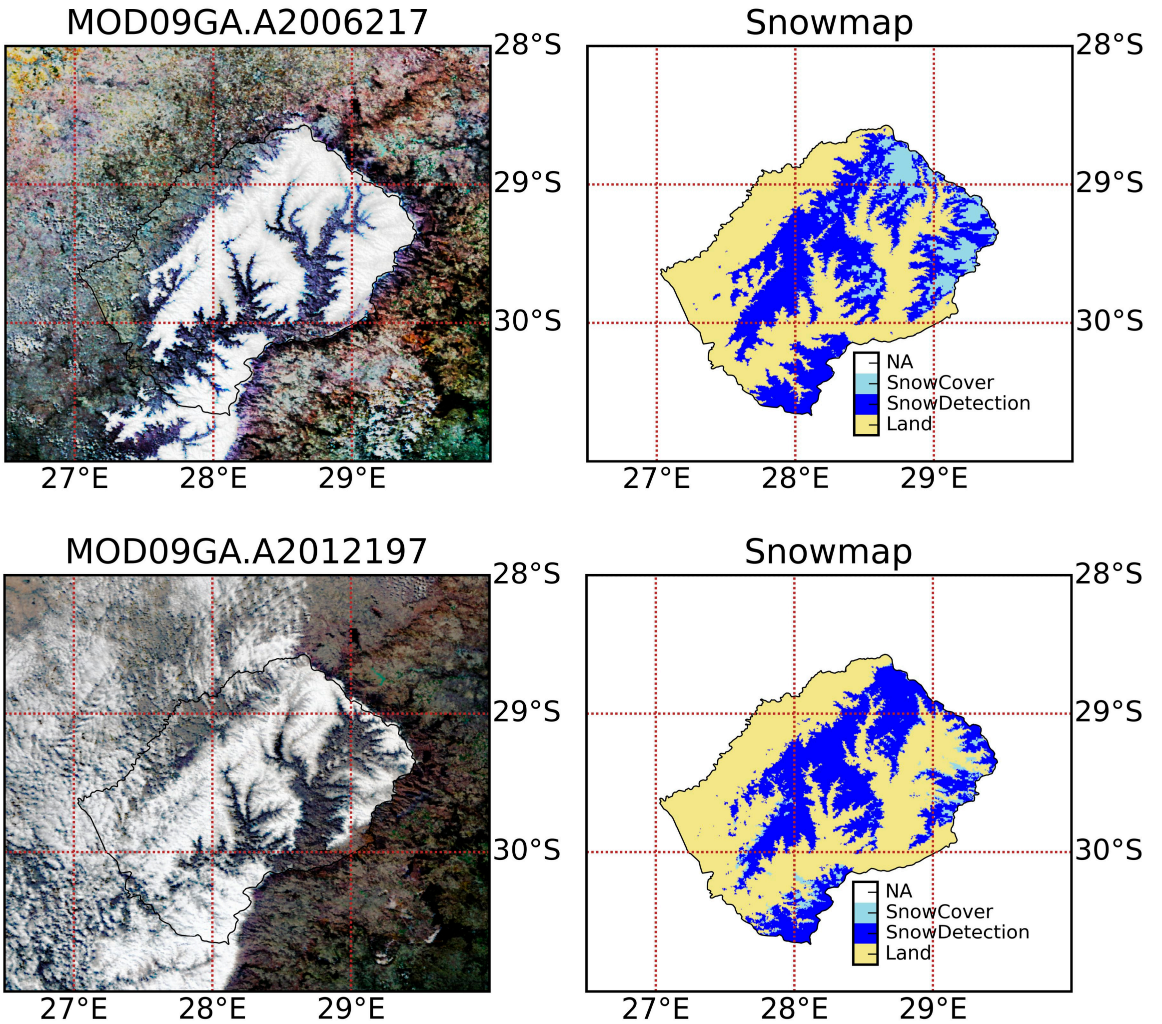

Figure 2. MODIS images (R: Band1; G: Band4; B: Band3) from 5 August 2006 (**upper row**) and from 15 August 2012 (**lower row**) with retrieved snow maps (**right**). Retrieval based on MODIS MOD09GA data (dark blue = "Snow Detection"); gap filling with temporal-spatial post-processing (light blue = "Snow Cover").

Besides the restrictive snow retrieval as described in the previous section, a pixel that is erroneously classified as snow can cause widespread artificial snow cover via post-processing. To minimize the introduction of erroneous artifacts, plausibility tests are conducted after the spatial post processing step (SNOWL), where the following conditions are checked: the cloud cover should not exceed 90% and the snow cover of Lesotho should be larger 0.1% ($\approx$30.4 km^2). In addition, the mean snow line altitude has to be higher than mean altitude of all snow free pixel and the 99% percentile of snow elevation should be above the 99% percentile of mean altitude of land elevation (snow free area).

Finally, every snow event was visually verified against MODIS RGB images to remove uncertain snow pixels from the final distribution pattern. This minimizes the inclusion of erroneous artifacts in the final time series, which would otherwise adversely influence the analysis.

2.3.5. Validation and Comparison

The quality of the final MODIS snow product is assessed by comparing the snow maps derived with satellite data at a higher spatial resolution. The snow information from the reference sources is compared with the MODIS snow map on a per pixel basis, after all of the reference data sets were resampled to the spatial resolution of the MODIS snow product. A contingency table (Table 1) was used to indicate the quality of the MODIS snow product: if both products identified the pixel as snow, it is labeled as a hit (h); when neither products indicated the pixel as snow, it is labeled as zero (z); if the MODIS product indicates the pixel as snow, but not the validation source, the pixel is marked as false (f); and if the opposite occurs, the pixel is indicated as a miss (m) [51–53].

Table 1. Contingency table used to determine hit rate and bias.

		Snow Validation Source (Landsat-TM or ENVISAT-MERIS)		
		yes	**no**	
MODIS snow product	**yes**	h: hit	f: false	h + f
	no	m: miss	z: zero	m + z
		h + m	f + z	n = h + f + m + z

Based on these measures, the hit rate (HR) and bias were calculated for each validation source (Landsat-TM and ENVISAT MERIS):

$$HR = (h + z)/n$$

$$bias = (h + f)/(h + m)$$

The hit rate indicates whether a clear match between the reference data and the retrieved snow cover is observed, whereas bias is a relative measure of whether the derived snow cover is over- or underestimated.

3. Results

3.1. Comparison

The hit rates are calculated based on Landsat and MERIS reference snow maps. Besides Landsat's high spatial resolution, cloud free data are limited and only partially cover Lesotho. As a result, only a few data points can be used for comparison (Figure 3, left). In addition, the selected Landsat and MERIS imagery depict situations with a limited snow cover; only a few data points represented snow coverage greater than 10%. In general, the hit rate is high (>90%), but slightly decreased with increased snow cover. A similar behavior was found when comparing the snow product with the MERIS validation data (Figure 3, right), where a reduced hit rate was calculated for areas with increased snow cover. This is likely due to the presence of snow of only a few centimeters deep at lower elevations, but with coverage that extended hundreds of square kilometers. The snow does not cover the surface completely due to the rough and inhomogeneous types of underlying land cover. A sensor with coarse spatial resolution receives a mixed signal that degrades the accuracy of the retrieved data, whereas the reference sensors are capable of capturing heterogeneous landscape with small patches of snow. The resampling of the reference data to the pixel size of MODIS degrades the information, but the logic behind the decision as to whether a pixel is classified as snow is based on a defined threshold of the fractional snow cover. It can be assumed that a resampled reference pixel, indicating "snow" is at least 50% snow covered. These findings were also highlighted by [29] and [30], which compared and analyzed the quality of the MODIS snow product (MOD/MYD10A1). The post-processing step resulted in a slight improvement to our MODIS product, with respect to an increase in the hit rate. However, it should be noted that most of the selected images were almost cloud free and only situations with low snow cover were monitored. Consequently, improvements due to the application of the post-processing procedure are mainly useful for situations involving persistent cloud cover.

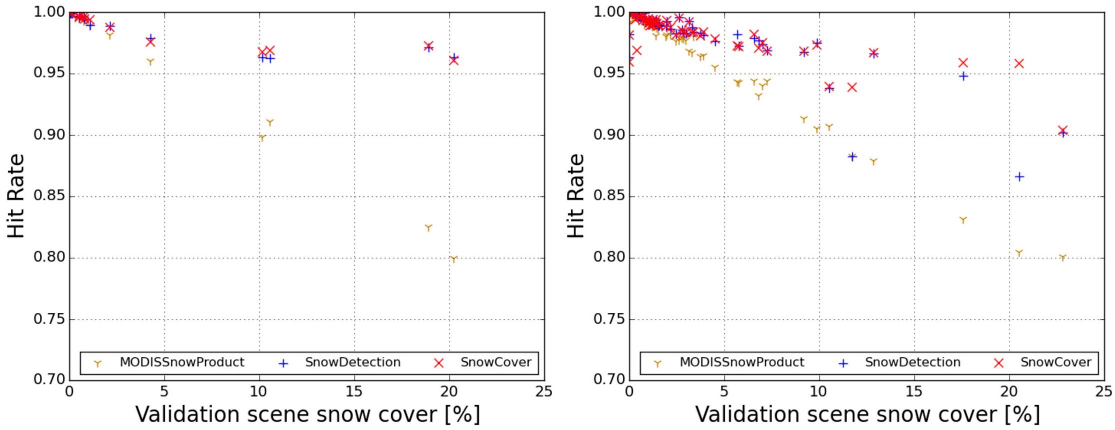

Figure 3. Comparison of MODIS standard snow product (MOD10A1) and the snow product based on MOD09GA data showing the calculated Hit Rate with respect to Landsat (**left**) and MERIS (**right**) data. The red x-marks indicate snow detection using NDSI based on MOD09GA data and the blue x-marks stand for the resultant snow cover after temporal and spatial post-processing. For comparison, the quality of the MODIS snow product (MOD10A1) is also shown (brownish x-marks).

The improved snow product, following the application of the post-processing steps, is clearly shown in Figure 4. The snow product based on MOD09GA underestimates the snow cover by approximately 15% when compared with the Landsat reference data (Figure 4, left); a slightly higher bias is observed when it is compared with the MERIS reference data. Higher bias values are found for lower snow coverages (<5%) of the country. For these situations, only some remaining snow in the mountains is measured and the spatial resolution of the sensor plays an important role to detect snow cover over rough terrain. Consequently, MODIS imagery with 500 m spatial resolution was unable to fully resolve the fine scaled snow distribution in the mountains, especially in comparison to systems with higher spatial resolutions. For comparison, the MODIS standard snow product (MOD10A1) is also shown in Figures 3 and 4 indicating a lower hit rate and a remarkable bias caused by the cloud mask, which miss-classifies snow as cloud.

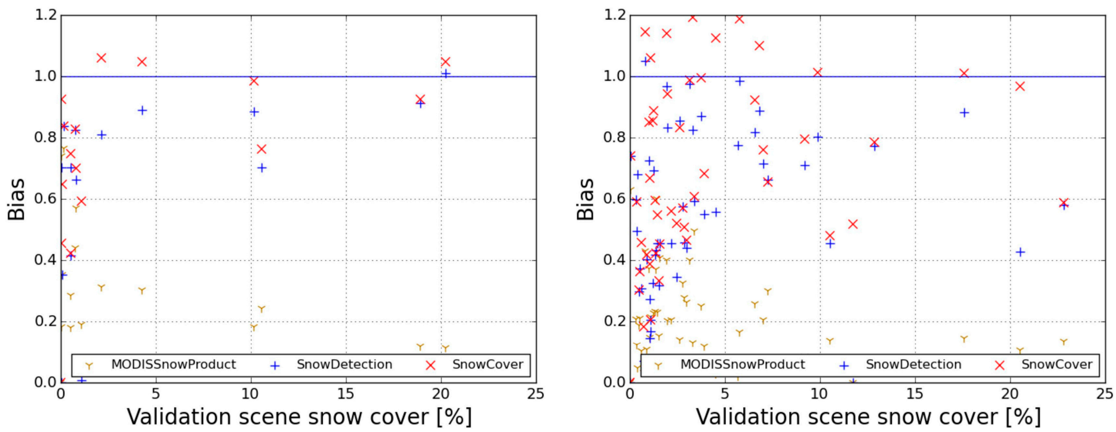

Figure 4. Calculated bias between validation source (**left**: Landsat; **right**: MERIS) and snow cover derived from MODIS data (MOD09GA) with the application of NDSI (red x-marks represent "snow detection") and after temporal and spatial post-processing (blue x-marks represent "snow cover"). For comparison the quality of the MODIS standard snow product (MOD10A1) is shown with brown x-marks.

The snow cover product was of a reasonable quality when compared with the reference data sets and was improved with the implementation of the post-processing steps, based on the consideration of the spatial distribution of snow and its temporal changes.

3.2. Time Series

Snowfall in Lesotho is common, but often occurs during the winter months with high inter-annual variability. The snow cover rarely exceeds 50% of the country and only persists at higher elevations for more than approximately 20 days. In general, a single snow event covers the upper part of the mountainous areas, but snowmelt starts shortly after accumulation. Similar cycles are also monitored in some other mountainous regions, *i.e.*, Moroccan Atlas [16] and the Tibetan Plateau [18]. This behavior results in a characteristic depletion curve that is characterized by an exponential shape. The lower parts of the country are only covered by some centimeters of snow, which melts rapidly (*i.e.*, within a day) after snowfall events. Consequently, snow extents sometimes decrease from more than 50% of the country's area (Figure A1; July 2001) to below 10% in a very short period of time (*i.e.*, less than a week). Only the snow cover at the highest parts of the mountains remains for a longer time due to the colder temperatures associated with these altitudes. This results in the exponential shape of the depletion curve (e.g., Figure 5; end of May 2006). The high inter-annual variability was observed in 2002 and 2003. In 2002, more than eleven snowfall events occurred during winter, which lead to the formation of a permanent snow cover at higher elevations for more than two months (*i.e.*, mid of June to mid of August). More than 40% of the country was covered by snow three times within this period. In the following year, there was only one major snowfall event (August 2003), which covered less than 20% of Lesotho. After one week, the country was almost snow free. A similar snowfall and persistence pattern was observed between 2012 and 2013. 2012 was characterized by exceptionally strong snowfall events, which occurred quite often during the wintertime. In the beginning of June, more than 40% of the country was covered by snow, followed by some days of snow melt, before the next snowfall event occurred (*i.e.*, in the middle of June), where more than 40% of the country was affected again. A third major snow event occurred in the middle of July, just before the snow from the previous event had completely melted. One of the strongest snowfalls of the 15-year time series was recorded in August 2012. More than 60% of the country was covered, and it took more than a week for most of it to melt. Two minor snowfalls in September brought the long winter to an end. In contrast to 2012, the country was only affected by three minor snow events that did not cover more than 15% of the landscape in the following year. Furthermore, limited amounts of snow coverage lasted for only a short duration in 2005 and 2010.

The high variability of snow distribution is clearly illustrated in Figure 6. The light colored area(s) highlight low percentages of snow cover, whereas the dark areas indicate coverages of more than 40% of Lesotho's area. The exceptional winter events in 2012 were characterized by the numerous snow days that resulted in more than half of the country being covered. This is contrasted to the short snowfall events in 2003, 2005, 2010, 2013 and 2014, with low snow cover percentages. The high daily variability is clearly visible for every single year. However, there are also notable differences in the number and intensity of events from year to year. The country was only continuously covered by snow for a few short periods (e.g., 2011, Days 187–197), and this was observed for less than 20% of the total land area.

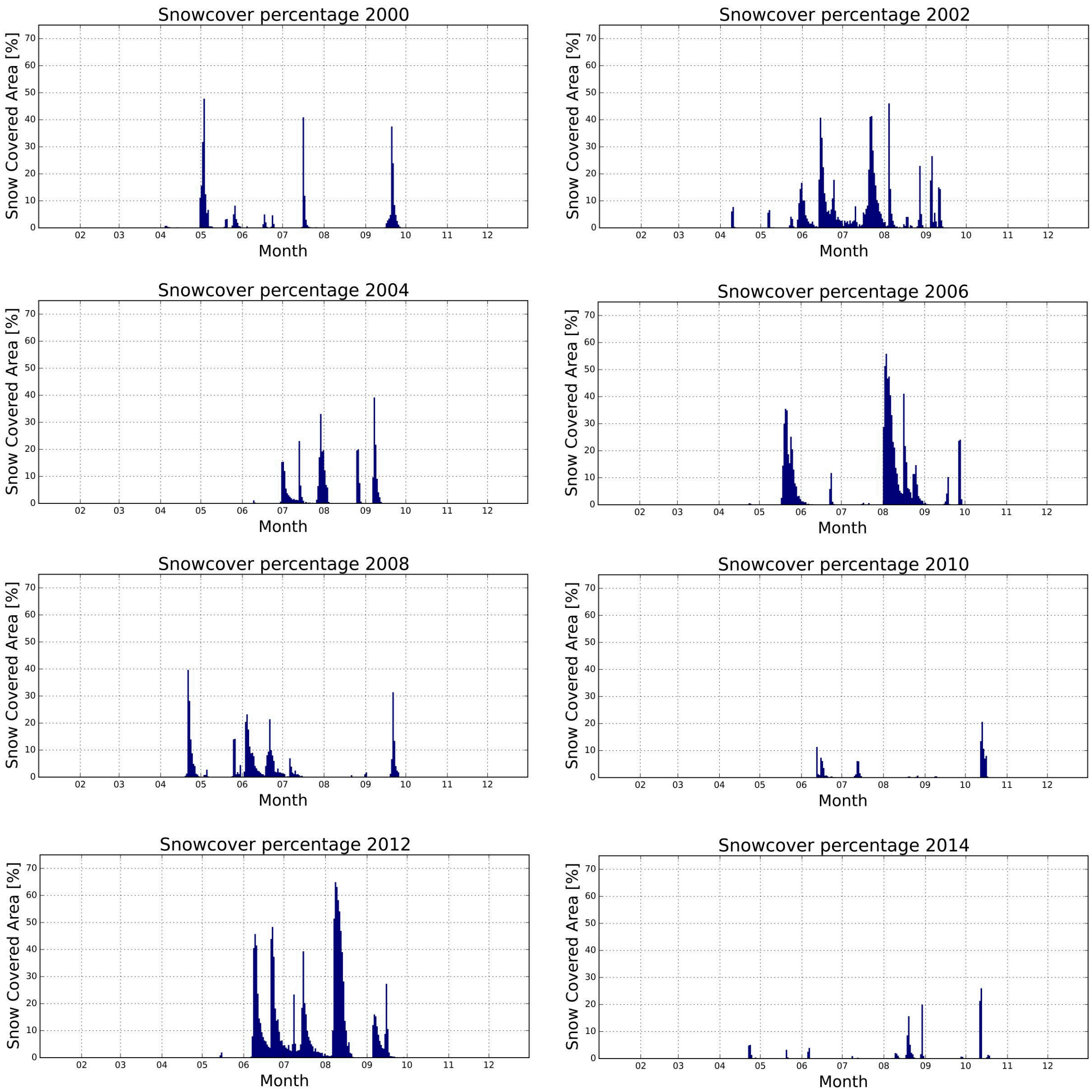

Figure 5. Snow covered area (%) of Lesotho between 2000 and 2014; compiled at daily temporal resolution. (Note: only even years are shown. The odd numbered years are included in the Appendix as Figure A1.) The maximum snow cover extent that was observed during the winter season (July and August) is clearly shown; the occurrence of occasional snow events was also observed during June and September.

The wide temporal range of snow events in Lesotho is evident. The first snowfall of the winter season often occurs at the end of April or the beginning of May. The high season begins in July or August, and the last snow events occur in October. Continuous snow cover lasting for longer than six weeks is only observed at the higher altitudes of the mountainous areas and covers less than 5% of the country.

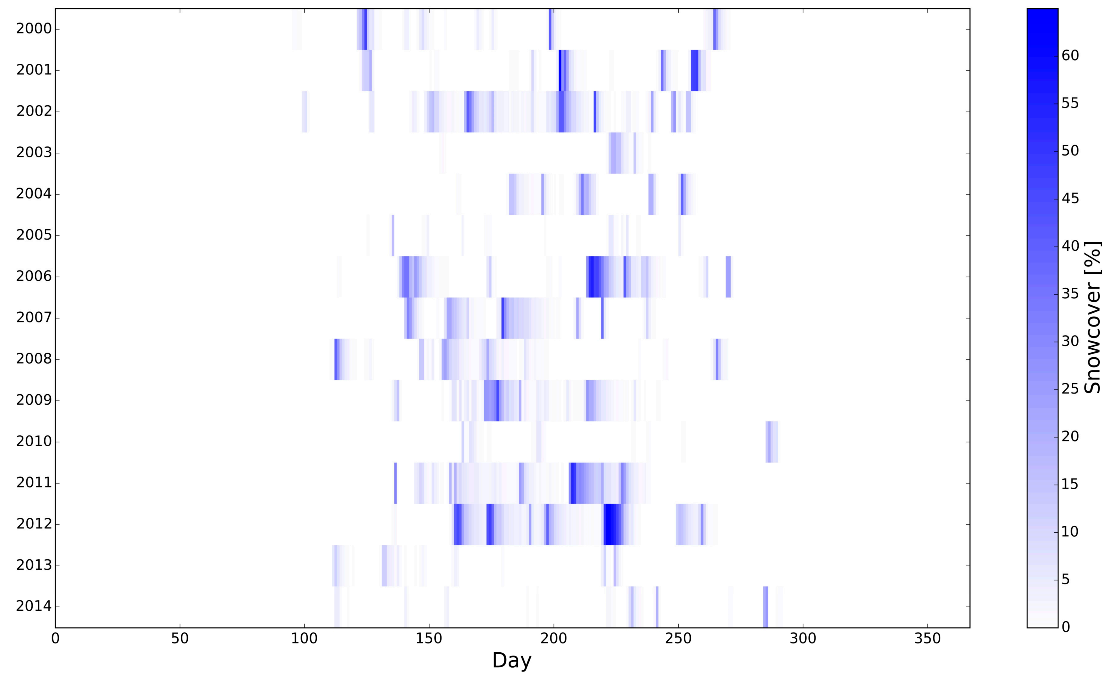

Figure 6. Daily distribution of snow covered area (%) between 2000 and 2014. The dark blue colors represent snow-covered areas that exceed 40% of the total land area; the light blue colors indicate areas in the highest mountain ranges in Lesotho with less than 15% of snow cover.

3.3. Analysis of Variability

Snow distribution in Lesotho is a function of the topography and the relationship between decreases in temperature with respect to the altitude of a particular location. Figure 7 illustrates the spatial distribution of snow duration (average of 15 years). On average, the mountain ranges are snow covered for 47 days per season at the highest elevations (>3000 m). This can be compared with the observation of 107 days of snow coverage at these elevations in 2002. In contrast, below average snowfall in 2005 resulted in only 10–15 days of snow cover in the upper mountain ranges. In general, the lowlands of Lesotho are not affected by snow (*i.e.*, on average, less than one day per year). The valleys are only affected for a limited number of days (*i.e.*, no more than five days on average).

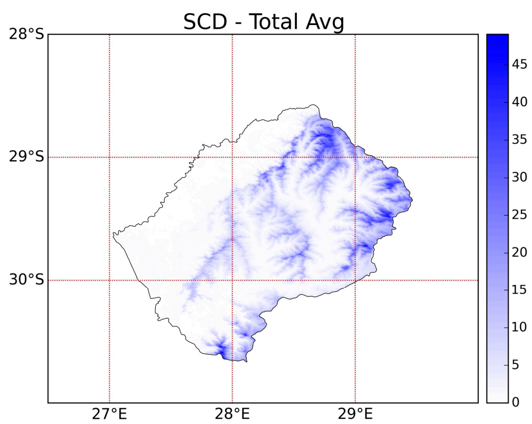

Figure 7. Snow covered days (averaged from data between 2000 and 2014). The dark blue colors represent areas with an average snow cover duration of more than 40 days, which coincides with the highest elevations in Lesotho. In contrast, the lowlands (valleys) are covered by snow for only five days or less (light blue colors).

Figure 8 shows the high inter-annual variability of Lesotho's snow cover. The presented anomaly is calculated as the annual departure of the long-term mean. Snow cover duration with lower than average values are represented by a gradient of red colors, whereas the gradient of blue colors indicate areas with higher than average snow cover durations. Dark red tones are dominant in 2005, which indicate that the yearly snow duration was far below the long-term average (with respect to elevation: 30–45 days less in the mountainous areas). On the contrary, the snow cover duration at higher elevations is more than 50 days longer than the long-term average observed in 2012, which is clearly indicated by the dominant dark blue colors. Depending on the prevailing weather conditions during the winter season, interesting snow distributions can also be seen (e.g., in 2008). At high mountainous elevations in the northeastern part of Lesotho, longer than average snow durations were observed. However, in the central part and the South the snow duration is below average. Consequently, not only does the temperature, and therefore the elevation, determine the snow distribution, but the paths of the storm tracks during the winter season also contribute to the location of snowfall events in a minor part of the country. The complex interaction between snow accumulation and temperature results in the snow distribution observed in 2008 (and *vice versa* in 2001).

Figure 9 illustrates the high inter-annual variability of snow cover days. A day is counted as a snow cover day whenever the country of Lesotho is covered with snow by more than 0.5% of the area. In 2002, 94 days were snow covered, but in 2005 and 2003, only 14 days were snow covered. On average, 48.9 days per year showed an SCA higher than 0.5% in the study period. It should be noted that most of the pixels that were included in the count were detected in the mountains. This results in high numbers of days with snow cover if the remaining amount of snow is persistent for a longer time due to cold temperatures. This feature is also shown in Figure 10, where more than 100 days of snow cover was observed for an area in Lesotho. The area had between 10% and 20% of snow cover and was located in the mountain ranges. Half of the country is only covered by some days (<10) for the whole period (2000–2015), and a snow covered area of more than 70% was not monitored in the investigated period; a maximum of 64% snow coverage was observed in mid-August 2012. This exceptional snow event in 2012 was also widely covered by the local media, as it caused damage to infrastructure and prevents supply of people in remote valleys. For example, on 16 July 2012, the media reported that 41 people were assessed and treated by emergency staff after encountering particularly heavy snowfall for several hours on their way back from Africa's only ski resort.

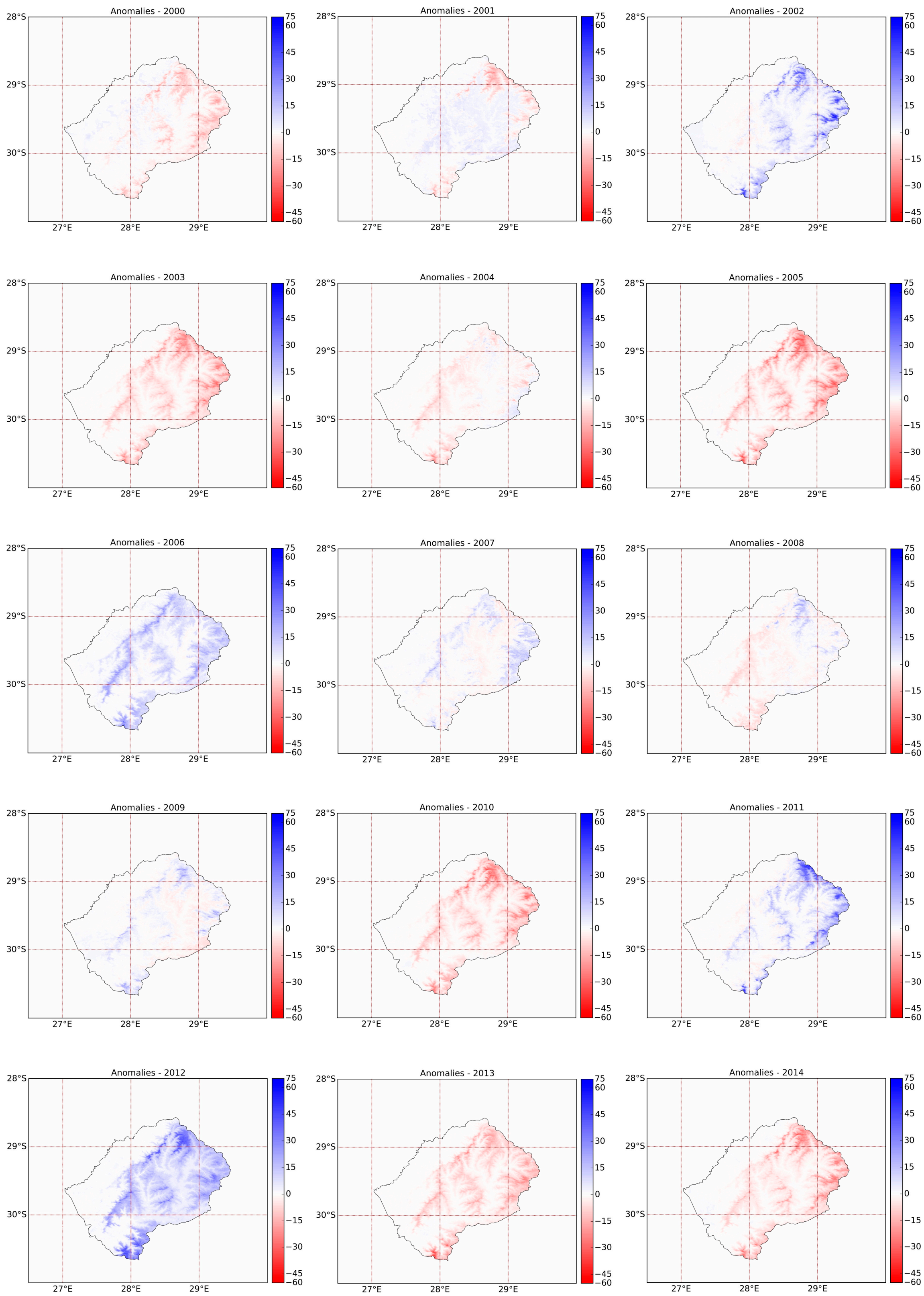

Figure 8. Annual snow cover anomalies as annual departures from the long term mean (in days) for Lesotho based on daily snow maps retrieved from MODIS MOD09GA data. The scaling in the ranges +60–75 days and –45–60 days is compressed to stretch the range with the highest probability. The reference period for calculating the anomaly is 2000–2014.

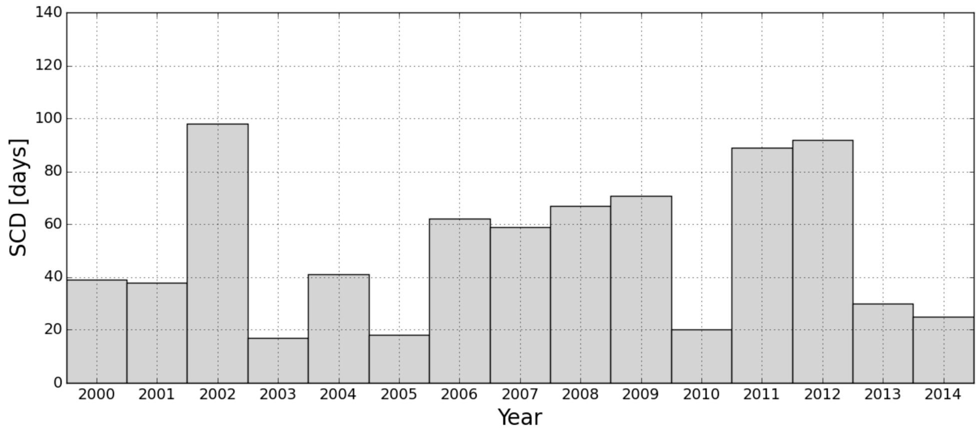

Figure 9. Annual snow cover duration (accumulated days); a day is counted as a snow cover day whenever the country of Lesotho is covered with snow by more than 0.5% of the area.

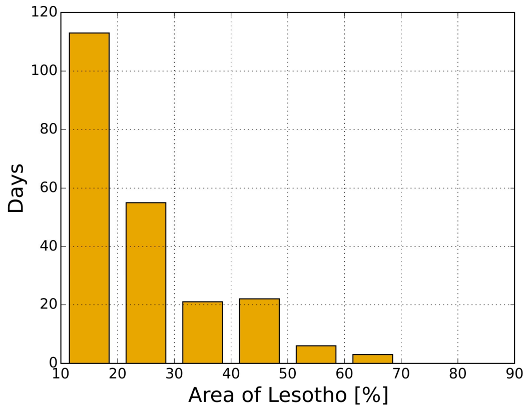

Figure 10. Absolute numbers of days with snow cover (in %) between 2000 and 2014; e.g., snow coverage of 30%–40% was observed for 23 days between 2000 and 2014.

4. Discussion

The standard cloud mask that can be used in conjunction with the MODIS snow product (MOD/MYD10A1) was found to frequently prevent the detectability of snow information on ground, which results in the under-detection of snow cover. This observation is in agreement with the results presented by [32], for a study conducted in Australia, as well as from [33]. The retrieval of a long time series on snow cover for Lesotho requires the development of a customized processing method, based on previous developments that apply the NDSI [29,35,41,44]. Apart from having processed and compiled the longest daily snow cover time series for Lesotho, a few issues remain unresolved, but are well documented. For example, the bias between the reference data and our MODIS-based snow product is minor and in the same range as reported by [30,36]. Different tests have been conducted with adapted thresholds for the NDSI to improve snow detection for some single scenes. However, the uses of these thresholds have also resulted in overestimation in many other images. A similar behavior of NDSI related to snow cover fraction was shown for Himalayan region [46] and Northwestern China [45]. Consequently, the current study was conducted with the widely accepted and proven threshold of NDSI $\geqslant 0.4$. Cloud detection remains an issue with the use of the MODIS snow product (MOD/MYD10A1). A customized cloud retrieval method based on the identified thresholds for wavelengths T11 µm, T3.9 µm, R1.38 µm by [54,55] was applied. However, this method did not result in any significant improvements when compared with the NDSI-based results.

Rittger *et al.* [30] and Salomonson and Appel [36] highlighted the importance of sensor spatial resolution for the detection of snow in the mountains. Furthermore, snow depths of only a few centimeters in the lowlands does not completely cover the areas of interest; this led to changes in reflectance values, which can result in lower NDSI values and the under-detection of snow cover. A sensor with higher spatial resolution increases the chance to detect smaller snow patches. However, the study also highlighted that daily temporal resolution is a strong requirement for the detection of ephemeral snowfall events in Lesotho. These events generally last for only a few days. For these reasons, the MODIS sensor onboard of Terra with medium spatial resolution and high temporal resolution was selected.

Due to missing ground measurements, only a comparison with the findings of [24] can be discussed. Figure 5 shows that exceptionally low snow cover, which was observed in 2003. Grab and Linde [24] also detected only one snow event in August. The results that were obtained in this study had a temporal resolution of one month. Hence, a daily comparison of the results of the two studies could not be conducted. Snow data retrieval on a daily basis not only describes the snow event during the same observing period (*i.e.*, August in [24]), but could also resolve the occurrence of two snowfall events and the shape of the depletion curve very well. A visual check of the MODIS RGB image and the processed snow map confirms the occurrence of a second snowfall event. In 2007, Grab and Linde [24] reported one snowfall event in May, two in June, three in July and two in August. Our results show that the same amount of snow events occurred in May and August; three snowfall events were detected in June and only one in July. The difference in the number of detected events in June may be attributed to the higher temporal resolution of our data, which enabled the detection of an additional snow event. Visual inspection of the July data did not result in the detection of any additional snow events. This is likely due to cloud misclassification as additional snow cover in the mountainous area.

5. Conclusions and Outlook

The current study showed that while snowfall is common in Lesotho during the winter, the inter-annual variability with respect to the number and intensity of the events was found to be very high (e.g., 2012 *vs.* 2005). Most of the snow accumulates in the highest mountains and persists for some weeks, depending on the temperature and the frequency of snowfall. The lowlands of Lesotho, where the capital Maseru is also located, are unaffected by snow cover. However, snow can remain for some days at slightly higher altitudes. All of the results are based on MODIS data (MOD09) and a customized retrieval procedure that considers both the NDSI concept and the application of spatial-temporal post-processing. The development of this procedure was motivated by the benefits of improving the existent MODIS snow product with its associated cloud mask (MOD10A1).

For the first time, a continuous and homogenous daily time series with the compilation of 15 years of data (2000–2014) is available; this time series describes the snow cover distribution of Lesotho. It has been shown that the occurrence of single snowfall events, followed by rapid melting, necessitates a daily snow product to detect the amount of coverage in the country. The post-processing step is essential to fill gaps caused by cloud cover and to generate a continuous time series [12]. The combination of previously implemented methods, temporal filling of missing information and elevation based filling (SNOWL) is capable of reducing the amount of gaps significantly as shown by [50,53,56]. Publicly available data (e.g., elevation model) are sufficient to support the development of an elevation dependent gap-filling procedure to generate a homogenous snow cover time series. The overall accuracy is considered to be good based on the high hit rate when compared with the Landsat and MERIS reference data. However, snow cover retrieval results showed slight underestimation attributed to the application of conservative thresholds to avoid the effects of cloud contamination. In comparison with the selected reference products Landsat and MERIS data, the under-estimation of snow cover is even more pronounced for events with less precipitation. The accuracy is improved if the percent of snow coverage is higher. Additionally, low snow depth could also lead to modifications in reflectance values due to the presence of mixed pixels, which effectively degrades the quality of resultant snow maps.

Single snow events lasting for only one to two days can cover more than 40% of the country. If melting starts immediately after the snowfall event, the extent of the snow cover retreats rapidly. In general, after some days, snow remains only in the highest mountains. The study highlighted the high inter- and intra-annual variability of snow coverage. The first snowfall generally began in May. However, in some years, the first significant snowfall was recorded at the beginning of August (e.g., 2003). The last snowfall of the winter is often in the middle of September; snow can also disturb daily life in remote villages of the mountainous areas in October. In the foreseeable future, satellite remote sensing remains the only viable source of data to monitor countrywide snow distribution in this particular region. The findings of the study have demonstrated the utility of using a MODIS-based method in combination with post-processing to provide instrumental snow monitoring information.

Based on our results and the feedback gained during the capacity mission in Maseru, Lesotho in December 2015, an operational downstream service would be especially beneficial for the country. This service could be based on the use of Sentinel-2, Sentinel-3 and Suomi-NPP VIIRS data, respectively. The product delivery procedure could use the previously implemented EUMETSAT infrastructure, within the framework of PUMA (Preparation for the Use of MSG for Africa) and ongoing MESA (Monitoring of Environment and Security in Africa) programs. If the proposed method were implemented in a downstream service, the daily snow information that is collected would effectively support the monitoring activities of authorities in Lesotho and in South Africa during the winter seasons.

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Author Contributions: All authors contributed equally to the paper. Stefan Wunderle designed the study, processed Landsat data, prepared the figures and wrote the text, Fabia Hüsler processed the MERIS data and contributed to the text, and Timm Gross processed the MODIS and Landsat data and prepared the figures.

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Abbreviations

The following abbreviations are used in this manuscript:

AATSR	Advanced Along-Track Scanning Radiometer
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AVHRR	Advanced Very High Resolution Radiometer
BEAM	toolbox and development platform for satellite remote sensing data
ESA	European Space Agency
FSC	Fractional Snow Cover
GDEM	Global Digital Elevation Model
IPCC-ARE5	Intergovernmental Panel on Climate Change – Fifth Assessment Report
LMS	Lesotho Meteorological Service
MERIS	MEdium Resolution Imaging Spectrometer
MNDSI	MERIS Normalized Difference Snow Index
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NDSI	Normalized Difference Snow Index
NIR	Near Infrared
RGB	Red-Green-Blue
SE	Snow Extent
SWIR	Shortwave Infrared
TM	Thematic Mapper
USGS	United States Geological Survey
VIS	Visible Spectrum

Appendix

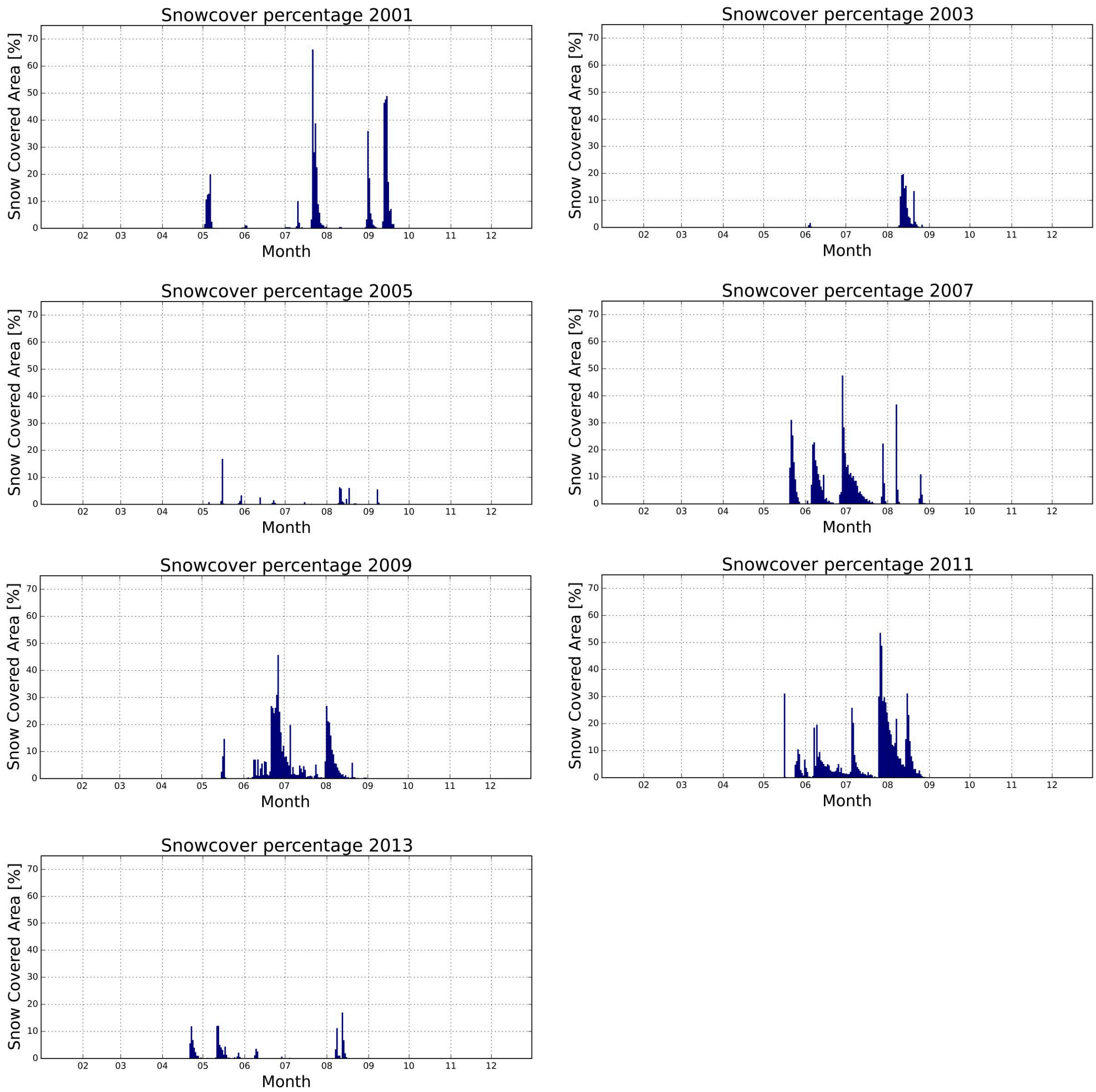

Figure A1. Snow covered area (%) of Lesotho between 2000 and 2014; compiled at daily temporal resolution. (Note: only odd years are shown. The even numbered years are included in the main paper as Figure 5.) The maximum snow cover extent that was observed during the winter season (July and August) is clearly shown; the occurrence of occasional snow events was also observed during June and September.

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