Investigation of Landsat satellite image change detection of snow and ice cover

A seasonal and multi annual time scale approach to evaluate this technique as a tool for water resource management

Master's thesis in Natural Resources Management

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Norwegian University of Science and Technology

Benno Rummel

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Abstract

94 Landsat Satellite images were analyzed regarding snow cover and perennial snow or ice patches in the mountains close to Oppdal. Special attention was paid to the ablation period. The Landsat scenes were processed and analyzed with ERDAS Imagine. Detailed analysis was conducted in ESRI ArcGIS.

The study aimed to analyze the temporal development of snow cover distribution in the study area. Of particular interest were perennial snow or ice patches as they might indicate climate change in the study area and because of their little researched character. The gathered information regarding the snow cover might be used to adjust existing management tools and strategies.

The snow cover was detected with the normalized differential snow index (NDSI) and a fixed threshold. It was a goal to develop a robust process that had the potential to be applied automatically. For detailed analysis the binary snow cover map was further used in GIS. It was applied together with a digital elevation model (DEM) to increase the level of information.

Landsat proved to be suitable to map the snow cover extent in the study area. The NDSI proved its reliability and it is possible to use it in an automated process.

The analysis with change detection techniques revealed large losses in area covered by perennial snow patches. The average loss for selected snow patches was 55%. Snow patches are usually located on the east facing slope of mountains, with variations towards north- or south-east. Finally snow cover is disintegrating in a similar pattern each year.

As a recommendation for water resource management in the area two things must be mentioned: climate change is altering the snow cover towards the end of the ablation season and the snow cover is disintegrating in similar patterns. Therefore this information can be incorporated in existing management tools.

Keywords: Natural resource management; remote sensing; normalized differential snow index, NDSI, Landsat, Oppdal, snow patch, ice patch, snow cover detection, change detection

Preface

First of all I would like to express my gratitude to Dr. Ivar Berthling for guiding me through the process of writing a master's thesis. Right from the beginning he kept a student with several different ideas on track. Along this journey he was always up for a conversation and very helpful input. Even towards the end of the semester he kept me calm. I will miss the skype conversations. Thank you very much Ivar.

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Finally I would like to address to the people at my reading room 7357 in the cave. It is nice to share the experience with you to write a master's thesis. Thank you Alexander, Fredrik, Jørn, Magnus, Morten and Tor Inge. Thank you Øistein for very interesting conversations.

Benno Trondheim, 10.05.2013

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1 Introduction

1.1 Motivation

In resource management remote sensing can play a key role. Large areas can be easily observed and furthermore regions with difficult infrastructure for regular monitoring are virtually accessible (Wang 2012). Information that is available in different scales and progress in electronic data processing enable widespread change detection for almost any environment (Franklin & Wulder 2002; Kerr & Ostrovsky 2003; Khorram et al. 2012). The gathered information can be processed in remote sensing software, widely considered as a subgroup of geographical information systems (hereinafter briefly referred as GIS) software. Vice versa the information can also be used in a general GIS subsequently.

It is the nature of earth sciences that any research is framed by the context of scale. For most of these scales suitable satellite remote sensing platforms are available and space born sensors are particular useful for assessment and monitoring of large areas and land cover change. The area of interest can be a glacier (Paul 2002), a region (Andreassen et al. 2008) or on national park level (Allen 1998). With growing remote sensing capacities and geographical information systems the abilities and tools to analyze landscape patterns have been growing as well. The result is a tradeoff between complexity and applicability, especially regarding management issues (Cardille et al. 2012).

Water is fundamental for human beings. It is a necessity as drinking water but also for industrial purposes (Tietenberg & Lewis 2009). As in most countries, in Norway water is a managed resource. Rain and snow are refreshing inland waters (NVE 2009). Compared with long term rainfall forecasts, which are highly capricious, snow water equivalent maps are a good tool for estimating potential water availability (Skaugen 1999). Snow is considered as a predictable source of fresh water supply, despite local variations by wind drift and local topography (NVE 2009; Skaugen 1999). Snow distribution is determined by weather conditions during the yearly seasonal cycle. Snowfall and wind distribution are the main driving factors. As a result the changing water availability from the melting snow can subsequently be a climate change matter (Jackson et al. 2001). Therefore knowledge regarding changes can result in advanced adaption and mitigation techniques and adjusted management approaches (Beniston 2003).

The predicted and regularly updated water equivalent map used in Norway is a widely used management tool. This map is published with free access rights (Alfnes et al. 2005). Detailed information regarding snow distribution can be relevant not only for electric power production but also for tourism, agricultural land use, forestry, civil engineering, river fisheries or fresh water supply for consumptive use. It can enhance local and regional management approaches. The information may contribute to natural hazard management and protection as well (Quincey et al. 2007; Skaugen 1999). Climate change has the potential to alter the snow cover distribution as it was observed in the past. From satellite images it is possible to determine the point in time when the annual snow cover is completely disintegrated. Furthermore it might be possible to detect a trend in the snow cover distribution, which can be considered as evidence of climate change in the study area.

Describing and tracking the snow cover disintegration during the melting period is difficult using field based methods, with respect to the large areas affected. Therefore remote sensing techniques can be used for tracking the areal extent of snow cover. In this study there is a special emphasis on perennial snow patches as they are little researched. The techniques for detecting snow cover can be used to detect snow patches as well. The development of the snow covered area is one among many indicators of the local climatic conditions. Snow patches seem to be stable landscape feature (Nesje et al. 2012). Archaeological artifacts were found close to snow patches. A detailed map of snow patches might contribute to archaeological studies. Unlike glaciers which are usually mapped in official cartographic map sheets, snow patches are not mapped on a regular basis. However it should be possible to map them with Landsat images. The applied mapping techniques can be tested towards their reliability in context of snow cover mapping. Therefore enhanced knowledge about the snow cover can contribute to adapted water resource management strategies in the region.

1.2 Objective

The objective of this thesis is to investigate the use of Landsat satellite images for change detection of snow and ice cover at seasonal and multi-annual time scales. The results should also be used to evaluate these tools for water resources management in the study area.

The objective will be briefly discussed and describe the frame of the thesis. Applied steps and techniques are introduced as well.

The normalized differential snow index (hereinafter briefly referred as NDSI) is used. It can be a tool for detecting snow cover in large scale applications (Hall et al. 1995; Salomonson & Mao 2004), but it is also used for glacier monitoring (Konig et al. 2001). NDSI can be considered as reliable (Hall et al. 1995; Hendriks & Pellikka 2007; Paul & Andreassen 2009; Silverio & Jaquet 2005).

First of all the snow cover will be mapped according to NDSI. With the created snow and ice cover maps it is possible to create overlays with a digital elevation model (hereinafter briefly referred as DEM) in a GIS. The local conditions of snow patches are described as well. Throughout an ablation season the melting process can be documented to some extent according with the aid of the Landsat archive.

The snow and ice cover map of late summer conditions will be used in a change detection analysis. The calculated results will document environmental changes in the study area over a longer time period. This can contribute to the documentation of climate change in the study area.

Finally the results will be discussed in respect to the reliability of the remote sensing data and applied techniques. The results will be discussed in the light of climate change. Finally the results are evaluated in respect of natural resources management and potential improvements of existing management tools and strategies.

1.3 Outline

This thesis has seven chapters. First of all the idea and a few introducing thoughts are mentioned, combined with the main objectives of the thesis. The study area is introduced in chapter two. Chapter three deals with the research question and important background in remote sensing. Special emphasis lies on the Landsat Mission, technical issues and potential outcomes. Applied techniques are presented in chapter four. There are two important categories to deal with, on the one hand remote sensing related techniques and on the other hand general computer aided processing techniques which are GIS related. Chapter five presents the results. Those are discussed in chapter six afterwards. And finally there are concluding remarks in chapter seven.

2 Study area

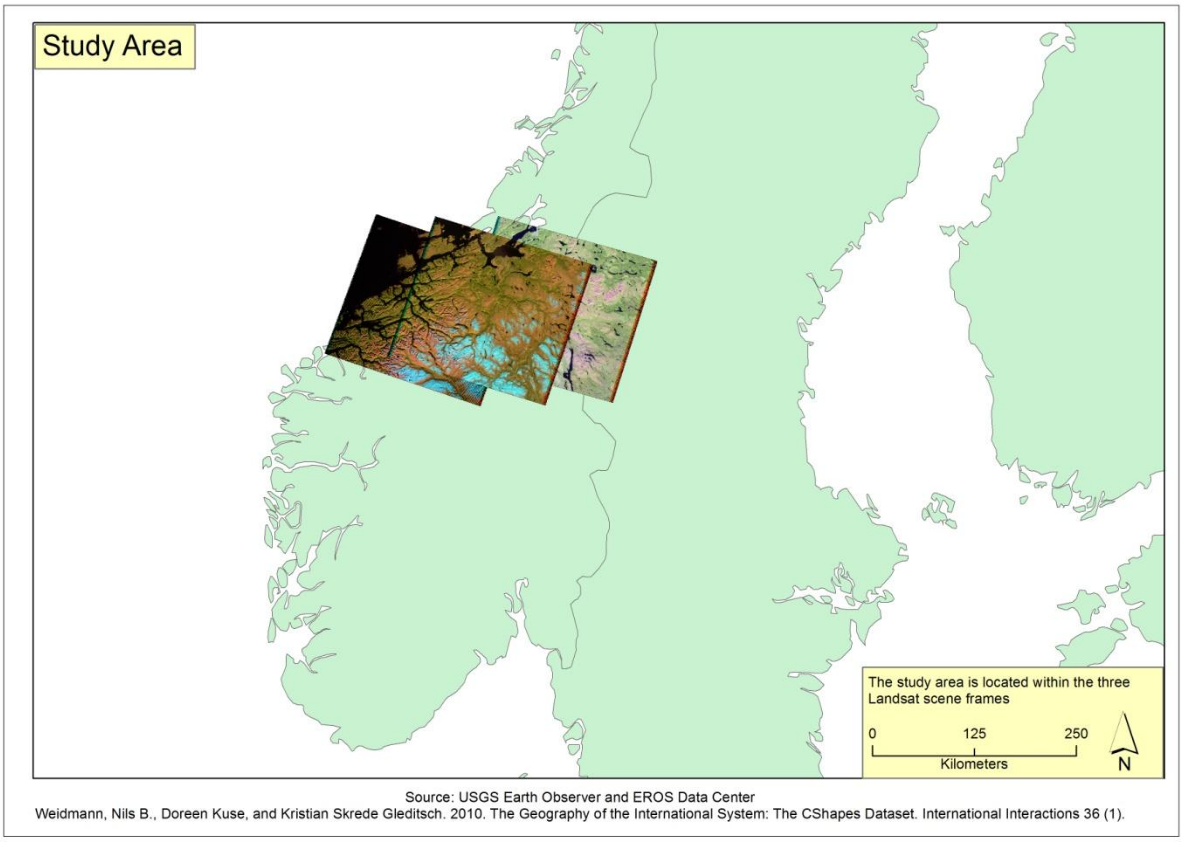

Figure 1: Study area

Figure 1 shows the Landsat footprints in the study area, the figure is based on Landsat data and the "cshape" dataset (Weidmann et al. 2010). The study area is located in the Sør-Trøndelag fylke and the Møre and Romsdal fylke. It roughly covers the region in between 62.3 – 62.8° N and 7.5 – 10° E.

This choice is already determining several characteristics of the study area. Most important and of course most obvious is the fact that it is a mountain area in a sub arctic region, which additionally was subject of several glacierization periods (Follestad 2005; Nøttvedt et al. 2006). The area is shaped by a mountainous climate in a humid region, a mountainous geo-morphology and mountainous biogeography. Furthermore the hydrology of the region is also shaped by climatic and geomorphologic constraints. Within this region, the thesis with areas only areas above approximately 1000 meters above sea level.

As already mentioned, the area was subject of glacierization. This is determining the morphology of the region to a certain extent. Cirques of former glaciers and steep valleys eroded by glaciers are the most obvious ones. Today the glacierization is limited to few spots, the so called Dronning- and Kongskrona Mountain close to Sunndalsøra in the west and at Snøhetta Mountain in the east.

In the study area the mountain areas have different morphologies. In the western part of the region the mountains are rather steep and they are surrounded by u-shaped valleys. Here the glacial history becomes most visible. Towards the east the topography is losing its roughness, mountains and especially their tops are becoming flatter. Finally in the east of the study area plateaus are dominating the study area.

The climate in the study area is influenced by several factors. First of all the study area can be considered as located in the mid latitudes on the western continental margin. As a result, the climate is considered as a moist maritime type with mild winters. This is a classification according Köppen-Geiger-Pohl (Holden 2008). In this context it is very important to mention the direct influence of the Gulf Stream waters as they are drastically increasing the mean annual air temperatures along the Norwegian cost. On a regional level the climate is modified by the study area itself, it is a mountain climate. Two consequences are most obvious: decreasing mean air temperatures with increasing altitude and orographic induced rainfall. And in the end the climate is modified locally by topographic effects, like shadows or other local factors like valleys. Furthermore during the winter time snow drift is observable.

The precipitation decreases from the west coast towards the rather continental east of the study area. In the west a total average precipitation between 2000 mm and 3000 mm per year is recorded in the Meteorologisk institutt (met.no) database and provided by Norges vassdrags- og energidirektorat (hereinafter briefly referred as NVE). In the east a total average precipitation between 750 mm and 1000 mm per year is recorded. These figures demonstrate the decrease of the precipitation in the study area with increasing distance from the sea. The temperatures show a similar distribution with increasing distance from the sea. In the west of the study area mean annual air temperatures of 4° C to 6° C are recorded, whereas in the east of the study area temperatures of -2° C to -3° C are recorded (NVE 2013a; NVE 2013b).

3 Theory in remote sensing

3.1 Research question

The overall question is whether Landsat is a tool for change detection of snow and ice cover. The study is based a seasonal and multi annual time scale approach to evaluate this technique as a tool for water resource management in the Oppdal region. An answer for this topic can be found in the following tasks or questions:

Is it possible to detect snow cover on Landsat satellite images in the study area? At first this question may seem to be a rather simple one, as snow cover is often optically visible in Landsat scenes. However for any use in semi automatic or even automatic algorithms this topic is very important. Digitally detectable snow cover information has the potential to increase the usability of digital water resource management tools. The manual snow cover detection and mapping in hundreds of different Landsat scenes would be nearly impossible. It is necessary to acquire this data digitally as well. It also increases interoperability.

The next important question is whether it is possible to combine the snow cover information with a digital elevation model. Any gathered information from digital satellite images is usually not containing elevation as this is a value which is not acquirable with optical satellite sensors. Therefore an overlay of the snow cover product and a digital elevation model is revealing information regarding elevation, exposition and inclination of the snow cover. It should be possible to describe the topographical setting of the snow cover.

Is change detection possible for snow cover products in the study area? Change detection is an important tool in remote sensing. It is describing changes over time. This is also important for describing any snow covered areas as trends are becoming visible. It should be possible to document ongoing natural changes. Existing management strategies usually incorporate experience gathered before the strategy was incorporated. As long as there is no change observable for the managed resource, the strategy needs no adjustment. But any shifts in nature should be monitored to adjust these existing management strategies for recent changes otherwise the strategy loses its efficiency.

3.2 Water resources management

Water is abundant in Norway (NVE 2009) and it is managed by the NVE. The NVE work is framed by the Water Recources Act, the Watercourse Regulation Act and the Industrial Licensing Act (NVE 2009). It includes research about water and water resources. Furthermore it includes the objective to protect the water quality.

These objectives can be found as management guidelines in scientific literature. The management of water resources should aim for a sustainable use. Management policies should rely on long term environmental, economic and social objectives. The principle of precaution, that demands no action that is irreversible wherever practicable, should be applied as well. And finally good management practice includes the monitoring of the applied actions (Dingman 2002).

In this context the water resource is considered as renewable (Tietenberg & Lewis 2009) and management actions are framed by this constraint. The snow cover is contributing to the surface water flow and to the groundwater flow. However the runoff of melting snow cover is mainly influencing the surface water flow (Dingman 2002).

The use of surface water can be split in two different types. There is a consumptive use observable and there is a non consumptive use observable. Consumptive users are industries, drinking water suppliers or agriculture for example. Non consumptive users are river fisheries or electronic power producers (Tietenberg & Lewis 2009). Each participant demands water for its purpose and therefore the allocation or the use of water is managed to fulfill different demands (Tietenberg & Lewis 2009). However any management practice depends on reliable prediction of water availability. The snow cover distribution maps are one of these essential management tools (NVE 2010).

3.3 Background in remote sensing

3.3.1 Atmosphere, scattering and satellite sensitivity

In the electromagnetic radiation (hereinafter briefly referred as EMR) it is possible to separate several wavelengths. From the whole spectrum only a few wavelengths are important for remote sensing purposes (Paul & Hendriks 2010b). These are positioned between the ultraviolet and medium infrared spectrum. The microwave spectrum is of interest. Furthermore the EMR passes through the atmosphere from a source to a sensor. On its way it is influenced by the atmosphere. Several parts of the EMR are absorbed or scattered by N_2O, O_2, O_3, CO_2 and H_2O. Figure 2 shows transmissive parts of the atmosphere in grey and only in these parts sensors are positioned (Albertz 2007; Paul & Hendriks 2010b).

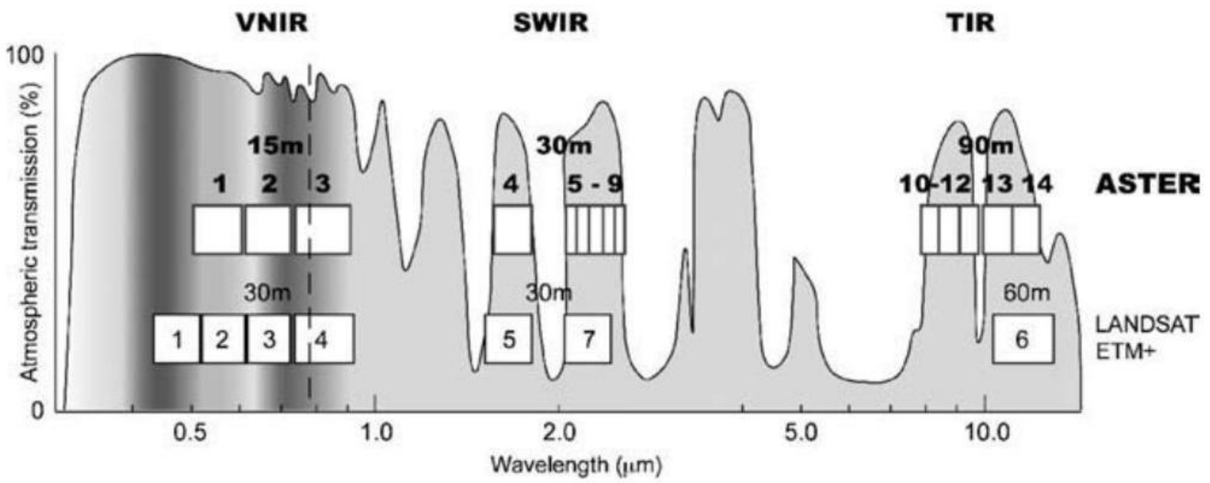

Figure 2: Atmospheric transmission and location of ASTER and Landsat TM spectral bands (Figure courtesy of A. Kääb) (Paul & Hendriks 2010b)

Any object scatters or emits EMR. Therefore in remote sensing it is possible to assume, that the EMR transports information regarding the physical properties of an object. This information is recorded by the sensor, and afterwards the values can be transformed into an image (Paul & Hendriks 2010b).

A remote sensing platform can carry several sensors. Each of them can be described with its sensitivity for specific parts of the EMR. This description can be split up in range and partitioning of the EMR, resulting in so called bands combining those two characteristics in their sensitivity. Overall it is possible to describe three different types of sensors. Panchromatic sensors include a single band. Multispectral sensors include several bands and finally hyper spectral sensors are covering up to several hundred bands (Albertz 2007; Khorram et al. 2012). Figure 2 explains the connection between range and partitioning for Landsat 7 and the ASTER sensor.

For each pixel the bands of a sensor must be exactly registered to each other. Several bands can be combined in a single usable file. It is necessary to achieve three geometric features for a satellite image. Beside pixel registration, images of the same spot must be able to register to each other and finally it must be possible to apply a user selected cartographic projection (Khorram et al. 2012; Wulder et al. 2008).

Radiometric resolution determines the sensitivity of the sensor itself and subsequently the recorded data. Landsat 5 and Landsat 7 images are acquired in an 8-bit resolution. 8-bits represent 256 different values and the recording value is also referred as dynamic range. High dynamic ranges represent a higher sensitivity in a band (Khorram et al. 2012).

3.3.2 Orbits, repeat intervals

In satellite remote sensing orbits determine several characteristics of the gathered data. The satellites over passing close to poles in circles, similar to longitude. Additionally several satellites are crossing the equator always at the same time during the day, which is called sun synchronous. It is assumed that such a behavior enables comparable acquisition conditions each day and overpass. The orbit itself keeps its position in space and planet earth rotates under the satellite (Albertz 2007).

Another possibility of satellite positioning is called geostationary, which is mainly used for weather monitoring sensors. Between these two orbits remains a huge gap in terms of altitude. Geostationary orbits are usually located in a distance of 36000 km above earth, compared to only 700 km to 1500 km above earth for polar orbiting image acquisition devices. Geostationary satellites are mainly equator oriented and their speed is adjusted to the rotation speed of the planet. They usually move sun synchronous. Communication between satellite and ground stations is comparably easy to maintain due to an almost fixed position (Khorram et al. 2012; Richards & Jia 2006).

Temporal resolution is dependent on certain constraints related to the field of interest, it often depends on whether cloud free images or a certain time during a vegetation period is preferred. Therefore an optimal temporal resolution is hard to define, or perhaps even impossible (Wulder et al. 2008).

3.3.3 Sensor types

Remote sensing platforms record EMR. Two origins of radiation can be discriminated: passive sensor systems are recording scattered sunlight and do not come with their own source of radiation whereas active sensor systems emit and capture artificial radiation. Figure 3 describes the two approaches in utilizing EMR as a source of information. It also describes, that thermal radiation is not of scattered origin. Thermal radiation is considered as intrinsic radiation (Albertz 2007).

Recent developments brought up active sensor systems which transmit their own radiation as Figure 3 shows. This system is sending out microwaves and it is recording the amount that is reflected to the sensor. An advantage of the system is its operability during the night, but the main reason is its weather independence (Albertz 2007; Khorram et al. 2012).

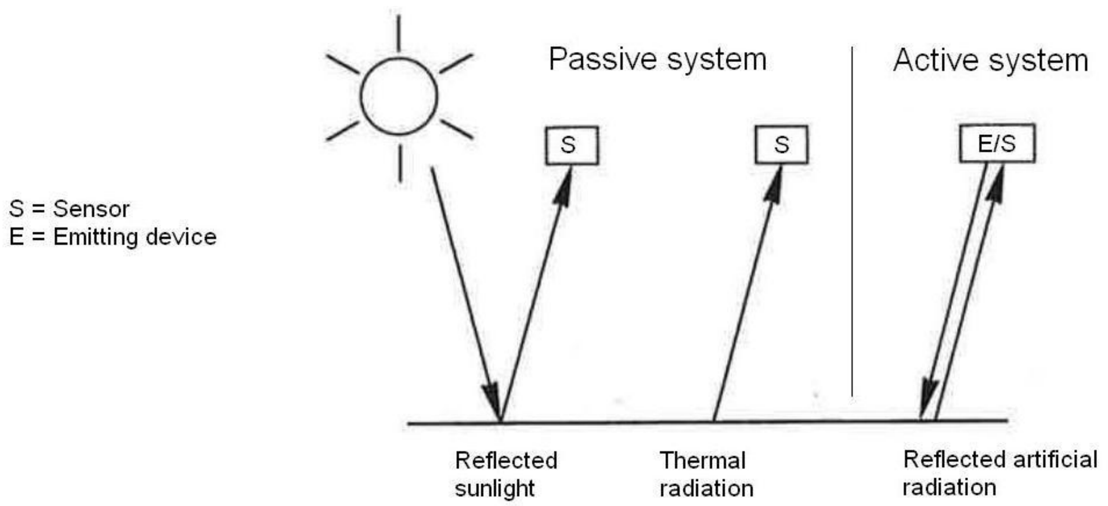

Figure 3: Schematic diagram of the radiation flux during data acquisition with passive and active sensor systems (modified) (Albertz 2007)

3.3.4 Spatial resolution

Today nearly any remote sensing platforms record digital information. Most of the electronically recording systems are using a raster for storing the information, so called picture elements (hereinafter briefly referred as pixel). Remote sensing is an object of interest. This object should be visible on acquired images in a size that is useful for the analysis. A Landsat pixel of 30 m by 30 m describes 900 m² on earth additionally multiplied by the number of spectral bands. All the 900 m² of landscape features are transformed into a single value (Khorram et al. 2012). On a landscape level relevant information could be represented by only a few pixels. Therefore it is always necessary to keep in mind that a pixel is representing a level of uncertainty (Khorram et al. 2012; Longley et al. 2011).

A definition of resolution in scale is helpful for avoiding any mismatching in terminology (Longley et al. 2011). Therefore the following segmentation in high, medium and low resolution sensor systems is helpful. Images with low resolution have a spatial resolution with pixel sizes above 100 m. Medium resolution images are referred to scales between 10 m and 100 m pixel size. Finally high resolution is therefore an image with less than 10 m per pixel (Wulder et al. 2008).

For land cover classification purposes it is often important to use a minimum scale of a hectare in the output datasets. Therefore very high resolution sensors image individual landscape aspects rather than land cover types. Afterwards these aspects must be merged and one dominant land cover class must be created (Wulder et al. 2008).

3.3.5 Landsat archive

Earth observation data is produced since 1972 by the Landsat program (Wulder et al. 2008). Today the whole dataset covers approximately 40 years. Especially in ecosystem assessment efforts the availability of long lasting datasets is of importance. Interactions between anthropogenic activities and ecological outcomes can be analyzed with long lasting datasets. Any interruptions are a clear drawback for monitoring the effectiveness of management strategies which have been applied during that time (Wulder et al. 2008).

In 2004 the whole Landsat program was named “National Asset” by the United States of America President’s Science Advisor. Beside economical and technological effects as a spinoff due to legislation acts especially the very high data quality was a major reason for that decision (Wulder et al. 2008). For the success of an archive also the ease of browsing it and data access is of similar importance (Wulder et al. 2008).

In 2008 the Landsat archive contains approximately 1000 Terabytes of data, see Figure 4 (Wulder et al. 2008).

Sensor	Records	Dates	Volume
Landsat MSS	649,412	1972–1992	19 TB
Landsat TM	692,566	1982–present [a]	347 TB [b]
Landsat ETM+	704,770	1999–present	654 TB [c]

[a] The USGS EROS data store queried on March 27, 2007.
[b] The volume of TM data is estimated to be increasing by 40 GB daily.
[c] The volume of ETM+ data is estimated to be increasing by 260 GB daily.

Figure 4: A summary of the National Satellite Land Remote Sensing Data Archive Landsat data (Wulder et al. 2008)

Long lasting datasets can be used for comprehensive analysis, for example change detection, or they can offer additional data in retrospective analysis. Historic Landsat data is already in use by several land cover monitoring programs, like the Coordination of Information on the Environment (CORINE) program of the European Union (Wulder et al. 2008).

3.3.6 Open Landsat archive

In many countries remotely sensed data is not freely available. Three drivers can be identified easily, strict property rights by data suppliers, license requirements for working with the data and finally prices at levels of cost-recovery (Wulder et al. 2008).

Early in 2008 the United States Geological Survey (hereinafter briefly referred as USGS) switched to a free of charge distribution policy of Landsat images. It is widely considered as a major step in monitoring global change. Beginning with Landsat-1 images dating back to 1972 it is possible to describe antropogenic land use changes and natural changes. During that time the population on earth roughly doubled and effects of climate change are becoming more and more visible (Woodcock et al. 2008).

In 2001 the USGS distributed 25000 Landsat scenes for approximately 600 $ each. In contrast data from 2010 is showing more than 2,5 million downloads of Landsat images. With increasing computational capacities for both distribution of images but also for the investigation of Landsat images the demand is highly increasing. Today the focus has switched from single scene analysis to multi scene large area analysis. Figure 4 is showing the raw amount of available data for scientific purposes. Therefore utilizing Landsat images is becoming more and more popular among various scientific disciplines. For multi temporal analysis similar radiometric properties of scenes is considered as a highly appreciated benefit as it is reducing friction and uncertainty. Constant maintenance and calibration is conducted by the USGS as well. (Kennedy et al. 2009; Wulder et al. 2012).

3.3.7 Advantages and limitations of remote sensing

Remote sensing is a suitable resource for covering large areas that would lack surveillance otherwise. It is nearly always possible to choose between desired areal coverage and resolution in scale. Surveillance of large areas can be expensive.

Glacier monitoring is a good example. In Norway there is a long dating history (Bogen et al. 1989; Hoel & Werenskiold 1962; Nussbaumer et al. 2011; Østrem et al. 1988), as in most other European countries (Bauder et al. 2004; Hoinkes & Lang 1962; Kasser 1964). But even in Europe not each glacier is monitored on an annual basis. Remote sensing draws a better picture as it can cover the gaps. Finally remote sensing can offer views into temporarily or permanently restricted areas, which can have political but also natural hazardous backgrounds. This can be the case in Tibet for example where traveling was restricted several times by the local Chinese governmental authorities (Kropacek et al. 2012).

The EMR and the pixel size therefore are contributing to the so called uncertainty. Avoiding mixels is not even possible with high resolution sensors. But the probability of recording a mixel is an inverse function of resolution in scale under the assumption of constant total area covered (Longley et al. 2011).

Optical remote sensing is dependent on weather conditions. A main source of disturbance is water vapor in the air. The water can be a clustered in relatively warm clouds in low altitudes but also in thin and cold clouds in high altitudes. Furthermore haze can induce major problems as well. Cloud cover is not a subject of a random distribution, it is an expression of a distribution pattern. Authors point out (Esche et al. 2002), that approximately 50% of the earth is always covered with clouds (Wang et al. 2009). Clouds mainly influence the visible parts of the EMR, which limits the usefulness of a scene. Furthermore clouds cast shadows, creating similar problems as mentioned above. Finally it is possible to conclude, that cloud cover is a more problematic in specific regions of the world, like the Amazon region or Norway (Wang 2012). Especially for the arctic and northern Europe where there were analysis's regarding this topic. Figure 5 shows cloud cover for the arctic, and it is obvious that it is rather difficult to get good quality images. Both regions of Norway show similar probabilities (Marshall et al. 1994).

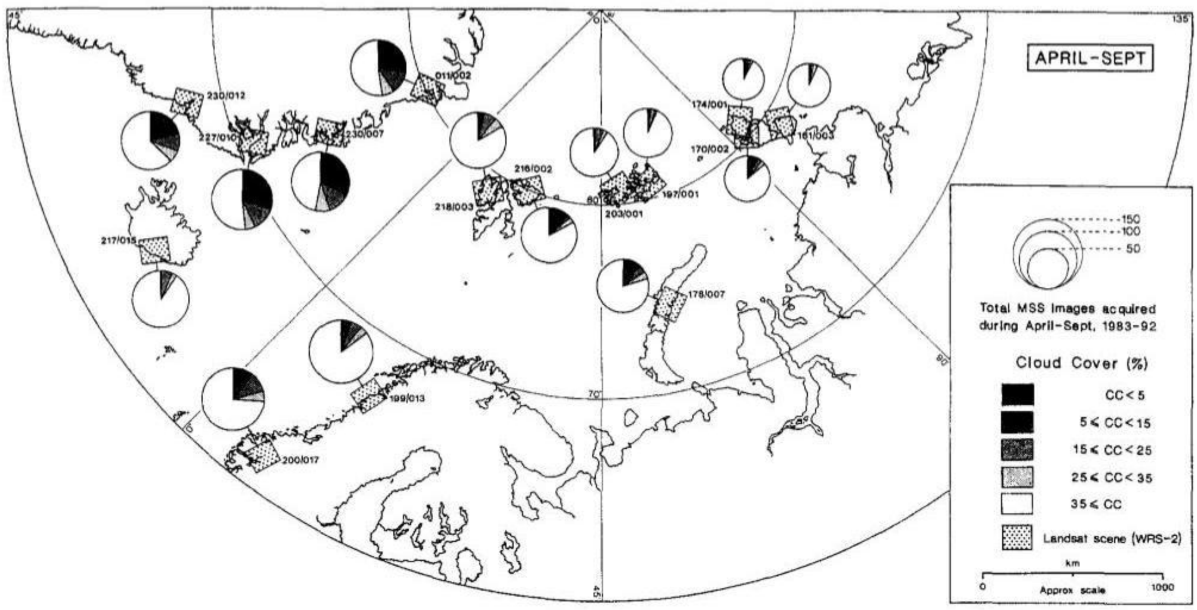

Figure 5: Spatial distribution of the relative frequency of cloud cover classes in Landsat imagery across the European Arctic sector for April-September 1983-1992 (Marshall et al. 1994)

3.4 Remote sensing of snow and ice

3.4.1 Application development

One of the most prominent and maybe even the best visible evidence of climate change are glaciers (Benn & Evans 2010; Nussbaumer et al. 2011; Oerlemans 1994). Glaciers react sensitively to global climate changes. This reaction can be measured within a few decades. For various purposes European alpine glaciers are used as global benchmarking climate change (Paul et al. 2004b).

Satellite remote sensing is a widely used tool in monitoring glacier extents throughout the world (Bolch et al. 2010; Lopez et al. 2010; Paul et al. 2004b; Racoviteanu et al. 2009). Monitoring the arctic and Antarctica is also wide spread. Glaciers are of particular interest, for example glacier monitoring in western Greenland (Chylek et al. 2007). Antarctica is mainly glacierized and therefore remote sensing of Antarctica is nearly always dealing with glaciers of all kinds. Even surprising events can be monitored, like the ice shelf which broke apart after the 2011 earthquake and following the tsunami event in Japan (Brunt et al. 2011). The highly remote location of Antarctica makes satellite remote sensing one of the few available and cost efficient ways of surveillance of the continent.

Also the monitoring of glaciers in mountain regions around the world is of interest for scientists. There are examples from all continents available, demonstrating the application of remote sensed data for Scandinavia or Tibet (Andreassen et al. 2008; Bolch et al. 2010). Many other studies could be found. Despite the fact that these areas are often populated, they are still remote areas in respect to accessibility for research purposes. Constant and reliable surveillance for years or maybe decades is difficult to achieve even today (Paul et al. 2004b).

For glacier mapping, and therefore for the mapping of snow the spectral resolution of the desired remote sensing platform is important. For automated and semi-automated classification purposes it is necessary to have several different bands (Pellikka & Rees 2010). Furthermore fine scale resolution data is always of advantage, as mentioned in 3.3.4, but for remote sensing of glaciers medium scaled data is sufficient (Paul et al. 2002).

3.4.2 Spectral properties of snow and ice

A key role in identification of snow and ice with remote sensing techniques plays their low reflectance in the mid infrared (Dozier 1989; Paul et al. 2002; Paul et al. 2004b; Racoviteanu et al. 2009). Often a ratio image between two bands is used to determine glacier outlines (Bolch et al. 2010; Paul et al. 2004b).

Although Klein and Isacks (Klein & Isacks 1999) prefer spectral mixture analysis of Landsat scenes for detecting the transient snow line, their figure regarding effective at-satellite reflectance is very interesting. At-satellite reflectance is a transformed expression of DN values, the figure gives valuable information of the spectral characteristics of snow and ice. It shows the spectral properties between snow / ice and rock / soil for each Landsat channel. As shown, especially channel 5 and channel 7 offer good spectral distinction between snow and ice and their common surroundings, whereas ice shows close spectral characteristics compared to its surroundings in visible spectrum. Channel 7 is considered as more noisy overall, compared to channel 5.

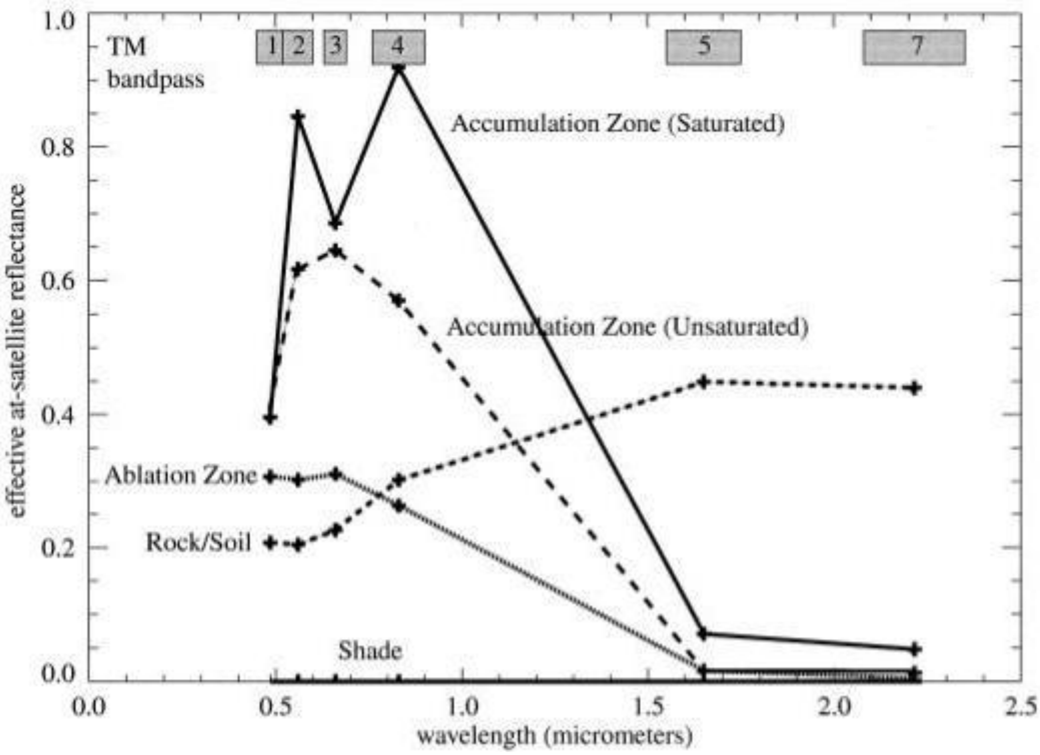

Figure 6: Endmember spectra used in the spectral mixture analysis (Klein & Isacks 1999)

Figure 6 shows the spectral properties of wet snow, dry snow, ice and bare rock and soil in the different TM bands. In the visible part of the EMR, bands one to three, snow and ice are more reflective than rock and soil. The infrared band four shows similar properties and unlike in vegetation cover analysis here it is not revealing relevant information. This also explains that MMS Landsat scenes are not particularly useful for snow cover mapping. MMS is not equipped with the decisive band number five. In band five the spectral properties are turned upside down. This contrast between the visible spectrum of the EMR and band the SWIR is very interesting. It can be exploited for the purpose of snow and ice cover mapping.

3.4.3 Normalized difference snow index

For snow and ice detection the green and short wave infrared (SWIR) wavelength is used. The two bands are selected following the constraints shown in Figure 6 (Dozier 1989).

The NDSI is calculated with the following formula:

$$\frac{Green\ (TM2) -\ SWIR(TM5)}{Green\ (TM2) +\ SWIR\ (TM5)}$$

In the visible spectrum of the light snow has a high reflectivity compared to the SWIR which has a very low reflectivity. Bare rock has a low reflectivity in the visible part of the light but a rather high reflectivity in the SWIR. Results range between -1 and 1. They are dimensionless and therefore easy to use. Most applications use a threshold of 0,5 ±0,1 for describing snow and ice (Hall et al. 1995; Hendriks & Pellikka 2007; Paul & Hendriks 2010b) . Compared to simple band ratioing for example TM3 / TM5 the spread of the results is small. Nevertheless both approaches give good results (Andreassen et al. 2008; Paul & Andreassen 2009; Sidjak & Wheate 1999).

3.5 Landsat satellite technical references

3.5.1 Landsat mission history

Landsat developed from early experiments with multispectral optics, for example aboard of Apollo 9. Landsat 1 up to Landsat 3 were designed with sensors called Multispectral Scanner (hereinafter briefly referred as MMS). They were recording in green (0,5 µm – 0,6 µm), red (0,6 µm – 0,7 µm) and two near infrared (0,7 µm – 0,8 µm and 0,8 µm – 1,1 µm) spectrum channels. All three satellites were launched in the 1970th of the last century. The primary objective for Landsat in the beginning was acquiring images for geological and mapping purposes. More and more the usefulness for biological purposes, mainly vegetation cover mapping, were discovered and noted. The whole program was controlled by the National Aeronautics and Space Administration (hereinafter briefly referred as NASA) (Albertz 2007; Williams et al. 2006; Wulder et al. 2012).

In the beginning most of the acquired Landsat images were analyzed by visual assessments. The available computer infrastructure and analyzing technology was not yet of a sufficient nature and had to be developed (Williams et al. 2006; Wulder et al. 2012).

Landsat 4 and Landsat 5 altered the whole program. First of all, both satellites came up with several technical developments. Most important to mention are the new Landsat sensors, which dramatically increased the resolution form the MMS 80 m by 80 m to 30 m by 30 m per pixel. The sensor generation is also increasing the scientific value of the Landsat image with additional spectral resolution in the mid- and thermal infrared range. The second important point is the transition of program control from the NASA to a private company. A brief summary of this shift: the earth observation capabilities were reduced due to pricing and copyright limitations as well as reduced image acquisition (Wulder et al. 2012).

Unfortunately as the rocket transporting Landsat 6 had a launch failure, the satellite never became operational. With Landsat 7 came another shift, back to governmental control of the program but also to incremental sensor evolution (Albertz 2007; Williams et al. 2006; Wulder et al. 2012).

Usually each satellite was used twice as long as the designed lifetime. Remarkably is the lifetime of Landsat 5 of 28 years. This is owed to additional fuel cells aboard the satellite for shuttle rendezvous (Betz 2013). Furthermore overlaps in active duty time are common as well. The overlaps are mitigating any failures of other devices. The long term recording of information is secured (Williams et al. 2006; Wulder et al. 2012). On 11th of February 2013 the Landsat 8 was launched finally, after the launch delays. The first satellite signals were recorded by the ground station on Svalbard (Cole et al. 2013).

3.5.2 Landsat TM

Landsat 4 and 5 were a step forward into a new sensor generation called Thematic Mapper (hereinafter briefly referred as TM). The pixel size was lowered from 80 m by 80 m used in the MMS sensor to 30 m by 30 m Furthermore the spectral resolution was increased as well. The sensor now covers also the blue spectrum (0,45 µm – 0,52 µm), the medium infrared spectrum with two channels (1,55 µm – 1,73 µm and 2,08 µm – 2,35 µm) and a thermal infrared spectrum (10,4 µm – 12,5 µm). The thermal sensor comes with a resolution of 120 m by 120 m. The satellite has a repeat interval of 16 days and it is flying 705 km above ground (Albertz 2007; Khorram et al. 2012).

Landsat 5 is not equipped with larger onboard storage device. It is not possible to acquire and temporarily store scenes. Therefore it is necessary to have contact with a ground station for image acquisition and storage. The recorded image is directly transmitted to the ground station for further processing. Over areas with low levels of infrastructure or political sensitive areas like Russia for example this constraint is leading to data gaps. Another aspect can be a delayed transfer of images to the USGS facilities (Williams et al. 2006)

As any other Landsat missions before Landsat 5 was designed for a 3 years mission. As mentioned, Landsat 5 was equipped with additional fuel for shuttle rendezvous in space. This fact later paid off during the time after the Landsat 6 launch failure and the Landsat 7 problems. It was possible to keep the satellite operational, despite several technical challenges (Betz 2013).

Soon after the Landsat 7 failure most of the globally distributed ground stations returned back onto Landsat 5 and started receiving information from the satellite again (Wulder et al. 2008).

Landsat 5 was the subject of ongoing maintenance and technical surveillance. Although its characteristics were altering over the years due to ageing, the acquired images are still useable. Technical papers regarding the satellites status were constantly published (USGS 2013).

3.5.3 Landsat ETM+

Landsat 7 is equipped with the so called Enhanced Thematic Mapper Plus (hereinafter briefly referred as ETM+). As the name is already indicating, the EMT+ sensor is an evolution of the TM sensor. The spectral properties are similar as well as the resolution except the thermal band which now as an increase pixel size of 60 m by 60 m. Furthermore the sensor is equipped with a 15 m by 15 m per pixel panchromatic channel. The panchromatic channel covers the EMR from green (0,52 µm) to the near infrared spectrum (0,9 µm) at once (Albertz 2007; Khorram et al. 2012).

Landsat 7 data that is archived by the USGS is usually collected by two ground stations located in Sioux Falls, South Dakota and in Alice Springs, Australia. Additionally two backup stations are located in Poker Flat, Alaska and Svalbard. The latter two are used for achieving Landsat mission objectives when data transfers from the satellite reaches peak levels. Unlike its predecessors Landsat 7 is equipped with an onboard storage unit. It is enabling image acquisition over areas lacking ground contact and it is contributing to peak levels of data transfer (Wulder et al. 2008).

Landsat 5 and Landsat 7 have adjusted repeat intervals. With both satellites linked it is possible to have a virtual repeat interval of 8 days (Williams et al. 2006).

3.5.4 Landsat 7 scan line corrector failure – ETM+ SLC-Off

Since May 2003 the scan line corrector onboard Landsat 7 is malfunctioning. The error does not influence the radiometry and geometry of the sensor. But towards both sides of the image data gaps are increasing, as Figure 7 demonstrates. Overall the SLC-off results in a loss of approximately 25% of information (Irons 2011; Markham et al. 2004; Williams et al. 2006).

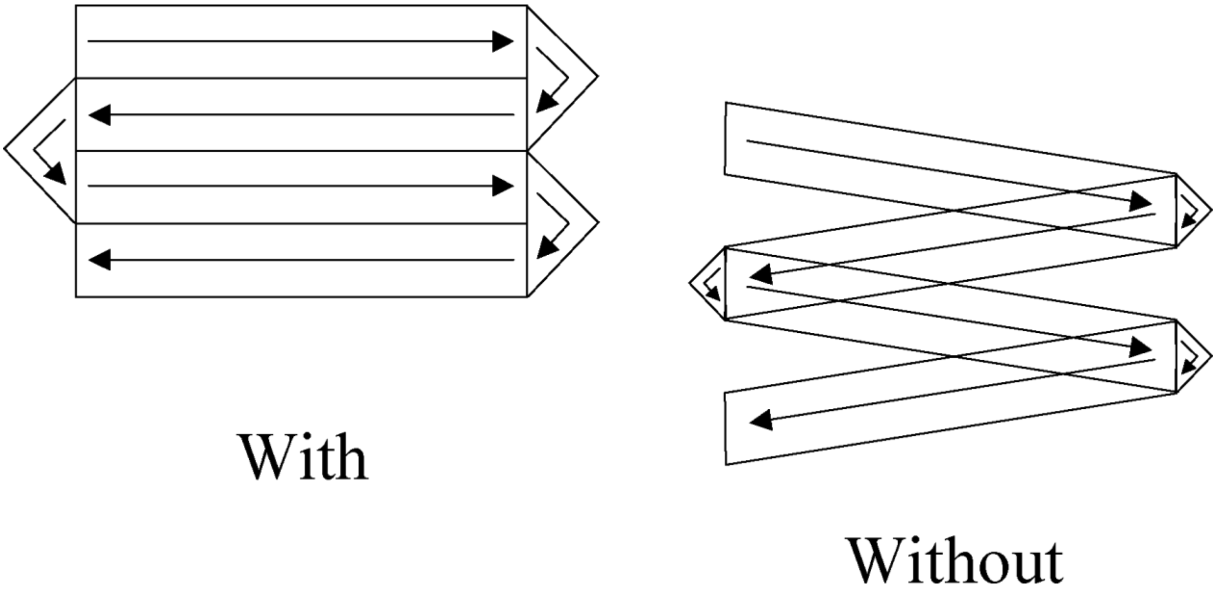

Figure 7: Data coverage with and without the operating Scan Line Corrector (Markham et al. 2004)

Since 2004 the long term acquisition program has been adjusted. Now one of the main operative tasks is gathering pairs of low cloud cover scenes, with special emphasize on the growing season. Images within a range of 32 days can be joined, which is an effort to mitigate the extent of the SLC failure. For several purposes, including snow cover investigations, data fused products can bias results due to differences in rapid land cover changes (Wulder et al. 2008).

4 Methodology

4.1 Scene selection

The image selection is comparably difficult in glaciology. Overall only images towards the end of the melting season are reliable. Additional problems are scene availability in respect to available funding and cloud cover. Therefore in pre 2008 studies it was common to use few images covering roughly a month (Paul et al. 2004b).

Today it is possible to browse and evaluate a lot of available Landsat images. Especially images that were neglected before 2008, mainly due to cloud cover, are now an additional source of information. Although their contribution is not big and they are not essential for demonstrating a land use change, the images can reveal a more detailed view of such a development (Griffiths et al. 2012; Paul & Andreassen 2009). Another important aspect is having the opportunity to look at each image individually in full resolution before making choices for further steps. Unfortunately this is labor intensive, but can improve the overall results. This is the approach used in this work. A lot of scenes were not useful due to cloud cover. (Paul & Andreassen 2009).

Whenever cloud free images are available, they should be preferred. Furthermore images of neighboring path can be used as well. A side effect is the reduced repeat intervals for the overlapping parts of the scene and therefore it is also increasing the chance to obtain suitable images (Paul & Andreassen 2009). For the study region they have an overlap of approximately 55 %. ETM+ SLC-OFF images can be used as well. Usually the missing areas are filled with older data. Unfortunately this is not a suitable approach in this study, as precise information regarding snow cover is one of the main objectives. Snow cover is altering slightly each year but might follow a distribution pattern (Bales et al. 2008).

The selection of images for direct change detection is restricted to scenes towards the end of the ablation season. As it is usually applied in glaciology this date is the first of October each year lasting to the thirtieth of September the following year, the so called calendar year (Benn & Evans 2010). When no suitable Landsat images close to this day are available scenes from earlier dates of the year are selected. Often snow cover or simple unavailability is predetermining the scene selection. Whenever an unusual date is selected, it is mentioned and explained. For analyzing snow cover development of selected areas suitable images of a single year were selected. Filling gaps in ETM+ SLC-OFF scenes would therefore make no sense at all.

4.2 Channel combinations

Combining Landsat bands of the red (TM 3), near infrared (TM 4) and middle infrared (TM 5) spectrum is suggested by several authors (Paul et al. 2004a; Paul & Hendriks 2010a). The image displays clear boundaries of snow and ice covered areas. Several other satellite remote sensing platforms are offering this spectral setup in a similar way and therefore it is increasing comparability (Paul et al. 2004a). For this work the channel combination TM 5-red, TM 4-green and TM 3-blue is always applied for any Landsat TM and ETM+ image as recommended (Paul & Hendriks 2010a; Pellikka & Rees 2010).

4.3 Applied routines

Landsat data downloaded from the earthexplorer webpage comes already preprocessed. According to the Landsat handbook an image comes with the following steps included: payload correction data processing, mirror scan correction data processing, ETM+/Landsat 7 sensor/platform geometric model creation, sensor line of sight generation and projection, output space/input space correction grid generation, image resampling, geometric model precision correction using ground control and terrain correction. The processing stage is called Landsat level 1T (Hansen & Loveland 2012; Irons 2011).

Usually it is assumed that bias resulting from inappropriate georeferencing of satellite images influences the results which are compared with external sources. Landsat level 1T data has a reference error smaller than the pixel size (Hall et al. 2003). Only one Landsat scene (etp199r16_4t19880908) was not properly referenced, it showed a one to two pixels shift of all pixels towards a north eastern direction. This Landsat scene was georeferenced to a level 1T Landsat 7 scene (LT51990162003221MTI01) from 20030809 using the automated georeferencing algorithms of ESRI ArcGIS 10.1.

It is recommended that whenever an image is subject of change detection, the conversion of digital numbers (referred as DN) into at-sensor reflectance should be applied. It makes it easier to distinguish between land cover change and sensor related aging processes (Chander et al. 2004; Chander et al. 2007; Chander et al. 2009). Furthermore it is often stated, that data processes at-sensor reflectance level is more accurate compared to data processed at DN level (Hall et al. 1995; Winther & Hall 1999).

Therefore several Landsat 4, Landsat 5 and Landsat 7 scenes were converted into at-sensor reflectance. The further processing revealed surprising results: whenever the NDSI and subsequent snow cover binary maps were developed, at-sensor reflectance images showed a high level of bias. Casted shadows were very often falsely classified as snow cover. This error is not reproducible with unprocessed DN images to such a huge extent.

As Figure 8 is showing, the false classification bias is huge. Casted shadows seem to be the greatest source of error. Furthermore Figure 8 is also showing, the total calculated extent of snow cover is approximately 9 times higher in at-sensor reflectance images. Even with the expectation that at-sensor reflectance images might be more accurate, this would also highly increase the further workload for additional masking of casted shadows. Therefore none of the images is converted to at-sensor reflectance and DN images are used instead as it is recommended (Paul et al. 2002). This approach is not uncommon for NDSI or ratio approaches (Hendriks & Pellikka 2007; Paul & Andreassen 2009).

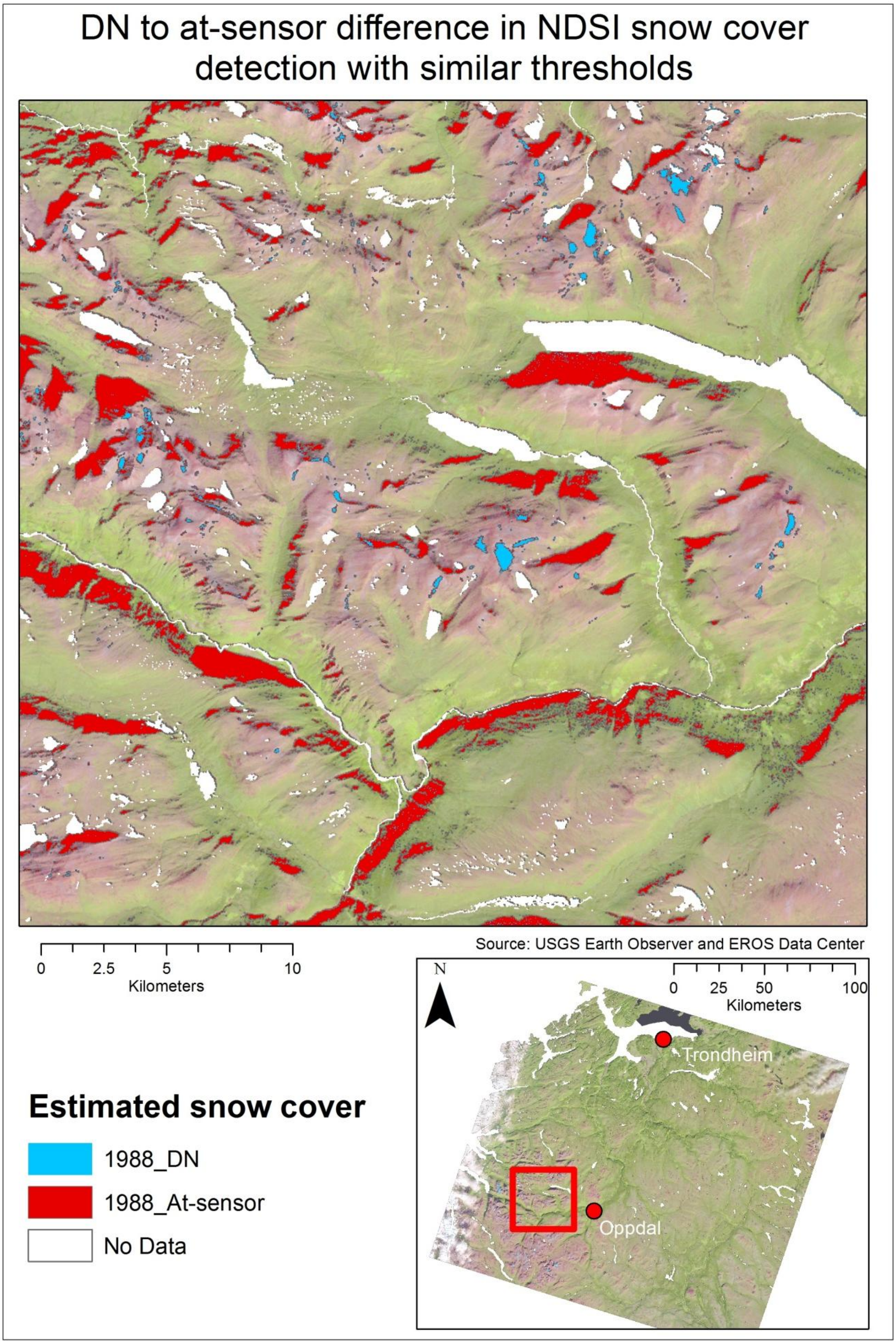

Figure 8: DN to at-sensor difference in NDSI snow cover detection with similar thresholds

4.4 Masking

Water is identified as a disturbance factor for snow cover detection as it has similar spectral properties as snow. Therefore it is recommended to mask water (Hendriks & Pellikka 2007; Winther & Hall 1999). A water mask can be established by the so called normalized differential water index (hereinafter briefly referred as NDWI) for example. It is similar to the NDSI and therefore it is a raster operation only.

Beside the NDWI it is also possible to use vector data for masking water bodies. The Norwegian mapping authorities are supplying a full water body vector dataset for continental Norway. The resolution of this dataset is 1:50000. For masking purposes applied on Landsat images the resolution is of supreme quality and exceeding the required resolution of at least 30 m by 30 m. Subsequently the data for fylke in the study area was selected in GIS and composed into a single file. Afterwards this file is the reference for an automated masking application in ERDAS Imagine.

4.5 Classification

Unlike glacier detection where debris cover is always a problem, the detection of snow in vegetation free areas is reliable. The main problem is debris cover dropping from surrounding rocks or dust. Characteristic moraines are not visible (Paul et al. 2002; Paul et al. 2004a). In the study area this fact seems to be of no importance. Therefore it is easy to apply the NDSI as described in 3.4.3. A threshold of 0.5 was used for this process.

Image filtering is usually a common way of enhancing optical properties of images. In this case a median filter (3x3) is applied for mapping snow cover changes when the results are designated for catchment analysis. It reduces noise, very small snow fields are deleted and small gaps between snow areas are removed (Paul & Andreassen 2009).

But all the above mentioned consequences would also be applied on snow patch maps when the filter is applied. Unfortunately it is not possible to apply the filter as small snow fields are of interest as well and would be deleted (Paul & Andreassen 2009).

4.6 Transformation into- and calculation of basic characteristics with Esri ArcGIS and Microsoft EXCEL

After the image processing and classification in ERDAS Imagine, the classified results are stored as raster image files. It is subsequently possible to open these images in ESRI ArcGIS as well. Fortunately any relevant information defined for the Landsat file is carried along with the classified image. Therefore it is not necessary to conduct any preprocessing in GIS. Furthermore it is useful to use the USGS Landsat files as a background map in GIS, without any raster calculations based on them.

The imported binary raster classification data is processed. As a first step, pixels classified as snow free are clipped. For this operation the raster clipping tool is used in the following way: any pixel with a zero value is clipped. Any remaining pixel represents a snow pixel.

After this process the product can then be converted into a vector file with the raster to vector operation. It is important to avoid any smoothing operation, as it is desired to keep the pixel structure of the dataset. Smoothing would increase bias and it would indicate an accuracy that is not represented by the dataset (Longley et al. 2011). This finally represents the snow cover maps.

The ASTER DEM data was downloaded from j-spacesystems which is founded by a cooperating between the NASA and the ministry of economy, trade, and industry of Japan (Cole 2012). Available was the latest edition of this dataset, edition no.2. This data can be downloaded and used without charge. It is downloaded in geoTIFF, which means it can be used in GIS directly. As the data is used as additional information and as it is not subject of any calculation, the vertical accuracy of approximately 20 m seems to be sufficient. Therefore the data was projected “on the fly” in the GIS, without any georeferencing. (Tachikawa et al. 2011).

Digital elevation models (DEM) offer the additional analytical opportunities. The binary snow cover map, which is not incorporating any elevation, cannot describe the environment of the snow any more. It is becoming less informative compared to a Landsat scene. By using the ASTER DEM it is possible to determine altitude, slope or aspect for the single snow patches and therefore the lost information regarding the environment is compensated (Paul et al. 2004b). ASTER DEM data is considered suitable for matching with snow and ice information developed from Landsat scenes (Bolch et al. 2010). The ASTER DEM will not be subject of any steps of processing. Its resolution of approximately 30 m by 30 m is not incorporated into the Landsat scenes or in the opposite direction. This would introduce unnecessary bias into the Landsat analysis. The incorporation is not deemed necessary (Kääb 2008; Nuth & Kääb 2011).

Some characteristics will be extracted in ArcGIS and transferred into Microsoft EXCEL. The calculations are based on statistical formulas and practical advices (Bahrenberg et al. 1999; Millar 2001)

4.7 Change detection

For change detection purposes it is useful to work in GIS as well, as the spatial extent of the change can be easily calculated. Each dataset should represent a certain date and the binary raster datasets of the final classification process including manual corrections are utilized. In visual change detection it is sufficient to designate different colors for each dataset and create an overlay. Overall more than three datasets for an overlay at the same time can result in confusion. Therefore it is chosen to use only two whenever suitable.

For computing change the raster calculator is used. With regard to the nature of binary data, simple addition of the datasets is sufficient for extracting spatial change. Any raster cells which are not subject to change are summed up. Subsequently the unchanged area can be calculated but also vice versa the area affected by change is also calculated. For spatial calculation purposes the raster files are converted to vector datasets as mentioned in chapter 4.6.

4.8 Flow diagram

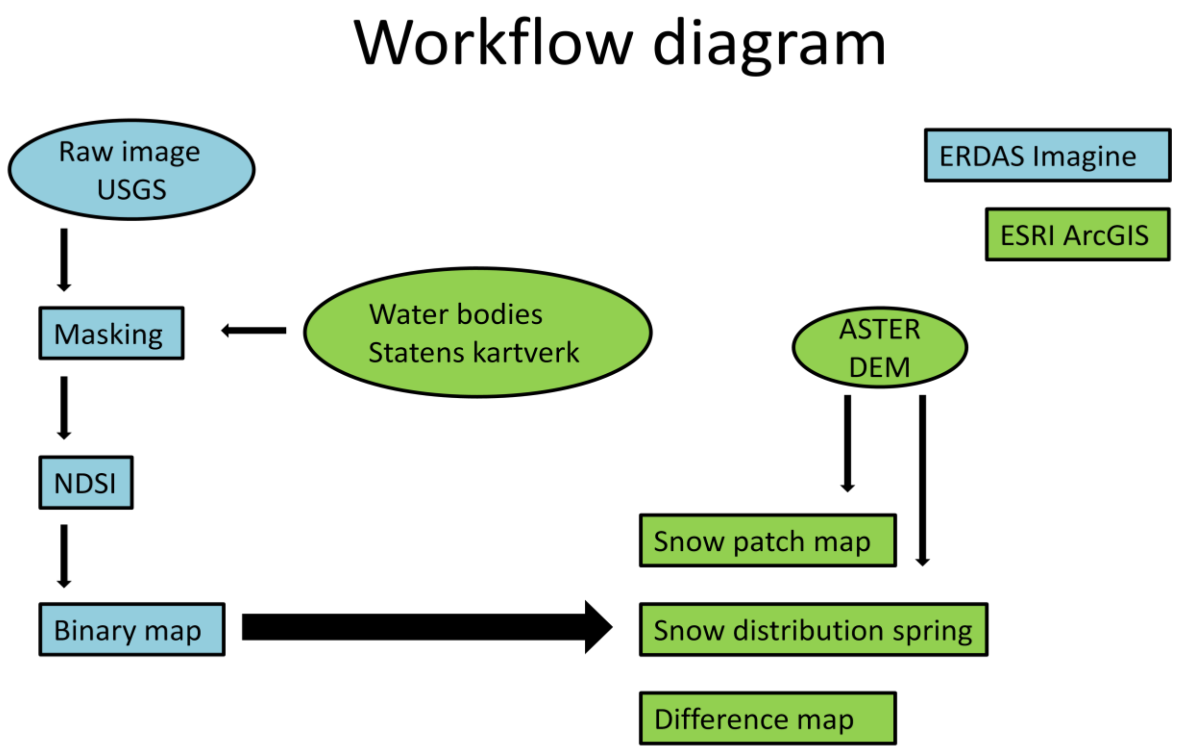

Figure 9: Workflow diagram

4.9 Potential sources of error

As it is necessary to reduce the information density of geographic objects in a GIS, nowadays satellite images are usually utilized as digital raster datasets. Raster represents objects in rectangular grid cells. The applied techniques described in section 4.3 are already altering the data. Raster data of this geometrical extent needs to be adjusted to the earth surface. Therefore it is introduces bias to the data at this early stage of data collection in order to increase accuracy (Longley et al. 2011).

Furthermore to any grid cell exactly one value is assigned. In case of Landsat this is a value for an area of 30 m by 30 m, which is stored for each band. For example rocks shining out of the snow cover are omitted to some extent. Only when they are large enough, they can alter the spatial signature of a pixel. Any information in this 30 m by 30 m pixel is a combination of ground reflectance. Overall it can be assumed that Landsat raster datasets cannot reveal information beyond this pixel size (Longley et al. 2011; Paul et al. 2002).

5 Results

5.1 Distribution in space and altitude

Figure 10 is an overview of the study area. It includes the frames of the figures used in this chapter. The color coding indicates each frame individually, due to the overlaps of the frames.

Figure 11 to Figure 15 are based on a Landsat 4 scene from the 8th of Sptember 1988. Cloud cover is low for most of the scene and only a stripe along the coastline is invisible. This scene seems to represent a snow free situation. Most of the seasonal snow, which is present in the rare available scenes prior to the date and in the later stage of gathering data, is not present. Unfortunately most of the earlier scenes are acquired with Landsat MMS, but nevertheless these images still allow the detection of a trend. Furthermore the whole scene allows an early observation in the Landsat mission history and is highly suitable for detecting later land cover changes. The 1988 image is also describing snow patch areas which are not detectable any more today. For any archaeological surveys this could be potentially helpful.

The Landsat scene cannot measure the altitude, but with the digital elevation model created from ASTER data the altitude and topography are becoming visible. In the following figures the altitude displayed begins at 1000 m above sea level. A detailed view of the valley altitudes seems to be unnecessary as snow patches are not detectable there. Therefore any contour lines of this low altitude would only increase confusion. The blue areas represent snow or ice based on the NDSI and a threshold above 0.5.

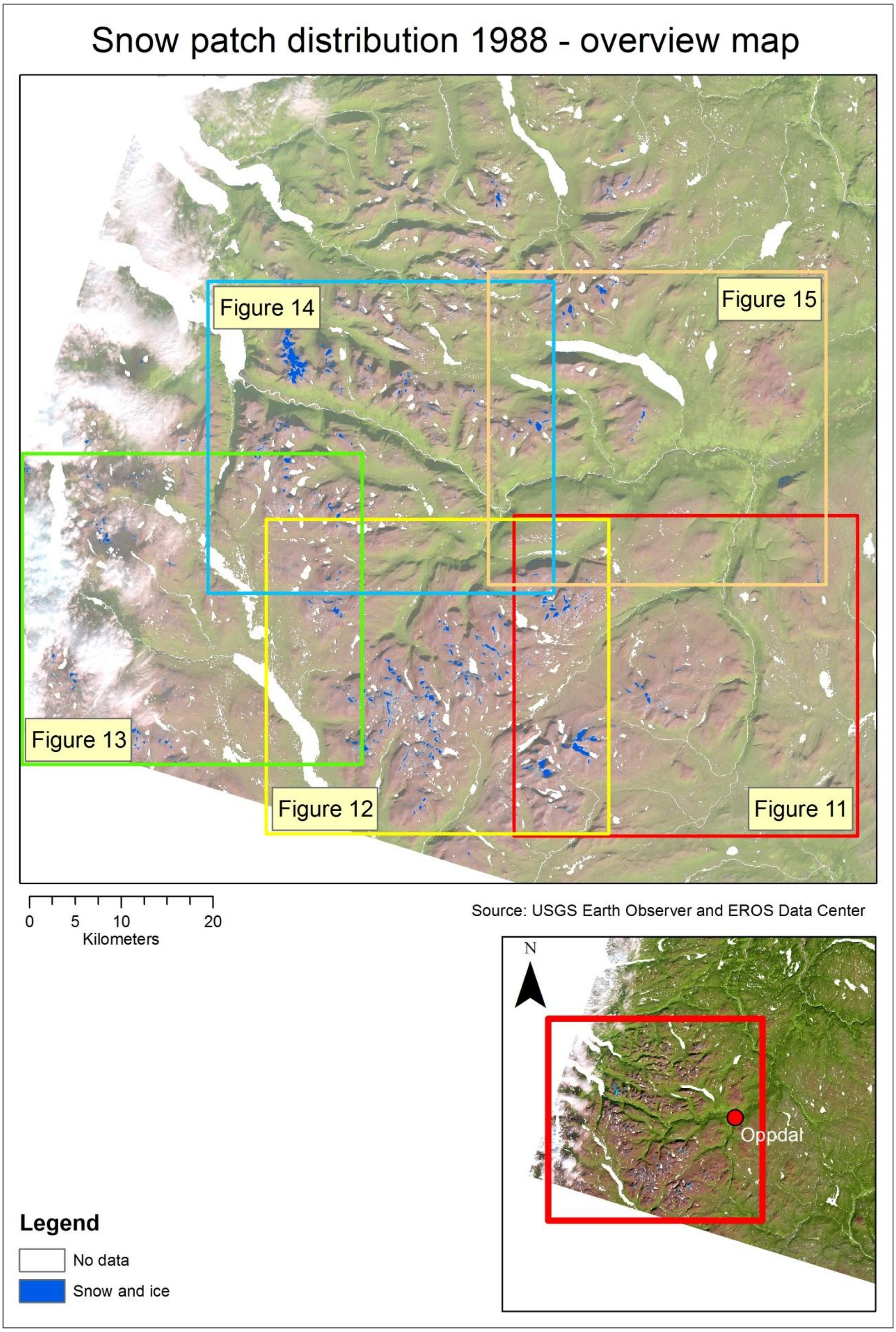

Figure 10: Snow patch distribution 1988 - overview map

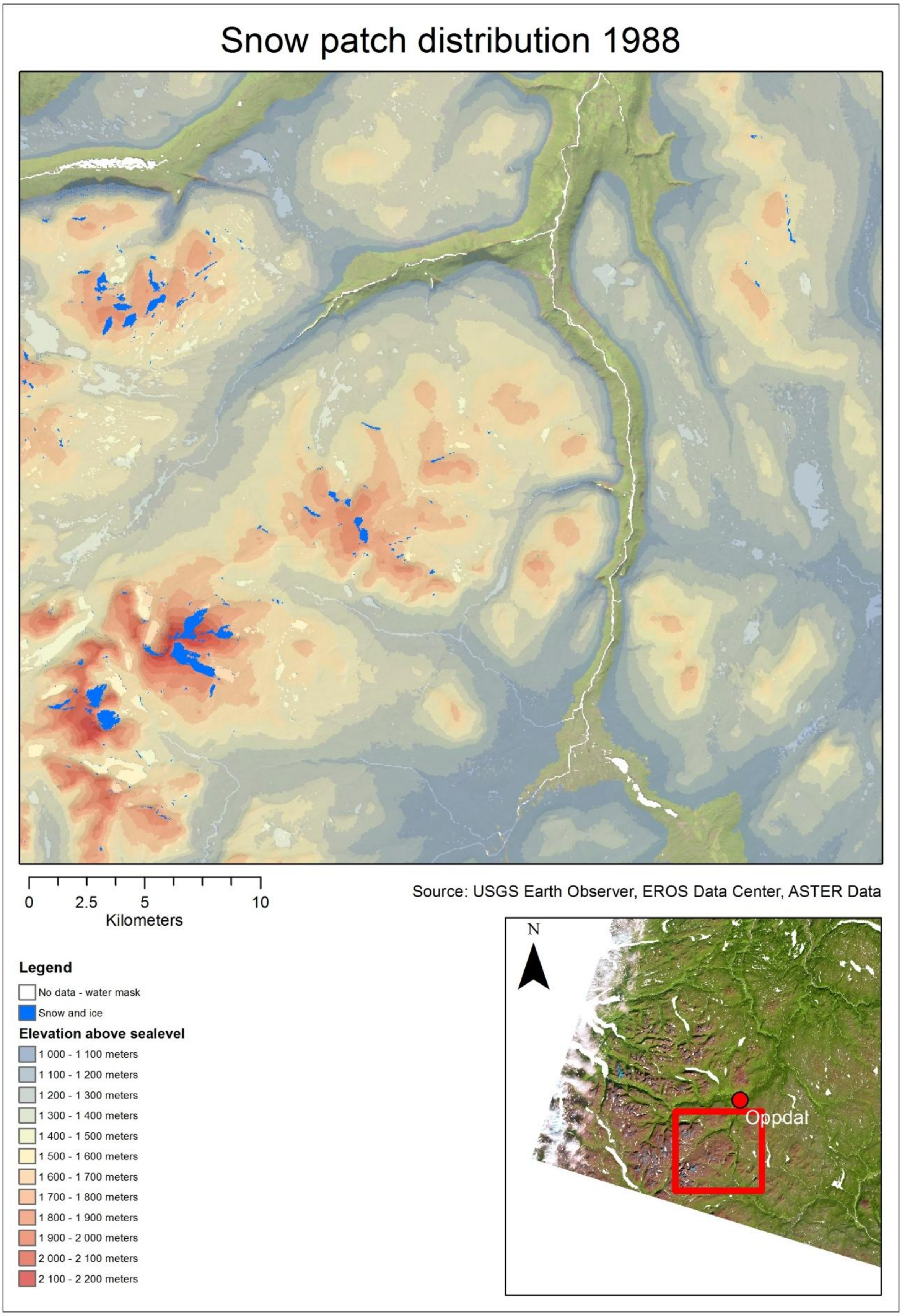

Figure 11: Snow patch distribution in 1988

In the study area a spatial pattern is visible in the distribution of snow patches. The total amount of snow patches is increasing from the east towards the west as Figure 11 is showing. It is visible, that snow patches seem to be coupled with topographic characteristics, as they mostly are facing eastwards. This is only an overall trend as several snow patches are also facing north eastern directions and rare ones also are facing south eastern directions. A good example for this south eastern setting is seen in the snow patch south of Snøhetta. Furthermore it is possible overall to see that snow patches are not located in valleys. This explains why there are larger gaps in the snow patch distribution.

The southeastern region of Figure 11 is showing no larger snow patches. In the northern part a plateau is visible with only a few snow patches present. The central part of the scene is dominated by an elevated area as well. This elevated area reaches up to approximately 1900 m with several areas identified as snow or ice. Storbreen in the center spreads from 1800 m above sea level down to 1700 m. Closely located snow patches are reaching down to 1600 m above sea level. A few snow patches are located at the 1500 m above sea level margin. This seems to be a soft threshold in altitude for the presence of snow patches.

In the south western part of Figure 11 larger connected areas of snow and ice are detected. This area of snow and ice is Snøhetta mountain and its glacier. Remarkably to the viewer is the altitude reaching approximately 2200 m above sea level. Such a high altitude seems to favor glacierization, as directly west of Snøhetta mountain two more glaciers are visible.

Towards the east hardly any snow patches are detectable. Only in the north east Kringsollfonna and Brattfonna close to Oppdal are visible. Kringsollfonna is located at the 1500 m margin as well as Brattfonna.

Remarkably as well is the north western part of the scene, dominated by snow patches which seem to be decorated along the elevated region. Figure 12 is clearly showing the whole extent of this snow patch favoring region.

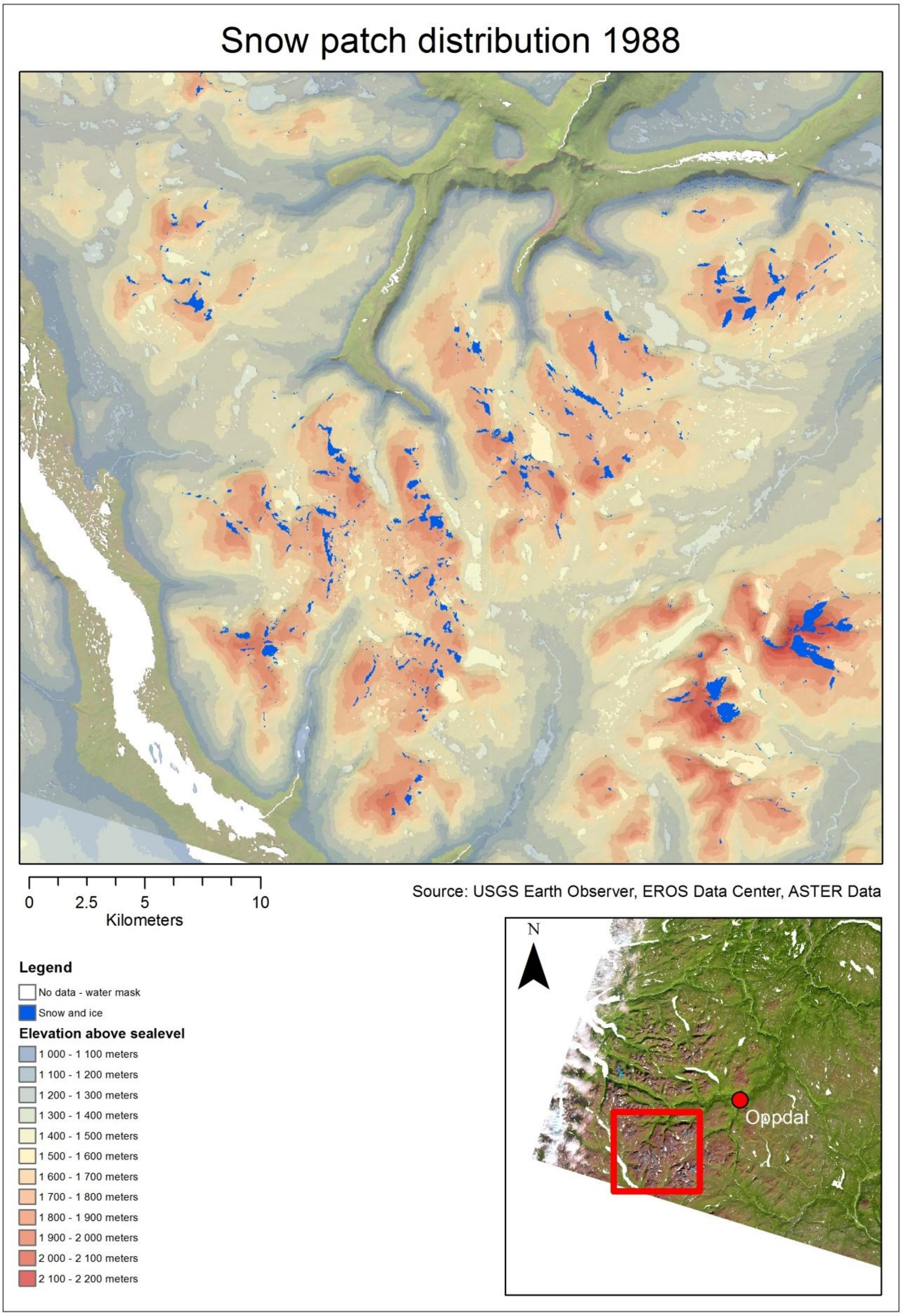

Figure 12: Snow patch distribution in 1988

In Figure 12 several snow patches seem to dominate the area. This domination is seen in the southwest of the figure stretching to the northeast. Some of these snow patches are visible in Figure 11, like Snøhetta as well. The snow patch favoring region is limited in the central southwestern part of Figure 12 by a large depression. This valley is dominated by a masked lake stretching in a northwestern direction. Towards the east the region can be separated by a valley with elevations up to approximately 1400 m, but a main elevation between 1200 m and 1300 m. All along the lake and valley no snow patches are mapped, the area is seen to not favor the location of snow patches. Towards the north a valley below 1000 m above sea level is visible and limiting the central region. In the west a similar boundary as in the east is observable with an elevation of approximately less than 1400 m.

In the central area of the figure several larger snow patches are mapped. Additionally numerous smaller ones are observable as well. Again most of the snow patches are oriented towards the east, with variations towards northeast and southeast. Overall most of the snow patches are located in altitudes between 1500 m and 1700 m above sea level. Especially the limitation towards 1700 m is misleading to some extent as this elevation is often not even reached by the mountains.

In the central western part of Figure 12 smaller snow patches facing a western direction can be observed. They are located in elevations between 1400 m and 1500 m above sea level. Furthermore a difficult situation can be observed as well: in the central western region snow patches are located in a depression between two elevations. It is not clear whether this snow patch is facing an eastern or a western direction without additional high resolution data.

Towards the northwest in the figure fewer snow patches are observable. Again most of them are facing eastwards with variations towards the northeast. Most of the snow patches are located between 1500 m and 1600 m above sea level.

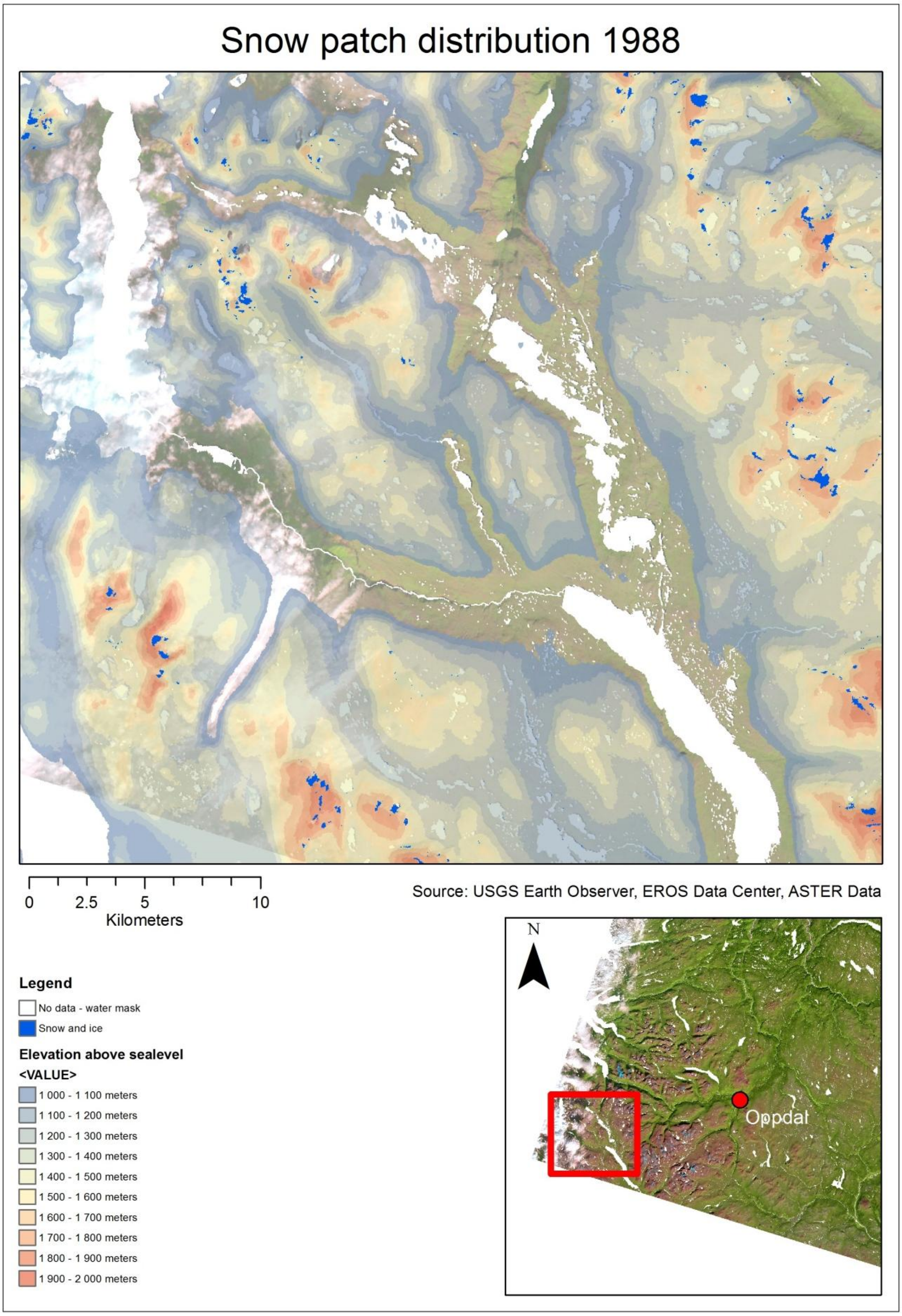

Figure 13: Snow patch distribution in 1988

Figure 13 shows snow patches on the eastern and western margin. Yet the central area of the figure is snow patch free. Most of this area is below 1600 m above sea level or it is valley bottom below 1000 m.

The southern region of Figure 13 reveals snow patches in an elevation between 1600 m and 1800 m above sea level. Most of the snow patches in this southern region are facing eastwards or in north eastern direction.

More snow patches are visible in the southwest, separated by a valley below 1000 m from the snow patches in the south. Here the snow patches are located in an elevation of 1600 m to 1800 m again. They are facing eastwards. Unfortunately this area of the whole Landsat scene and especially of Figure 13 is subject to strong bias, as this part is partly cloudy. Therefore it is not unlikely that more snow patches could have been mapped on a totally cloud free scene.

Further in the northwest snow patches become visible as well. Again this area is separated from the southern part by valleys, masked water bodies and mountains of elevations up to approximately 1500 m above sea level. But mainly these mountains have lower elevations. The snow patches are located close to mountains with elevations of approximately 1700 m above sea level. Mainly the mapped spots are ranging from 1400 m to 1600 m and again several snow patches are facing in an eastward direction with variations towards northeast. But it is possible to observe a few spots facing directly westwards. Unfortunately this part of the scene and figure is subject of cloud cover as well.

The northeastern part of Figure 13 reveals snow patches in elevations between 1500 m and 1700 m above sea level. Most of the mapped areas are facing eastwards. Again variations are observable, mainly towards the northeast. The snow patches are usually located to mountains with elevations between 1700 m and 1800 m above sea level.

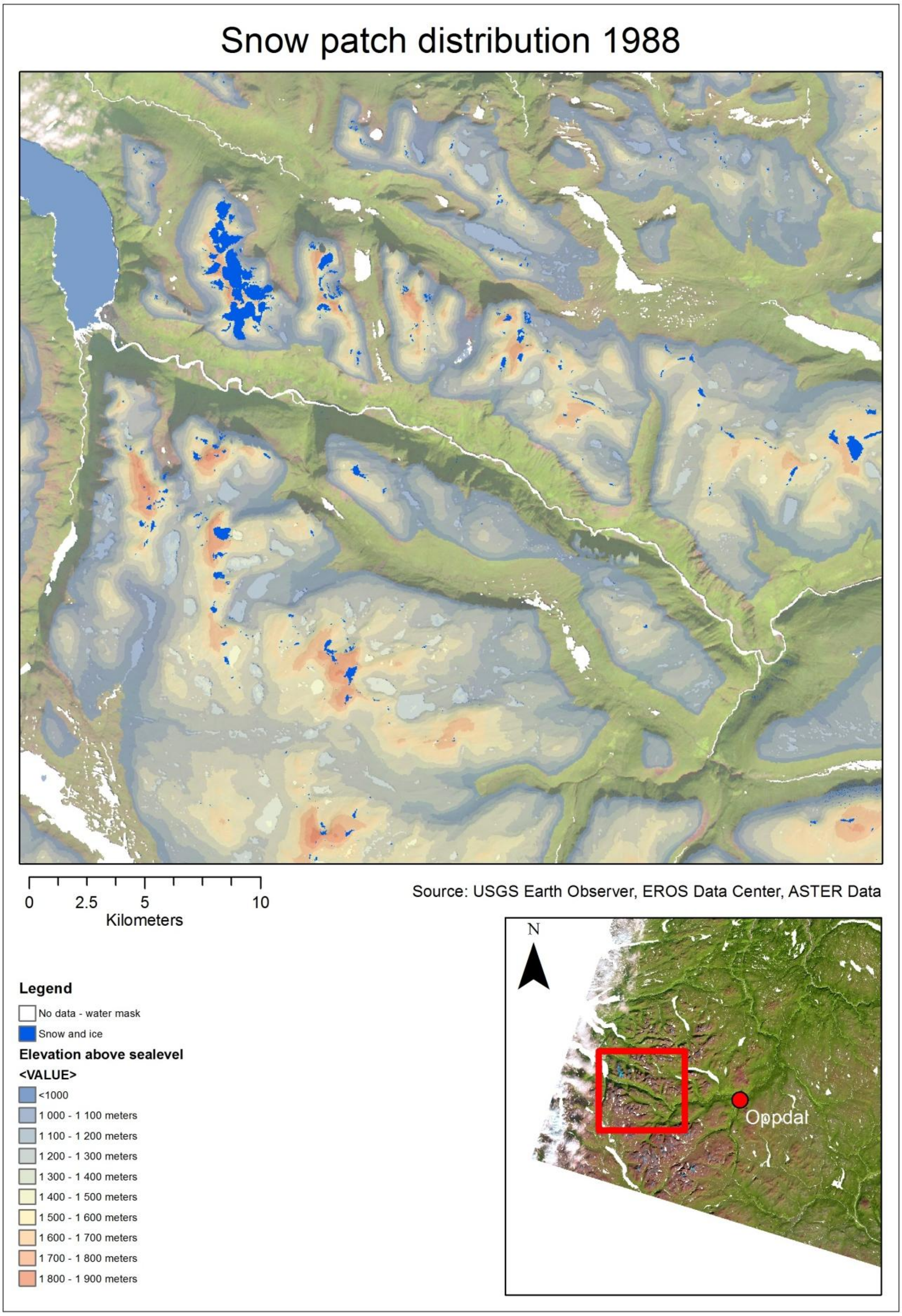

Figure 14: Snow patch distribution in 1988

Here in Figure 14 large areas are valleys below 1000 m above sea level. The snow patches visible in the south and southwest can be observed from altitudes between 1500 m and 1700 m above sea level. The exposition is usually facing eastwards with variations towards the northeast. A mountain with approximated altitudes of 1700 m to 1800 m seems to be close to any snow patch.

In the northwest a remarkably accumulation of snow and ice can be mapped, directly originating from Dronning- and Kongskrona. The mapped areas are glaciers. The glaciers seem to have their origin in elevations of 1700 m above sea level. It is this spot that they are spreading in any given direction including the west. But a major direction of exposition towards the east is still observable.

From there a mountain chain is stretching eastwards, separated by several valleys below or at approximately 1000 m. Close to Dronning- and Kongskrona in an eastern direction snow and ice can be mapped in elevations between 1400 m and 1600 m. Most of the mapped areas are facing eastwards, but variations towards north or south are observable as well. A few snow covered areas are mapped in elevations between 1100 m and 1400 m as well. Any of the mapped spots are closely located to mountains of at least 1700 m above sea level.

In eastern direction most of the mountain areas are located below approximately 1400 m above sea level and hardly any snow patches are seen to be mapped there. Most of the mapped areas are facing a northeastern direction. Overall this stretch in mountain area from the west towards the east also describes the difference between sharply formed mountains in the western part of the study area and rather gentle and round shaped mountains in the east.

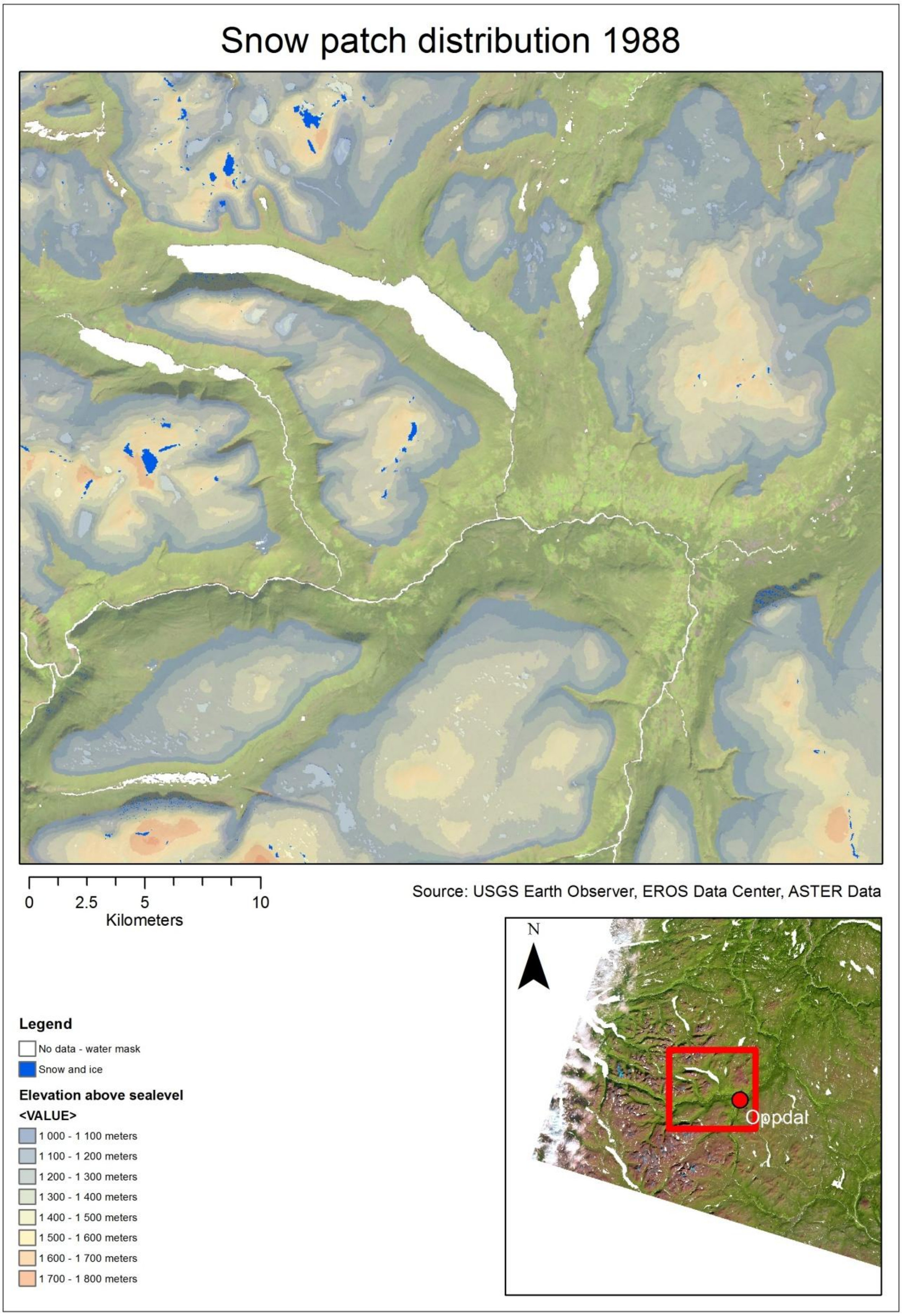

Figure 15: Snow patch distribution in 1988

In Figure 15 the area close to Oppdal is seen to be almost snow patch free. Overall snow patches are not as present as in other figures, as the conditions seem not to favor snow patches. On a large plateau south of Oppdal no snow patches are mapped, as it is reaching elevations of usually less than 1500 m above sea level. In northern direction of the city a few smaller snow patches can be mapped in elevations between 1400 m and 1600 m above sea level.

Figure 15 shows snow patches in western direction from Oppdal as well. They are mapped in elevations between 1400 m and 1500 m above sea level and are facing in an eastern direction. Separated by a valley and directly in the west Evighetsfonna can be mapped in an elevation of 1500 m. The snow patch is facing eastwards and furthermore it is located at a mountaintop of at least 1600 m above sea level.

In the northwest of Figure 15 several snow patches are mapped. Most of them are located in elevations between 1400 m and 1500 m above sea level. Most of the mapped snow patches are facing in a northeastern direction. On exception can be found: a cirque snow patch located in an elevation between 1000 m and 1100 m above sea level. This cirque snow patch is facing south.

Further towards the north and not mapped in any of the figures, the terrain reaching elevations of more than 1000 m above sea level becomes a rarity. Therefore only very few snow patches were mapped. They are located in elevations between 1300 m above sea level and 1500 m above sea level. Again the exposition is towards the east with variations towards north- and southeast.

5.2 Detailed development throughout a single year

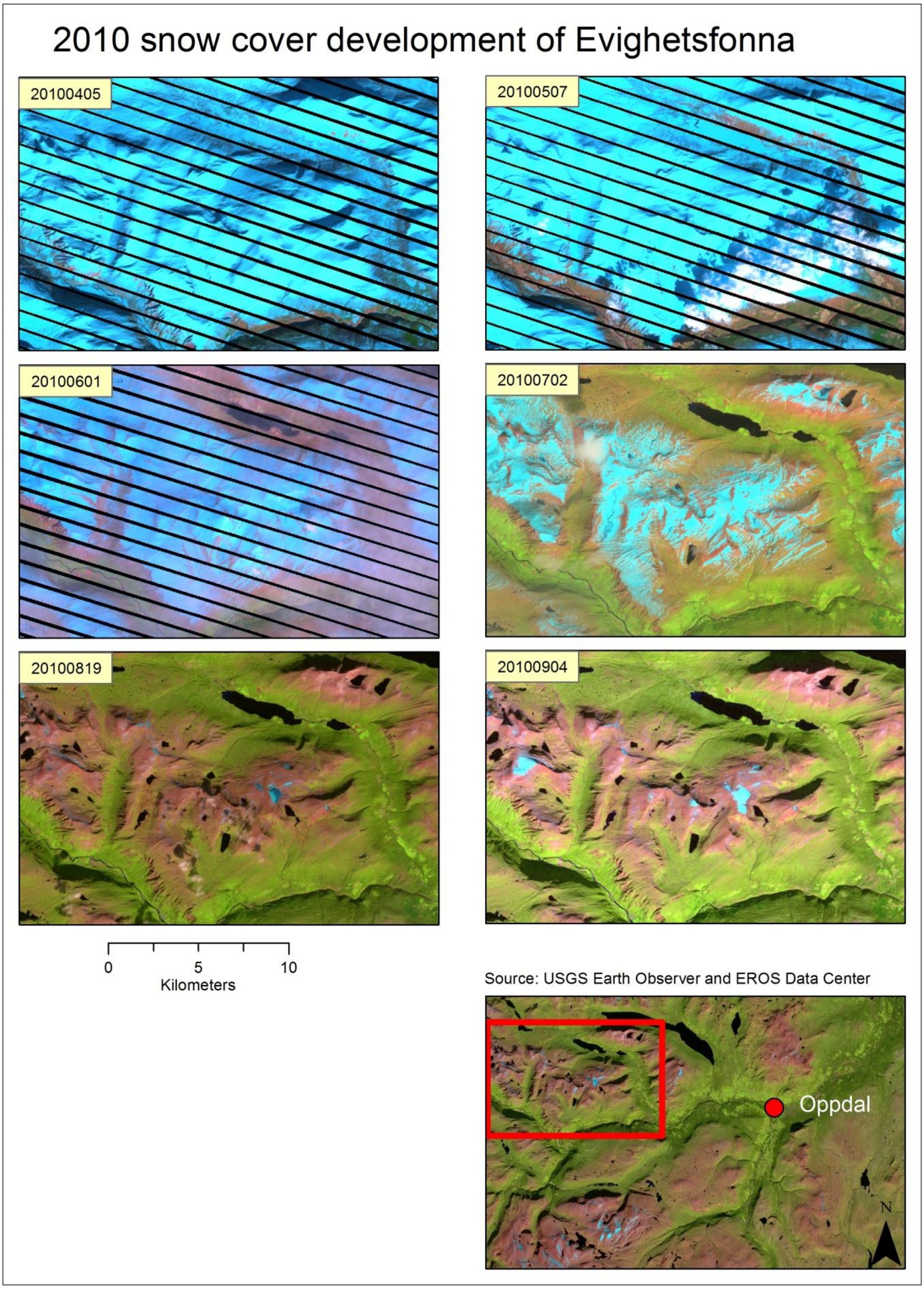

Figure 16: 2010 snow cover development of Evighetsfonna

In the year 2010there were 13 Landsat scenes overall which were in suitable quality and available in the study area. This is a very good coverage, with respect to cloud cover and illumination difficulties during the winter time. It is partly possible due to the availability of two operational Landsat platforms at that time. Unfortunately one scene is not showing Evighetsfonna, as it is on a flight path further in the east.

Figure 16 and Figure 17 show these 12 scenes. Beginning in early April most of the area is covered in snow. Most parts of the valleys are snow covered as well. As the satellite image is not revealing any information regarding snow depth the snow seems to be distributed evenly. Shadows from elevations seem to create a map like texture. In detailed analysis some steep valley walls are not snow covered. These steep valley walls mainly facing westward are not snow covered.

In early May the situation appears to be very similar. Unfortunately clouds and cloud shadows reduce the visibility. Still the snow seems to be evenly distributed in the mountains. The shadows are becoming smaller, which increases the impression of equally distributed snow. Valley bottoms with low elevations now are no longer snow covered. The snow cover disintegration at west facing valley walls is slowly continuing.

The image acquired early June is containing high altitude cloud cover and therefore its usability is limited. It is during this time that the valleys are free of snow cover. Additionally it is becoming clear that the snow cover is not evenly distributed in the mountain area. Bare soil or rock is visible as outcrop well as in the snow cover. Lakes in higher elevations are still appearing in light blue, indicating a snow cover.

In early July the melting process is reaching higher altitudes. Still a soil or rock outcrops are visible in the snow cover. The pattern of these outcrops is similar to those of the June scene. In addition the outcrop is following roughly a southwestern to northeastern stretch in the eastern part of the scene. Here the snow might be accumulated in narrow hollows, a result from glacial processes (Follestad 2005).

For August a scene acquired in the middle of the month is available. The snow cover entirely disintegrated and only a few snow and ice covered spots remain, including Evighetsfonna. Evighetsfonna was displayed in two different colors: a light blue indicating snow cover and a darker blue indicating ice.

The early September scene is remarkably. First of all it can be noted that it is displaying lighter blue colors only in the snow covered parts of the scene. This indicates snow cover, therefore close to the date of the image acquisition there was snowfall. Most of this snow is melted again, but interestingly the remnants of it are located where snow patches were visible in the August scene. The Landsat 7 scene acquired one day after the Landsat 5 image showed basically a similar winter scene and might display a slightly smaller total snow cover due to melting.

Landsat 5 acquired another scene in mid September that is unfortunately partly cloudy. Low altitude clouds are visible together with casted shadows, but in the same time high altitude clouds are observable as well. Therefore this image is treated as auxiliary data only. However Evighetsfonna is visible, displayed it in light and dark blue again. The whole snow cover disintegrated. Overall it is interesting to keep sudden landscape changes in mind, as this process might happen again at any time in the late summer and fall. Landsat images are only a snapshot.

The late September scenes are showing another snow fall event. The snow is distributed almost evenly again, it seems that the snow cover distribution is determined by the elevation. The elevations are casting larger shadows again. A direct comparison of both scenes can also indicate, that interpolations in the SLC-OFF areas might be useful to a limited extent. One requirement must be that the area is covered with almost evenly distributed landscape features. Furthermore the gap must not be too wide.

Finally a scene is captured in early October. Again this scene is cloud covered and therefore can only be used as additional information. But again the snow cover seems to be disintegrated as Evighetsfonna is visible in light and dark blue again.

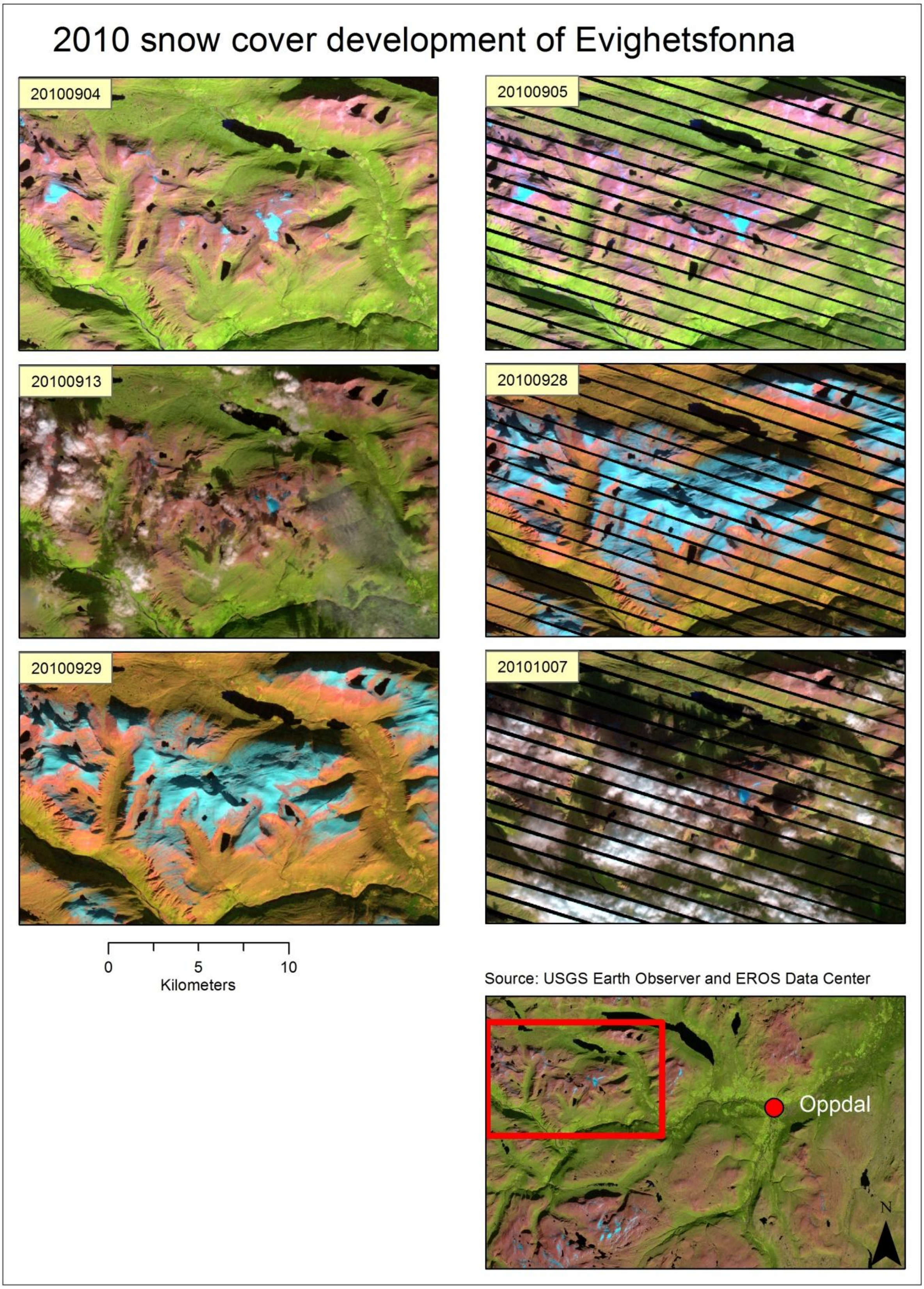

Figure 17: 2010 snow cover development of Evighetsfonna

5.3 Trend analysis with change detection of selected snow patches

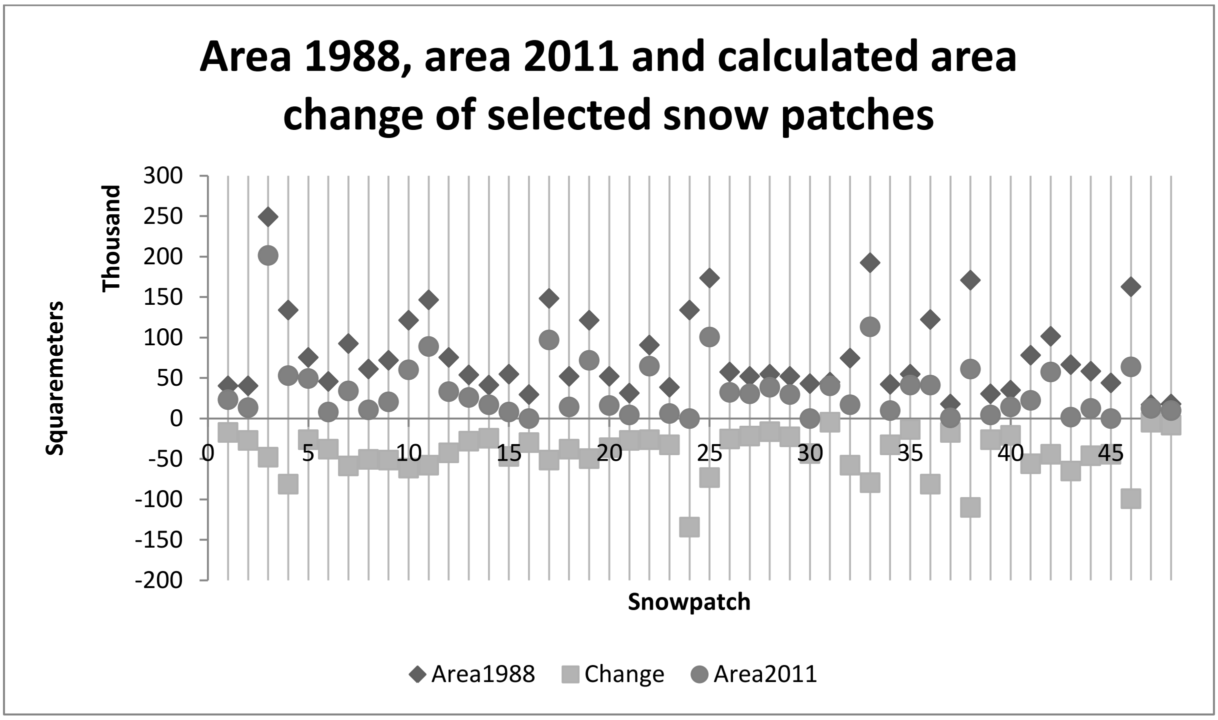

Figure 18: Area 1988, area 2011 and calculated area change of selected snow patches

In the whole study area 48 different snow patches were selected. Several different properties led to the selection. The snow patches should be unaffected by the Landsat SLC-OFF error, which is causing bias. Snow patches stretching in a direction from the north towards the south are more likely affected by the SLC-OFF error. Furthermore small snow patches were less often selected, because of the labor intensive work they imply. Finally several snow patches were not visible in the year 2011 anymore and were omitted as well. It would be an option just to calculate the overall amount of pixels that were classified as snow in each scene. Then the raw amount could be compared. However this approach would be biased due to falsely classified pixels in shadows for example. It would be biased due to the SLC-OFF error. It would hide the heterogeneity of the snow patch properties to some extent, as they would be expressed by a single value.

Figure 18 shows each snow patch with the areas covered in the year 1988, the year 2011 and it describes difference in covered area. In the year 1988 the snow patches are larger as the same snow patches in the year 2011. No area gain is observed at any of the selected spots.

Descriptive statistics		Area1988 [m²]	Area2011 [m²]	Change [m²]	Area left [%]	Area lost [%]
Arithmetic mean		78600	35044	-43556	45	55
Median		56250	22950	-40050		
Modus		52200	0	-26100		
Range		232200	201600			
Variance		2706548936	1440504215	726612726		
Standard deviation		52025	37954	26956		

Figure 19: Statistics for area 1988, area 2011 and calculated area change of selected snow patches

Figure 19 is on overview of the descriptive statistics for the observed snow patches. In 1988 the average size of a snow patch was 78600 m², whereas in the year 2011 the average size of the snow patches is approximately 35000 m². The average calculated area decrease is approximately 43600 m². Furthermore the average percentile area decrease of the snow patches is approximately 55 %. Both Figure 18 and Figure 19 show the large range of included snow patches. The large range is observed in both years. In the year 1988 the standard deviation from the arithmetic mean calculation results in approximately 52000 m². In the year 2011 the standard deviation from the arithmetic mean calculation results approximately 37900 m². This is larger than the arithmetic mean calculated for this year. However the mode for this year indicates that the several snow patches disappeared totally and they are skewing the figure. However their extent cannot be lower than 0 and this contributes to these results, especially with the range in mind.

However, any calculation regarding area is misleading to some extent. The minimum pixel size of Landsat is 900 m². For example the average snow patch area in 2011 is approximately 35000 m². It shows a virtual accuracy for the last two letters that will not be possible to observe on a Landsat image (Bahrenberg et al. 1999; Millar 2001).

5.3.1 Storbreen

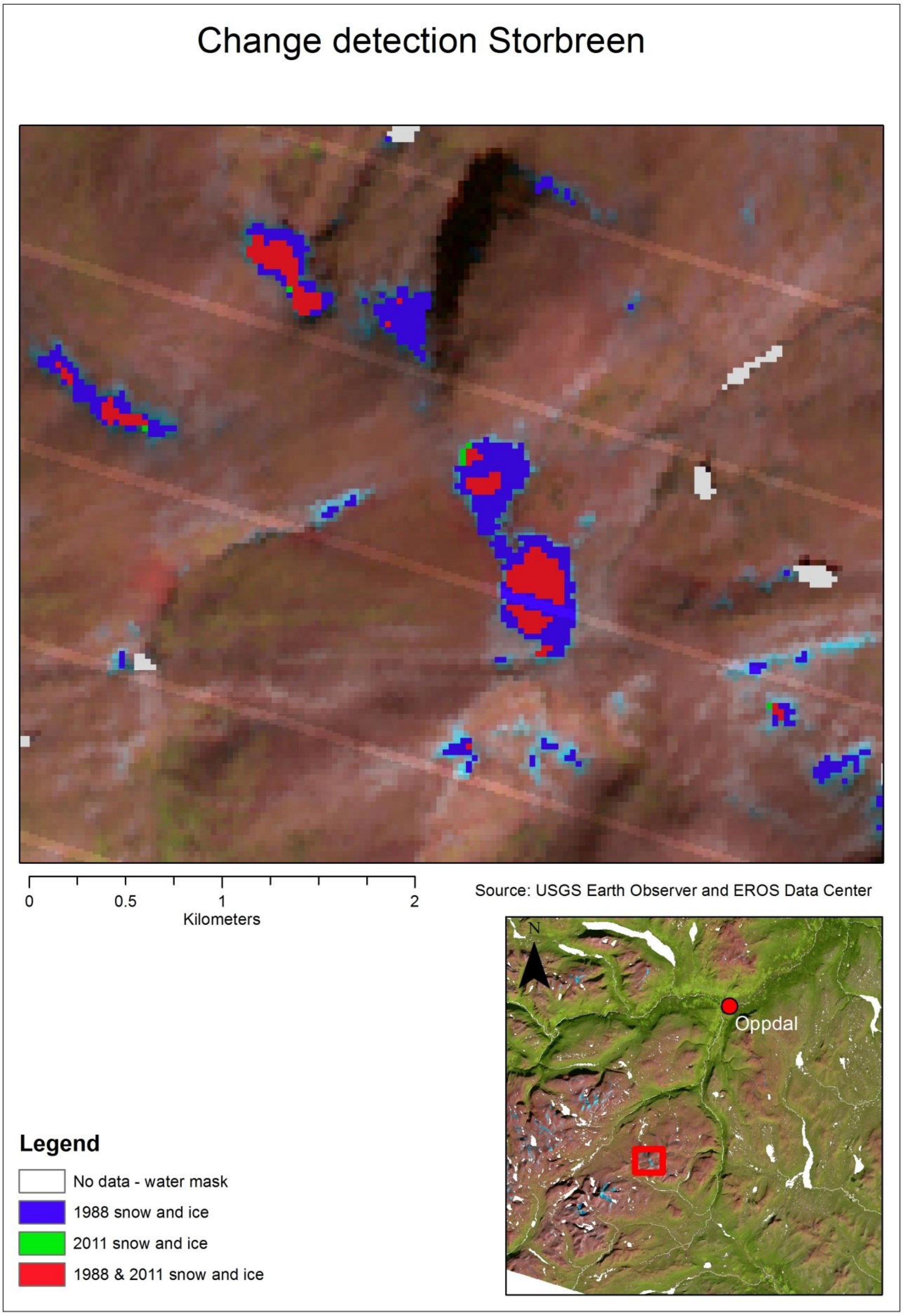

Figure 20: Storbreen change detection between 1988 and 2011

Storbreen covered an area of 312300 m²in 1988. Over the period of 23 years it lost approximately 204300 m² resulting in remaining 108000 m². The Landsat ETM+ SLC-OFF gap mask reveals a gap for the southern part of the snow patch. Therefore in this area was no data gathered by Landsat 7 unfortunately and the area for the year 2011 is underestimated. One of the most obvious results of the change detection analysis is the fact, that the snow patch melted apart. With auxiliary data (see Figure 23 and Figure 24) it can be dated back at least to the year 2002 or at least 2003).

In the 2011 scene each single snow patch seems to be split apart again. As mentioned, the SLC-OFF error is resulting in a data gap here. For avoiding bias no interpolation was introduced to fill this data gap. In the northern part of the snow patch a similar split is visible. Here it seems like the snow patch melted apart in three pieces.

Surrounding smaller snow patches reveal a similar melting behavior. Unfortunately most of them have different landscape characteristics contributing to their origin. Remarkably is the snow patch in the northwest of Storbreen clearly visible in 1988. In the year 2011 it was almost completely melted and two single pixels remain.

Figure 20 is not bias free. It is visible that the NDSI is not covering all potential snow pixels due to the fact it is using an unadjusted threshold value of 0,5. This bias could be reduced by detailed investigation of NDSI thresholds, but it would increase the needed labor force dramatically. This bias is expressed by approximately one undetected snow pixel directly close to detected pixels. Calculations of areas therefore are biased with decreasing area covered. Furthermore stretched snow covered areas seem to be more influenced then rounder areas.

Very few pixels are newly detected as snow in the year 2011. Figure 20 shows that they are positioned at the outer limits of the snow patches. Here the above mentioned variation in NDSI thresholds seems to affect snow in 2011 but not in 1988.

5.3.2 Kringsollfonna

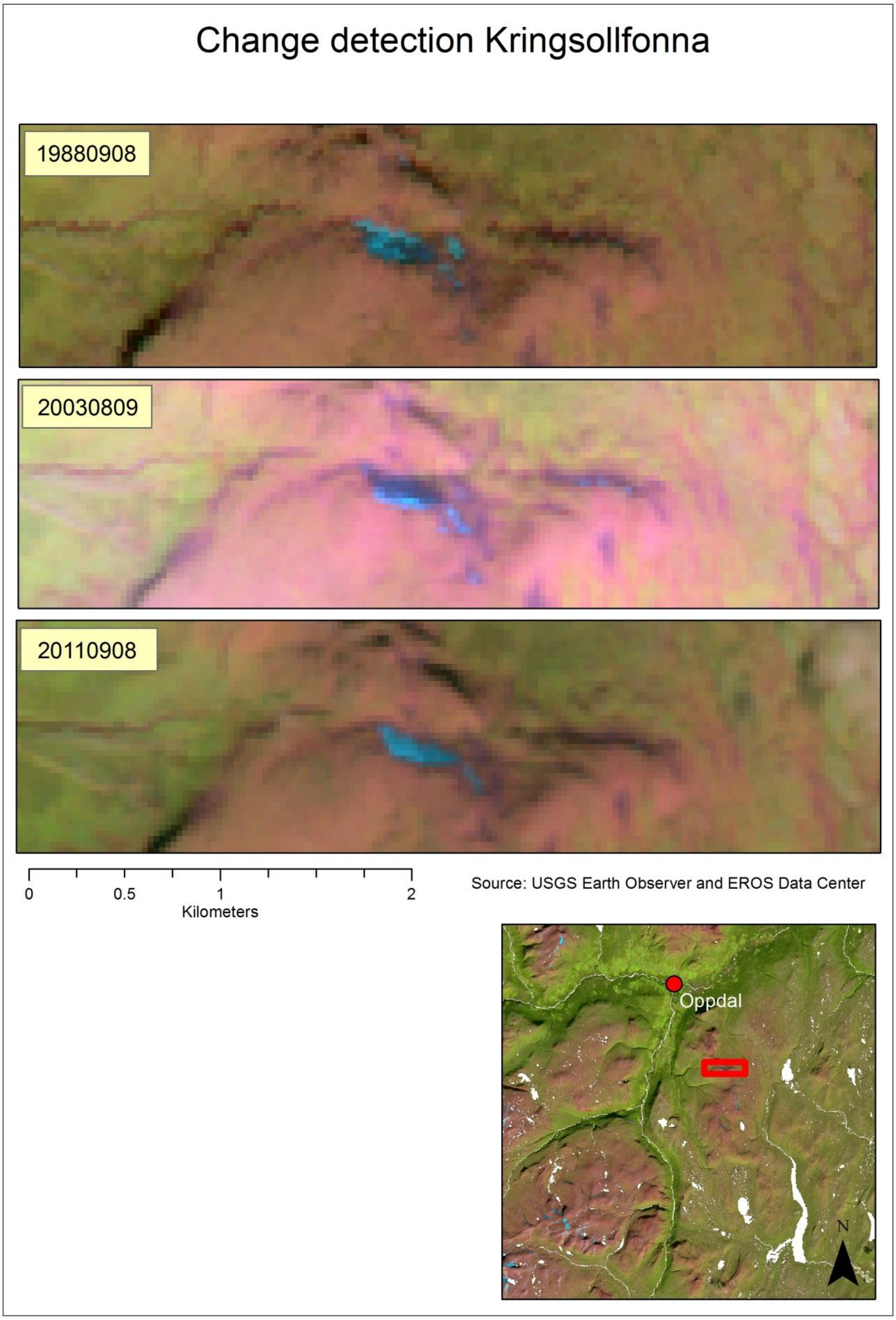

Figure 21: Kringsollfonna change detection between 1988 and 2011

Kringsollfonna reveals a heterogeneous development through the last 23 years. Especially the year 2003 is remarkably. In this extreme year the Landsat images indicate that the snow patch seems to be disappeared almost completely. However field investigations observe the presence of ice, covered by a layer of soil. In the following years accumulation of snow is observable again. Therefore this fact also indicates a comparably stable process at this spot as well. Most change detection observations in the area indicate a melting trend. At Kringsollfonna melting is observable as well, but new snow accumulation is also detectable. Since the year 2003 the snow covered area has increased again.

Figure 21 shows the snow covered areas for three years in combination. For the year 2011 a large increase of snow or ice covered area is observable. Auxiliary data reveals a more complex situation as the change detection indicates in the first instance. Appendix 2 shows a layer of debris cover on the snow patch. The image was taken in the year 2003. During the following years snow must have accumulated on top of it again. With this information the change detection of the year 2003 can be considered as biased.

The Kringsollfonna snow patch shows snow covered area loss but also snow covered area gain when analyzed with change detection techniques. Change detection also shows a central spot which is not subject to any change. Since 2003 snow is again accumulating closely around this spot in north western and south eastern direction. Maybe this stable spot is representing a minimum areal extent under extreme climatic conditions.

5.3.3 Cirque patch

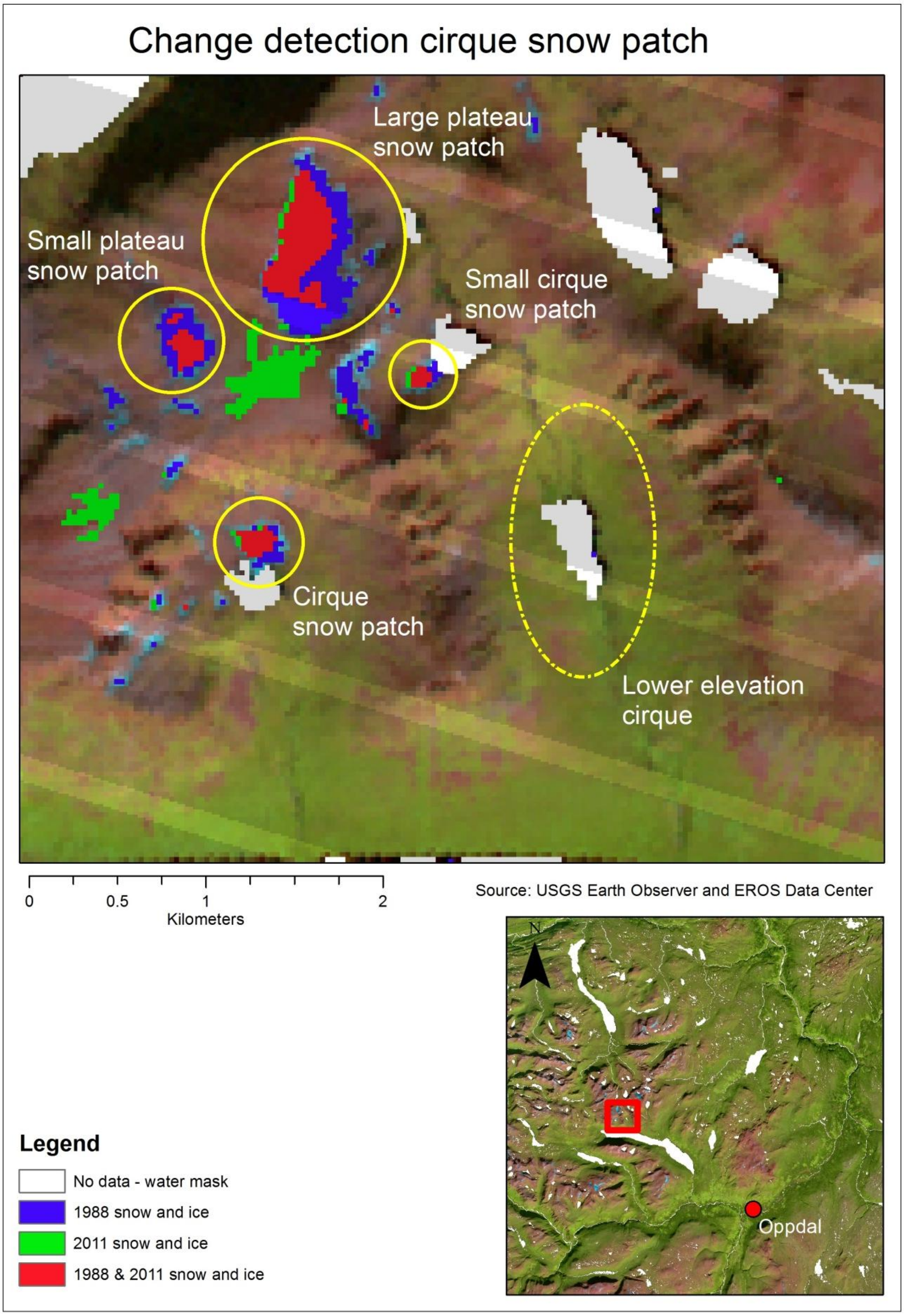

Figure 22: Cirque snow patch change detection between 1988 and 2011

Figure 22 shows a cirque snow patch in the central southern part of the map. The cirque has its origin in a plateau. On this plateau more snow patches are visible north of the cirque. Surprisingly the areas in the north are subject to clearly visible change, whereas the snow covered area in the cirque remains rather constant.

The snow patches in the north reveal similar behavior in snowmelt as Storbreen reveals. In 1988 the area covered by snow was 333000 m^2 for the north western part snow patch, which was reduced to 177300 m^2 in the year 2011. Similar patterns are recorded for the northern snow patch in 1988, covering an area of 84600 m^2. In 2011 the area decreased to 33300 m^2, but unfortunately this value is not free of bias. Due to the SLC-OFF error some snow covered area can potentially not be recorded.

In comparison to the described snow patches, the cirque snow patch seems not to be subject of rapid disintegration. A fact that is even more surprising particularly as it is kept in mind, that the snow patch is facing in a south eastern direction and has a lower elevation. In 1988 it covered an area of 43200 m^2, in 2011 it covered 30600 m^2. Therefore it is clear the snow patch is subject of change.

In Figure 22 a similar snow patch is in close neighborhood in the north east. Unlike in the cirque to the east the conditions in the two cirques seem to favor the presence of snow patches. The second cirque snow patch is smaller. However it also seems to be less affected as the map is revealing.

The fresh snow covered area in the year 2011 is seen in green to represent a thin layer of freshly fallen snow. Therefore the snow cover on any other snow patch in the area is representing new snow. However the image also shows, that the extent of this new snow is limited.

5.4 Selected sites detailed development

5.4.1 Storbreen

Figure 23 shows selected Landsat scenes of the Storbreen snow patch spot. Selection criteria was mainly based on visibility. None of the images were subject to any preprocessing steps, except the 1988 scene, which was georeferenced. Therefore all the scenes show different illumination effects and they are not radiometrically corrected. Nevertheless for visible inspections the contrast between snow and ice compared to bare soil and rock is sufficient

In 1988 the extent of the snow patch is clearly visible. For this snow patch it is a reference, as any other images acquired before this date are either captured with the MMS or cloud covered TM scenes. Ice cover is not visible, it would appear in dark blue. In 1989 the snow cover of the area is much larger. The lower and higher parts of the snow patch are widely connected.

Between 1989 and 1999 no suitable scenes were available, unfortunately. The 1999 scene is clipped from the western boundary of the Landsat image and it is therefore not complete. Again the extent of the snow patch is very similar compared to the 1988 scene. Two dark lines heading towards northeast are clearly visible, which could be a melt water stream, as they are joining in a characteristic way. In 1999 the color of the snow is slightly different compared to earlier scenes, it is slightly darker. This is partly a result of casted cloud shadows but in the northwest two additional snow patches indicate similar color characteristics.

In the year 2000 two suitable scenes are available, captured roughly in a month between each other. Interestingly the snow cover is high in both images although the earlier one is clearly cloud covered. An image acquired late during a year can still reveal interesting information, in this case the later image indicates a late onset of fall and a late accumulation of continuous snow cover. The snow patch seems to be of large extent, having a comparable extent as in 1989. Furthermore in both images the surrounding snow cover seems to have the same distribution as in 1989.

Again in 2002 the shape of the snow patch is similar to the 1988 scene. But the color distribution is clearly different, it appears to be much darker. Hardly any snow cover is visible close to the snow patches and the snow patches in the northwest seem to be in a similar condition. Shifts in computational color distribution are unlikely due to the fact that rock and soil still show similar optical characteristics as they did before.

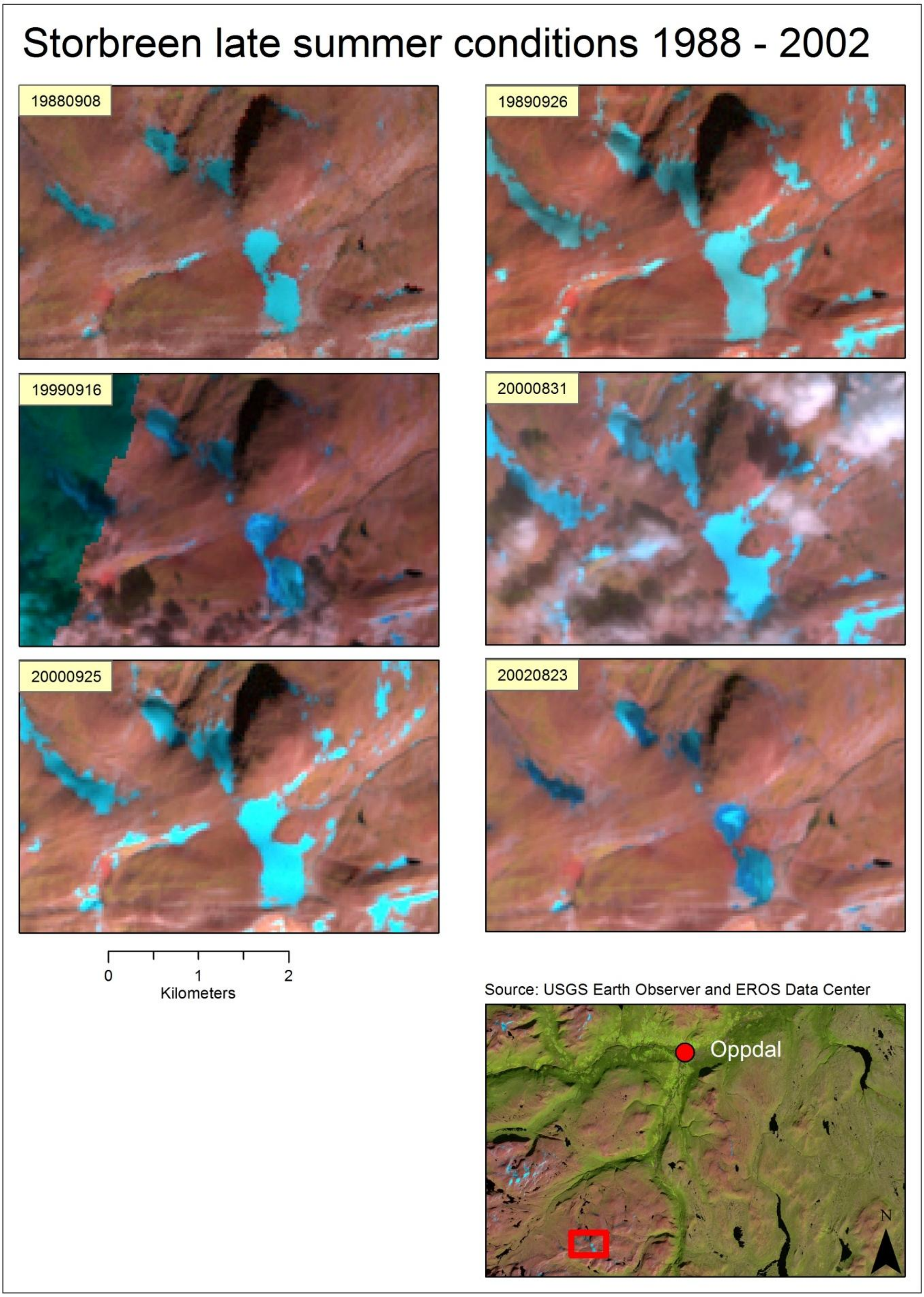

Figure 23: Storbreen late summer conditions 1988 - 2002

For the year 2003 Figure 24 shows two suitable scenes of Storbreen. Both images portray very dark colors for the snow and ice region again. The first image is selected from an unusually early date during the year. The reason for this choice is the snow free conditions close to the snow patch. But the main reason is the development of the snow patch, as it has melted in two parts: a larger southern one and a smaller northern patch. A comparison with the year before reveals that the connection melted away. Additionally in the second scene of this year the snow patch west of Storbreen melted apart as well. This is difficult to see in the second scene due to cloud cover and uncertainty at the satellite picture boundary. Nevertheless this also indicates ongoing melting processes at Storbreen, at least for the time period between the first and second image acquisition.

The next scene of the year 2005 is lacking information due to the Landsat ETM+ SLC-OFF error. Storbreen is covered with a lot more snow again, the connection between both parts seems to be reestablished. Compared with the year 2000 the snow distribution follows similar distribution patterns, as long as the snow cover is visible. Although the snow cover seems to be of minor extent than in 2000. Two examples can be mentioned: the snow stripe in northeastern direction north of Storbreen and the snow accumulation in the south eastern part of this scene.

In 2010 the Storbeen snow patch is again smaller as compared with the extent of the year 2003. The northern part is melted apart in two very small spots. The snow patches in the northwest also reveal ongoing melting. No other snow cover is visible close to the snow patches and the snow patches itself are of darker color again.

Figure 24 is showing the situation in the year 2011. In this scene the Landsat ETM+ SLC-OFF failure is of minor importance as the details are still visible for an optical assessment. Strobreen is still losing snow or ice covered area. The color of the snow patch is rather dark. Surrounding snow patches are showing similar behavior also.

Finally Figure 24 shows the situation in the year 2012. Unfortunately no other suitable scenes are available yet. Therefore this image from the middle of the ablation period is not the best. It shows error due to the SLC-OFF failure. Luckily it is still revealing information for visible assessment, although some parts of the image are cloud covered or show casted shadows. The snow cover is of light color again and the snow cover distribution is very similar to the distribution in the year 2000. Again the image shows this constraint of similar melting patterns. Storbreen covers a large area and the two parts seem to be reconnected.

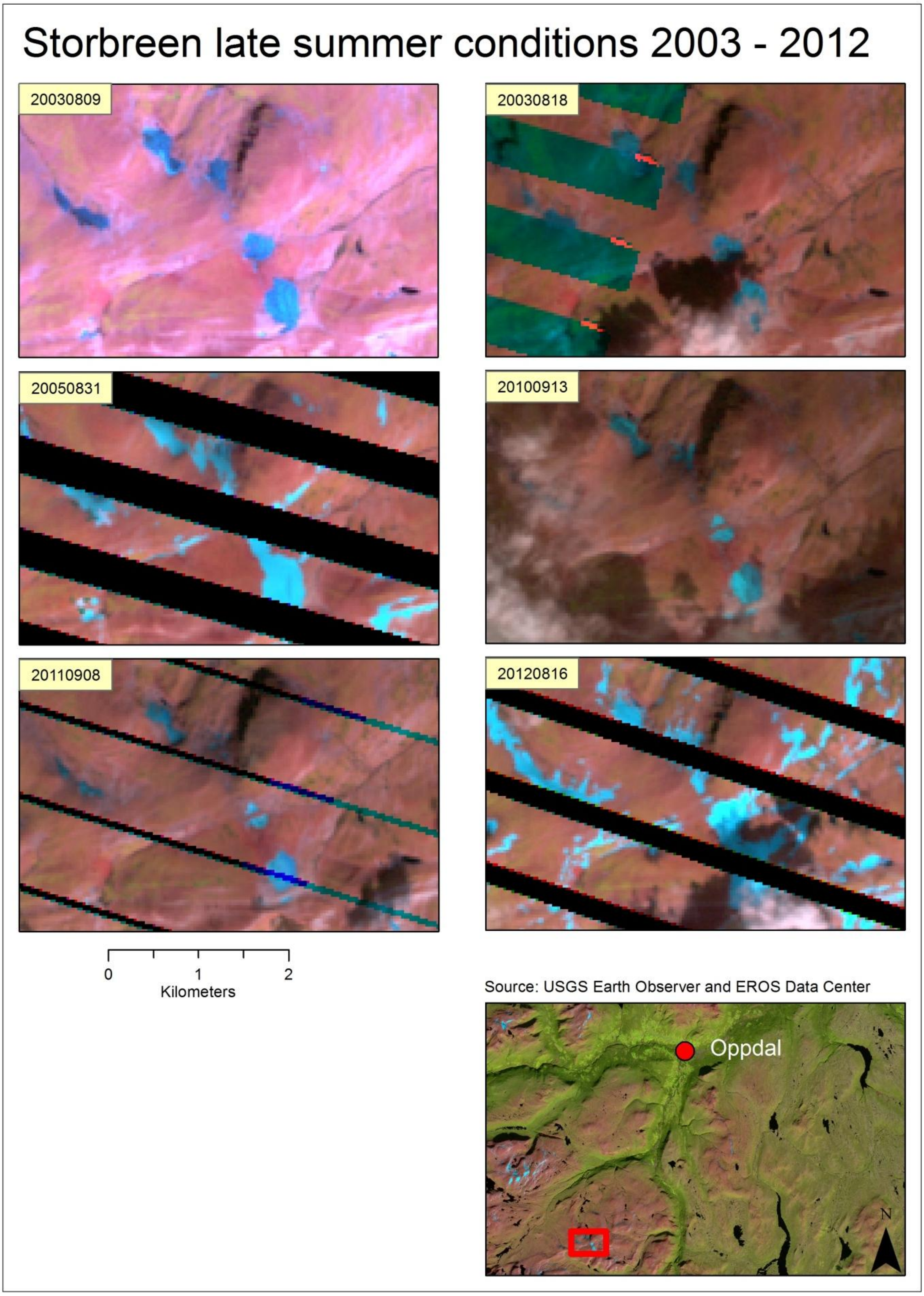

Figure 24: Storbreen late summer conditions 2003 - 2012

5.4.2 Evighetsfonna

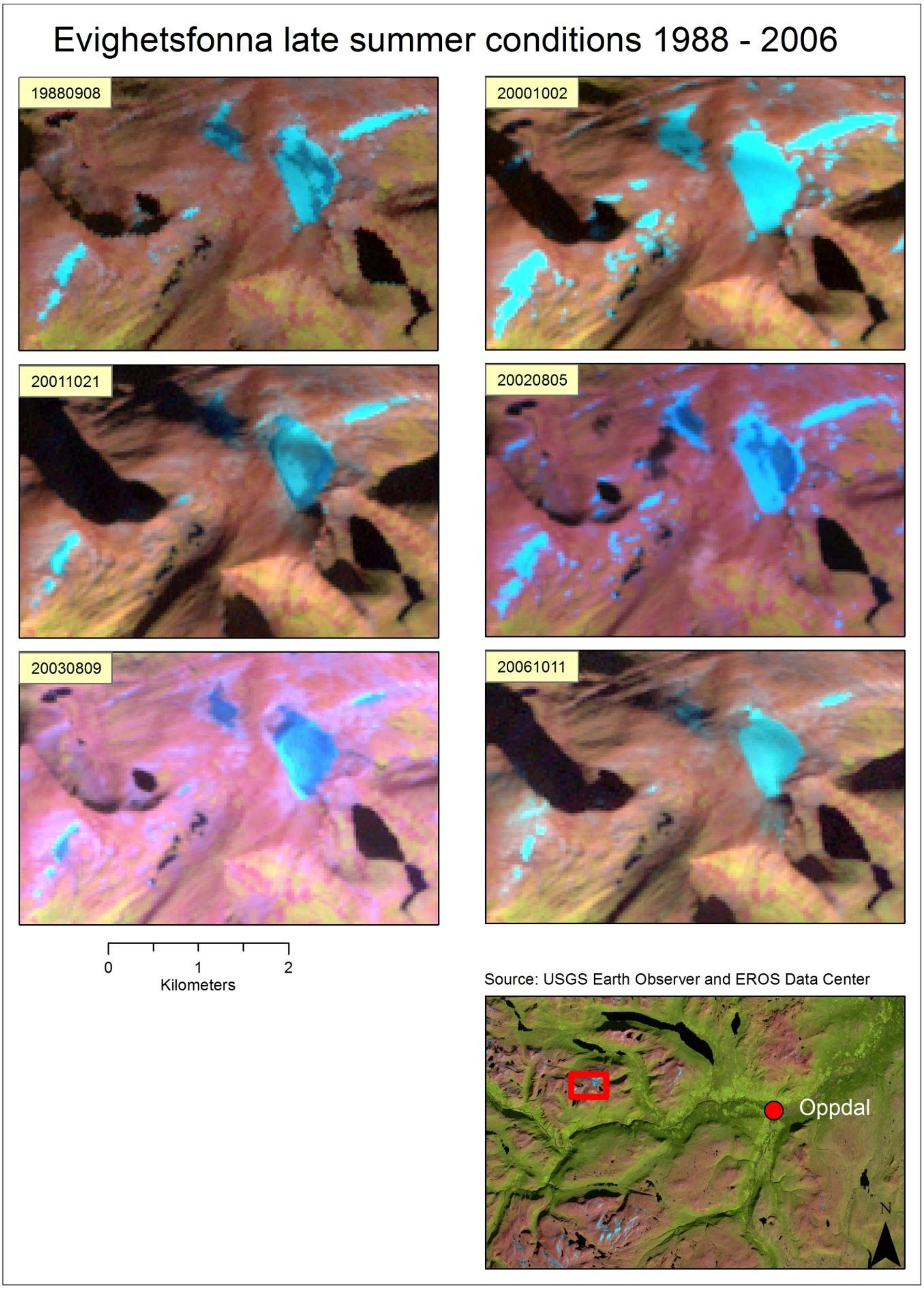

Figure 25: Evighetsfonna late summer conditions 1988 - 2006

Figure 25 and Figure 26 have been created in a similar way as the figures in chapter 5.4.1. Again the data quality is sufficient for visual assessment. For Evighetsfonna no suitable Landsat scenes were recorded prior to 1988. In 1988 the snow cover is low, as the mixture of light blue indicates snow whereas darker blue indicates ice. Close to Evighetsfonna a smaller snow patch is visible, too. Furthermore some stretched snow patches are observable in the northeast of Evighetsfonna and in the southwest.

For the next decade the data density is low and no images were selected for closer inspection. In the year 2000 more snow cover is visible as in 1988. Again the snow cover distribution is similar to the 1988 distribution, although most of the snow patches seem to be of larger extent.

In October 2001 the snow and ice cover seems to be as large as in 1988. But this time Evighetsfonnas snow cover appears to smaller in extent compared to 1988. Dark blue ice is dominating the snow patch. In the northwest the smaller snow patch close to Evighetsfonna seems to be snow free as it is visible in dark blue only. But this observation might be biased due to the casted shadow of the mountain ridge.

For the year 2002 a scene acquired in August is available, showing a surprising snow distribution. The snow cover distribution is very similar to the distribution recorded in 2000, although the 2000 scene is from the end of the ablation period. Again some icy areas are visible on Evighetsfonna which seem to be distributed in a similar way as in the year 1988.

The following year is revealing a completely different situation compared to the previous records. In August 2003 Evighetsfonna is not showing any snow cover with a small exception at the western margin of the snow patch. Even this snow covered part is hard to detect. The snow patch close to Evighetsfonna is visible in dark blue colors as well, indicating bare ice. Its extent appears to be smaller compared to the extent in 1988. Furthermore the stretched snow patches in the northeast and southwest are showing ice the first time and they are much smaller as in the images recorded before.

In 2006 the snow patches are snow covered again. The whole scene is very similar to the scene acquired in 2001. Evighetsfonna is snow covered, as most of the other snow patches. But it is surprising, that the snow patches in the northeast and southwest are smaller now when compared with the scene from 2001. The snow patch close to Evighetsfonna is located in casted shadows again, but it appears to be smaller than in the year 2003 and it is displayed in rather dark blue.

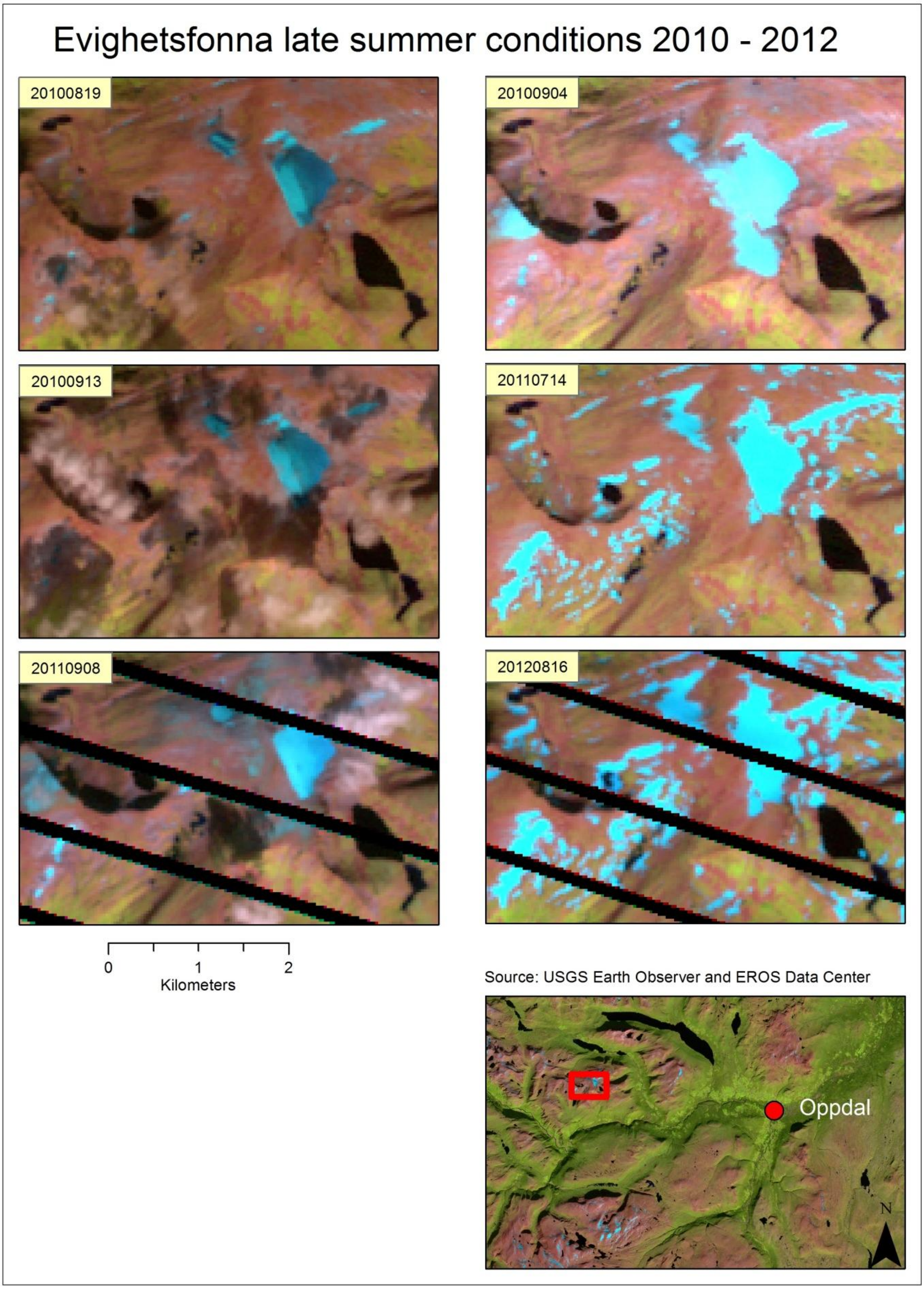

Figure 26: Evighetsfonna late summer conditions 2010 - 2012

The next suitable scene was acquired in the mid of August 2010, visible in Figure 26. The southwestern corner of the image is cloud covered by low altitude clouds and casted shadows are visible as well. Again, Evighetsfonna is displayed in mixed color. Ice is dominating most of the snow patch, only a smaller amount in the western margin seems to be snow covered. The snow patch in the northwest appears to be partly snow free as well. In September two scenes are available. Acquired in early September, the scene is showing freshly fallen snow. It is remaining on known spots. Nine days later another image is recorded by Landsat 5, but it is cloud covered as well. Evighetsfonna is mostly visible and the ice covered area is dominating the snow patch again.

For the year 2011 two images are of interest. The first Landsat scene is acquired in mid July, showing larger snow covered areas. Once more the snow cover is following a distribution pattern similar to the pattern shown in Figure 25. When it is compared with the scene from 1988, most of the snow cover is visible in areas that were snow patches in 1988. The second scene of the year 2011 was captured by Landsat 7 in early September and therefore it is lacking some information due to the SLC-OFF error. Furthermore the scene is partly cloudy or is showing casted shadows. Evighetsfonna seems to be snow covered, as the snow patch close to it. Some light blue areas close to the snow patch and in the west are indicating fresh snow, comparable to the fresh snow cover of the 2010 scene.

The last suitable scene available for the study area was recorded by Landsat 7 in mid August 2012. The known bias is visible. In direct comparison to the year 2011 the snow cover in the year 2012 is of larger extent. Furthermore the scene in 2012 was acquired roughly one month later, also indicating a longer lasting snow cover. Again the snow cover is following the known pattern.

6 Discussion

6.1 Data quality, sources of error and RS inherent constraints

6.1.1 Data quality

In total 94 TM or ETM+ (incl. SLC-OFF) Landsat scenes are available in a quality that allows closer inspection. However this large number of scenes is becoming smaller when detailed site specific analysis is necessary. Reasons for site specific image selection were mainly related to cloud cover and whether the image was acquired at a suitable point during the year.

Artifacts in the Landsat files are almost not present. The Landsat scene of 1988 had a misleading georeferencing: an offset of a few pixel was observable. In ArcGIS this problem was solved with an automated georeferencing routine.

6.1.2 Data gaps in the Landsat archive

There is a problem in the availability of Landsat scenes for the study area in Norway. Unfortunately for Norway the probability of capturing good quality Landsat scenes is very low due to high cloud cover in average being 35 % or more per scene (Marshall et al. 1994). Although a Landsat image is not directly useless due to cloud cover, it deserves a careful treatment in the analysis. Any analysis based on automatic or semi automatic classification is usually not possible for larger areas. Furthermore cloud shadows might alter ground reflectivity of actually cloud free spots. Therefore the use of additional data to allow closer inspection for closely acquired cloud free Landsat images is made possible. However images with cloud cover should be avoided for any other purpose.

For the study area approximately five month of the year are not properly monitored by Landsat satellites. In this case the low angle of the sunlight is causing difficulties as the reflected sunlight towards the satellite sensor seems to be very low. Partly this effect might be connected with large snow covered areas. An example for this difficulty is given in Figure 16 and Figure 17. Figure 16 shows an already presentable image of an early year scene but its flaws should still be visible. Whenever cloud cover is present in a scene of another year the image becomes that of an even more awkward look. Furthermore steep topographic elevations may cast larger shadows. The shadow extent is dependent on the sun elevation as well. Shadows usually alter the reflectivity of the surface. The data of these spots is harder to analyze. Snow patches in shadows are either enlarged due to a false classification of the shadow as snow or ice or they are not mapped properly due to general lack of reflectivity.

A problem for detailed analysis is the data availability. Especially for the early years the coverage is low. Beginning with the launch of Landsat 7 this problem is of lower importance. But before this date larger data gaps are obvious, potentially caused by different acquisition schemes (Wulder et al. 2012). Therefore the development during the 1980th and 1990th is not well documented in the Landsat database (Goward et al. 2006).

6.1.3 Remote data acquisition instead of direct sampling

Landsat data is gathered using a space born platform. Therefore its data is lacking a close connection with the subject of study. For example no information regarding snow depth is acquired. Even apparently snow free pixels might contain snow cover but this small extent is subject to generalization and is neglected by the sensor.

This is related to some philosophical issues, mainly whether remote sensed data is considered as "primary data" or whether it is considered as "secondary data". Reasons for classifying Landsat data as "secondary data" are mainly connected with the fact that the data is gathered by a platform not directly operated by the researcher. Furthermore it is only available in a dataset and needs further processing. A reason for this point of view is the constraint that the researcher was not physically present when the data was gathered in the study area. Finally a major problem seems to be due to the fact that Landsat data is connected with uncertainty and generalization.

Reasons for treating Landsat data as "primary data" are mainly related to the fact that the data is representing a study area as it is, although determined by the quality of the onboard sensor. Landsat is only recording information that is directly available. Any steps in preprocessing the gathered data are well documented. The data is not altered by a third party. Finally it is possible to acquire and process data with a degree of uncertainty and a level of generalization as "primary data" whenever this constraint is documented and mentioned.

6.1.4 Atmospheric influence

Beyond regular cloud cover at least in the year 2003 an atmospheric phenomenon was observable that was not directly visible in the satellite images. However during the mapping of the snow cover a larger snow patch was only partly mapped. In a detailed view it was possible to detect a slightly darker area which seems to be of atmospheric origin. Nevertheless it is showing different optical characteristics as common high altitude clouds.

6.1.5 Automated processes – masking and classification

The water masking process is overall very precise. On rare occasions however it is not covering the whole body of water resulting in mapped pixels falsely represented as snow and ice. The error is usually at pixel level. The error means that not more than one pixel is falsely present. A reason for this behavior could be an increase in the water level, resulting in a land covered pixel turning into a water pixel for example. Another reason might be a different mapping source or generalization process applied in the dataset used for the masking reference. For further studies an additional pixel in any direction could be added to the masking layer to reduce this kind of error. Although it would also introduce a different error and would potentially increase the level of uncertainty.

Shadows seem to introduce potential errors during the classification process. In shadows snow and ice is mapped where auxiliary images reveal bare soil or rock. Reduced reflectivity in the shadows might contribute to this type of error. But it is also possible that in the shadow area snow or ice is not mapped where auxiliary data reveals a feature of a snow patch. This type of error is also a contributor to the reduced reflectivity in shadows. In some cases falsely mapped snow and ice pixels are scattered in the shadow. This creates greater scattered area but not where the pixels are usually formed in the larger connected area. Rarely the whole shadow is mapped as snow and ice, as visible in Figure 8 for example.

The classification process was developed with the perspective that it would be applied on several different satellite images. It was necessary to use a fixed threshold upon NDSI information in order to discriminate between snow and ice and other land cover types. In this way the classification process causes almost no problems and it is simple to apply. However it has drawbacks as well: from time to time it seems that the developed snow cover maps are biased.

Usually this bias is not larger than one pixel that seems to be falsely classified as bare rock or soil. Overestimations of snow covered areas are not observed.

The Landsat 7 ETM+ SLC-OFF error is contributing to potential underestimations of snow covered area as well. It is not unlikely that snow covered areas are hidden behind information less gaps. They are therefore never mapped by the automated mapping process. Subsequently some snow patch areas are also potentially underestimated.

Finally in specific parts of the study area, glaciers are mapped regularly according to the definitions in the classification. They represent areas of snow and ice, but they are not focused. It would be necessary to mask these areas as water bodies were masked. But unlike water bodies glacier data is much more difficult to implement. Several snow patches are listed in the dataset of Statens Kartverk as glaciers. They would subsequently be masked as well. Therefore it is preferred to keep glaciers unmasked.

6.1.6 Fixed date scene selection advantages and disadvantages

For reasons of simplicity it was a goal to use images acquired close to the 30th of September of each year for detection of late years snow cover extent. As mentioned in chapter 4.1 this approach is widely used in glaciology. It seems that this fixed deadline is a good guideline for remote sensing of snow and ice as well, but some flexibility might be necessary from time to time. It is observable, for example in chapter 5.4.2, that even beyond this fixed date snow melt can be relevant.

It might be more useful to distinguish between the comparison of scenes for a single year and for any kind of change detection. For annual analysis the fixed date is a landmark to be aware of but not to be regarded in a static sense. Interesting developments might be observed beyond the date and would be neglected by a strict application of the fixed date

In terms of change detection a rather strict application of the fixed calendar year approach is supporting comparability. But again it might be more difficult to find Landsat scenes exactly acquired on that day. Even when the fixed day is considered as a “fixed week” it might still be difficult to find a suitable scene mainly because of cloud cover. Beyond these drawbacks the Landsat archive is a great resource. Furthermore with each year of ongoing image acquisition by Landsat satellites the probability to find a good image is increasing.

Overall it might be a good idea to consider this date with some flexibility. A flexible approach can be an option in glaciology as well (Benn & Evans 2010).

6.2 Interpretation of change detection

The change detection revealed different developments for each snow patch investigated. It also proved that change detection techniques can be applied for the goal of monitoring the development of snow cover. It is likely that the results of each spot reflect unique developments. However in the context of topographic similarities these developments might be observable at other spots as well.

Two scenes for the change detection might represent a biased selection. Biased scene selection cannot be avoided completely, due to satellite scene availability and cloud cover. With auxiliary data, for example the collection of late summer conditions in chapter 5.4.1, it is possible to see detailed results. It might help to investigate additional satellite scenes to reduce the extent of bias. The change detection reveals a general melting trend in the study area.

For mapping the extent of snow patches the change detection revealed that the use of older satellite images might be more useful as recent images. This is, of course, only valid as long as the described trend is still observable. Using scenes that were not acquired towards the end of the ablation season only indicates the summer snow cover distribution. However it does not indicate the snow patch distribution of former years. Therefore the Landsat archive holds very important information.

For the observed development several factors might be relevant: precipitation, wind drift, temperature regime or a combination of those mentioned. Additionally the topographic setting of the snow patch is relevant, as the observable melting at selected sites is varying. Rare spots seem to be almost unaffected. The melting process is not as strong as it is usually observed in the study area at these spots. Topography is a parameter that can be indirectly determined on Landsat scenes, as shadows are indicating elevations. A DEM can further enhance the analysis of Landsat images in this particular study as elevation is rather static whereas precipitation, wind drift and temperature vary. The DEM can especially reveal where the topography is relevant and where it is of minor importance.

6.2.1 Storbreen

The Storbreen snow patch was subject to melting. Unfortunately the Landsat 7 ETM+ SLC-OFF error does not reveal the full extent of the landscape change. Interpolation might be possible but would clearly be biased. Surrounding smaller snow patches reveal similar behavior and several of them are in the 2011 Landsat scene.

A DEM reveals that no topographic features are present that favor the presence of snow patches, such as ridges or cirques. Therefore the assumption can be made that at the Storbreen spot the conditions favoring snow accumulation are out of balance with the present climate.

6.2.2 Kringsollfonna

Kringsollfonna is located directly at a steep slope. Landsat scenes show that the snow patch is located in the shadow of this elevation. Therefore this spot is very different compared to Storbreen for example. The change detection revealed a surprising development as there was a reaccumulation of snow or ice observed. In the year 2003 the snow patch was almost completely melted. In the following years it has covered a larger area again. This is an interesting fact. It highlights that some snow patches are accumulating on the same position again when the conditions are favoring accumulation. At the Kringsollfonna spot the factors favoring accumulation and melting are still balanced (Allen 1998).

6.2.3 Cirque snow patch

The cirque snow patch observed in chapter 5.3.3 is subject to melting as most of the other snow patches are as well. But compared with Storbreen for example the melting seems to be at a much slower process at this particular spot. Even closer located snow patches are showing higher rates of melting area. A DEM reveals that the snow patch is located in an elevation of approximately 1100 m above sea level only, whereas snow patches in the surrounding area are located in elevations between 1400 m and 1600 m above sea level.

Therefore this spot must have a special configuration that determines its relative stability in snow covered area. The DEM reveals steep walls close to the snow patch and these walls surround the snow patch in northern, western and eastern direction. During the winter time drifting snow might accumulate in cornices at the top of these walls. Furthermore the snow has mainly drifted in an eastern direction during the winter time. It is also likely that the drifting snow if forced downwards at this depression. Avalanches from the cornices then might increase the snow accumulation at the observed spot (Allen 1998; Debeer & Sharp 2007).

6.3 Literature discussion regarding glaciers and snow patches

As mentioned, glacier monitoring has a long tradition in Norway (Nussbaumer et al. 2011). Recent studies revealed regional differences in glacier flow behavior. In northern Norway it is observable that glaciers are advancing or glacier area growth is recorded. The extent of the advance is increasing with increasing continentality (Paul & Andreassen 2009). Whereas in southern Norway glaciers are retreating or glacier area decreases are recorded (Andreassen et al. 2008). Jotunheimen region is relatively close to the study area. For Jotunheimen region a temporal increase of glacier mass was recorded between 1989 and 1995. Unfortunately this event cannot be found in the Landsat dataset in the study area, no suitable Landsat scenes could be found. But in a larger framework the trend of decreasing glacier covered areas is observable as well. Chapter 5.3 is describing this trend with change detection techniques, as well as chapter 5.4 is describing detailed site specific developments. The melting trend is visible in the whole study area.

In northern Norway it was observed that smaller glaciers with extents of one square kilometer or less are gaining extent, possibly merging together and forming larger glaciers. This mass gain is described as a rather quick process (Paul & Andreassen 2009). Under the assumption that smaller glaciers are reacting more sensitive to changes, snow patches might react even more intensive. A spot for such an observation could be Storbreen, as the trend would be comparable when snow patches close to glaciers are monitored. The glaciers on Snøhetta are not showing similar decreases in snow or ice covered area as the Storbreen snow patch. This behavior is in contrast to the north Norwegian observations but it is reflecting the south Norwegian observations. In fact, on Snøhetta the precipitation is strongly increasing with altitude. For example the precipitation on 2000 m above sea level is approximately 1.75 times as high as on 1400 m above sea level (Fossum 2012). Storbreen is located on elevations between 1800 m and 1700 m above sea level and therefore maybe subject of lower precipitation.

In northern Norway it was observed, that small glaciers with extents of less than one square kilometer are showing positive mass balances and that they are covering larger areas. This observation was made together with the observation, that this effect became stronger with increasing continentality (Andreassen et al. 2008). A similar pattern is not observable in the study area. Even the central part of the study area is subject of large area decreases of snow or ice cover. Even snow patches located in the east of the study area are showing large area losses. Storbreen is a good example, as the details in chapter 5.3.1 demonstrate. Only Kringsollfonna is showing a different snow melt and accumulation pattern, described in chapter 5.3.2. At this spot, snow seems to accumulate after the year 2003 again. Hence there are local topographic variations favoring the accumulation of snow, although this accumulation is against the trend. Even detailed analysis of close snow patches like Storbreen are documenting ongoing area decrease, see chapter 5.4.1.

The trend in the study area is similar to observations of other studies mainly published in glaciology (Barry 2006; Debeer & Sharp 2007; Gjermundsen et al. 2011; Granshaw & Fountain 2006; Heid & Kääb 2012; Narama et al. 2010; Paul et al. 2004b; Racoviteanu et al. 2008a; Racoviteanu et al. 2008b). Decreasing snow or ice covered areas are observed worldwide with rare exemptions. Area decrease is recorded for virtually any snow patch in the study area as well, strongly indicating that snow and ice is melting. As this trend seems to be observable in any part of the study area it is likely that changes in precipitation or temperature regime are uniform in the study area (DeBeer & Sharp 2009).

As already mentioned, the data quality is good. Approximately one decade is covered in a good temporal resolution. Many studies rely on change detection, comparing two satellite images only (Silverio & Jaquet 2005). The results are similar compared to studies using additional satellite data acquired during the study period. Nevertheless detailed studies can document developments more accurate and it is possible to identify single events. Often change detection studies can only give average values for mass or area gains and losses. But as this study is revealing in chapter 5.4, single occasions like the year 2003 are potentially more influential. An average can therefore lead to false assumptions, as they incorporate some bias.

6.4 Management implications and opportunities

6.4.1 Landsat as a management tool

Landsat is offering a detailed, maintained and consistent archive. This is important for natural resource management purposes and monitoring projects (Kennedy et al. 2009). The available Landsat images are overall of very good quality. For the purpose of snow cover detection and the long term monitoring of snow patches it has proved to be useful. Especially the radiometric consistency and the barrier free archive are advantages. Landsat is therefore a consistent measurement tool of landscape conditions. The detailed archive gives the opportunity to reassess previous resource management efforts.

For resource managers quick land use changes are often difficult to assess or to monitor to their full extent. Here Landsat is a tool for mapping the spatial extent of ongoing rapid changes. This is especially helpful for the surveillance of areas that are close to managed areas but that are not included (Jones et al. 2009). Still these areas are influencing the managed space through feedbacks. Therefore it might be necessary to develop strategies for the managed area that respond to developments beyond their borders. Landsat is also a very good tool for the detection of slow changes over time. Trends can be detected and management strategies might respond to it. This is especially helpful for larger areas that are difficult to access.

The Landsat remote sensing platform gives the opportunity to observe and monitor key resources. This is possible with other methods as well, but nevertheless it is proved that it is a useful tool among others. In chapter 5 Landsat proves its usability for describing the snow cover extent in a study area. Upon the observation of the key resource, in this case water, management strategies can be improved. Unfortunately the ability to monitor key resources is limited. Usually Landsat images are not available in real time. They become available after a delay. It is possible to use similar resources with quick delivery services instead, whenever it is deemed necessary.

Landsat enables natural resource managers the possibility to observe large areas. The study area is roughly covered by one Landsat scene with a total size of 180 km by 180 km. The objective is limited to mountain areas, which are limited in their accessibility. Detailed surveys would be labor intensive, and when it comes to long term monitoring maybe even impossible, due to the total costs.

Satellite images of approximately thirty years are available in good quality. Resource managers can easily utilize this archive for their purposes. Some features might not be monitored, but suddenly they become important. Then it is possible to go back in time in the archive and assess them. Although assessing remote sensing images is labor intensive, the images are digitally available. At this point it is possible to implement automated routines. Landsat is a very good tool for using automated routines, as chapter 5 demonstrates. Combining detailed automatically generated information with other ongoing monitoring programs, potentially enhances the basis for decision making.

Finally change detection techniques reveal more information compared to a single image analysis. To rely on only one image is difficult as it might only represent a snapshot of the subject of study. An example can be found in chapter 5.2 as it demonstrates the snow cover fluctuations towards the end of the summer. A single image cannot demonstrate the whole extent and duration of the snow cover. It is therefore important for resource managers to keep transient characteristics of the studied object in mind. This is relevant when the studied and managed object is not long lasting. Ecosystems can be assessed by single spot analysis to some extent (Jones et al. 2009). Still even in these cases change detection might contribute in the collection of additional information.

6.4.2 Remote sensing as a management tool

When remote sensing is embedded in a conceptual framework within a management process it can be a helpful tool. Four key criteria are relevant: data acquisition, preprocessing and image enhancement, analysis and evaluation (Jones et al. 2009; Kennedy et al. 2009). As a first step the data acquisition should be considered. Two aspects are important: pixel size with usually connected revisiting period and image quality in respect of suitability in timing. For the study area the revisiting period of two available satellites is sufficient. However one satellite is not flawless and cloud cover may reduce efficiency as well. The satellite images are of good quality when they are cloud free. As the archive strongly enhances the potential of suitable scenes over a long period of time the total coverage is good. Remote sensing is a very reliable tool when it comes to long term natural resource management projects or projects relying on long term data. This is demonstrated in chapter 5.

The Landsat database is already preprocessed and therefore this step cannot be influenced any more. Image enhancements were applied for the study area, as the snow cover was transformed automatically in a binary map for further analysis. In the dataset of the study area is an uncertainty between snow and ice as the applied algorithm cannot tell the difference. But for the management objective it is still possible to say that the mapped object is water in a solid state.

The derived geodata than can be utilized in geographical information systems, with all the benefits that these systems offer. For example it is possible to combine the gathered snow cover information with a DEM. Usually the snow cover map is a raster file lacking information regarding elevation. The map and the DEM together can be analyzed in a much more detailed way. It is revealing information that can only be obtained together. Limitations of this analysis should also be kept in mind, as snow cover does not give information about snow depth. Therefore the snow cover maps generated with Landsat data must be combined with snow depth information. Furthermore it is necessary to be aware of the fact, that the error is carried along the analysis and each dataset is increasing the error. It is a tradeoff between the detail of the analysis, increasing error and increasing computational demands. Chapter 5.1 can be much more precise when the NDSI data would be used directly. However it would be necessary to compare each pixel as a float value instead of a binary value. Applied on larger datasets it would increase complexity.

Natural resource managers can use the available data for single Landsat image analysis, like chapter 5.2 for example. Furthermore single image analysis can contribute in detection of reference areas for ongoing phaenological projects and monitoring, identification of test sites for stratified random sampling or archaeological surveys (Kennedy et al. 2009).

6.4.3 Natural resource management of snow

Natural resources management of snow usually is connected with snowmelt. The water is mainly used for water power production. But it is used for industrial purposes as well as it is almost always a source of drinking water. Therefore modeling of snow cover and in connection with it snow water equivalent modeling are tools for predicting the runoff. Subsequently runoff modeling and runoff predictions are used for water resource management.

Snow cover models rely on statistical data in connection with terrain information. The models are incorporating terrain. The high resolution of the data gathered in 5.1 increase the level of detail. It is possible to adjust modeled results according to the gathered Landsat snow cover maps. On regional level the Landsat data is highly increasing the resolution of the snow cover, Compared to coarser satellite remote sensing platforms. Furthermore an independent DEM can cross validate the results. An alternative modeling approach is dealing with snow drift. These models rely on physical constraints. Again the detailed snow cover information can be used to validate the modeled results in connection with the independent DEM.

Both approaches modeling approaches contribute to the water resource management. However the statistical modeling approach is considered as rather easy to apply. Therefore the Landsat snow cover maps can be used.

The snow cover is dynamic and therefore it is difficult to rely on long term snow cover predictions. Changes in timing and extent of seasonal processes are leading to dynamic behavior. Therefore single observations lead to false assumptions and subsequently biased management objectives. Updated observations and modeling can reduce this bias. The snow cover determines discharge in river systems and subsequently influences the water quality. Most important are nutrients and dissolved oxygen which highly contribute to stream biological activity. Management plans might take these variations into account and offer adjusted actions with respect to the observations (Dingman 2002).

6.4.4 Improvement of existing management tools

Some interesting similarities are visible in the Landsat images. Chapter 5.4 reveals similar snow covered areas in different years. This snow cover is subject of melting. However it seems to follow a distribution pattern and the speed of melting is determined by snow depth and temperature. Subsequently it should be possible to track this pattern in detail. Maps based on detailed snow cover pattern dependent on selected snow depth measuring spots might increase spatial resolution of snow cover maps. These maps could be added to already existing water resource management models. In Norway for example these maps might increase the detail level of the available snow cover maps during the spring season.

An alternative way to map the snow cover can make use of fuzzy-logics. Several different satellite scenes acquired in different years at the same date are used. Each year has a specific snow cover and the different snow cover extents might reveal a distribution pattern as well. Areas that are very likely snow covered in any of the scenes should become visible and they could be mapped as very likely snow covered. Areas that are often snow covered, for example in approximately 90 % of all cases, might be mapped as likely snow covered. Subsequently for any observable stage a fuzzy term can be described. The next step is creating this type of map for a reasonable amount of days during the spring season. However this approach lacks a direct link into practical usability, as it is difficult to apply. Fuzzy-logic maps might be an alternative for long term planning purposes as they give an overview.

Snow patches might serve as observation areas for snow cover when it comes to remote sensing of snow. Several Landsat images were partly cloudy. But usually one or two larger snow patches are always visible. Several selected spots could be mapped in detail including their surrounding snow cover. Furthermore this work must be done in reasonable intervals for the whole spring season. Afterwards the snow patches might be used as proxies for describing the snow cover extent in the area. It might be helpful, whenever the satellite scene is partly clouded but snow patches are visible. It might contribute to more detailed snow cover estimation. However this prediction method is limited and subject of bias. It would not describe the situation, but return an interpolation.

7 Conclusion and future work

7.1 Conclusion

Landsat proved its suitability for mapping snow cover and environmental changes in the study area. Snow and ice cover detection worked very well with several different Landsat satellite products. The availability of satellite scenes from different years and different seasons of a year highly improved the gathered information. The high resolution in time gives various opportunities: change detection techniques can be used to reveal long term environmental changes. Single scenes can be used to map the snow cover extent at a certain point in time. Several satellite scenes of a single year can be used to track seasonal changes in snow cover extent. Finally the Landsat archive gives the possibility to describe the developments of landscape features in detail over several years.

The satellite scene evaluation towards its suitability needs human interaction. For the identification of snow and ice the NDSI proved its usability. Especially for large datasets it is easy to apply in an automated process. This process must be applied with some tolerance and therefore the derived product is not completely bias free. Dependent on the source image error on pixel level is possible. However it is providing reliable information and is easily applied.

The snow and ice cover data can be used together with a DEM. This combination contributes to the description of the locations of snow patches in the study area. One drawback of the snow and ice cover product is its lack of additional information as it is a binary file. Therefore it must always be coupled with additional information like the Landsat scene of origin and a DEM.

Remaining snow and ice covered areas can be considered as perennial snow patches or glaciers. Often these spots appear in dark blue colors on false colored images, indicating bare ice. It is possible to use the late summer snow cover product for mapping the position of snow patches. This might be important because snow patches are unlike glaciers often not mapped on official maps of the study area.

Based on the snow and ice cover products environmental changes can be documented. For a time period of 23 years the change detection revealed a melting trend of snow patches in the study area. Several snow patches melted completely in this period. With the data provided by the Landsat archive it was possible to document the snow patch extent of the year 1988.

For a single year the snow cover disintegration can be documented with Landsat satellite images in detail. Potential improvements of existing water resource management tools can rely on medium scaled remote sensing images. The lack of Landsat satellite image coverage could be mitigated by other remote sensing platforms.

7.2 Future work

Several different medium resolution remote sensing platforms could be combined to increase the resolution of existing snow cover maps. As these maps are important tools for water resource management it could lead to a more detailed view. With detailed available information potential actions can be applied more precise.

A future technical application might be an unmanned aerial vehicle (hereinafter briefly referred as UAV) tracking the snow cover in detail. As UAVs are available on comparably low cost levels and as they can be equipped with almost any desired payload they have the potential to increase the detail of existing snow cover estimation tools dramatically. A well located UAV airfield gives the potential to map snow cover in large areas of Norway on demand.

In terms of snow water equivalent modeling the gathered Landsat data can be used to validate modeled results from the past with observed values. Maybe it is possible to determine the snow water equivalent that is melted in connection with the snow density reference. Two Landsat scenes from the same spring are compared regarding the change of snow cover and the changed are might be transformed into snow water equivalent.

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Appendix

Date	Reference number	Path	Row	Sensor
18.6.1974	LM12160161974169AAA01	216	16	MMS
9.8.1976	LM22160161976222AAA02	216	16	MMS
17.8.1976	p215r016_1dx19760817	215	16	MMS
17.8.1976	p215r16_1m19760817	215	16	MMS
27.8.1976	LM22160161976240AAA04	216	16	MMS
27.8.1976	p216r016_2dx19760827	216	16	MMS
27.8.1976	p216r16_2m19760827	216	16	MMS
21.9.1976	p214r16_1m19760921	214	16	MMS
3.10.1982	LM41980161982276AAA03	198	16	MMS
25.5.1984	LT51980161984146XXX03	198	16	TM
10.7.1984	LM52000161984192AAA03	200	16	MMS
20.8.1984	LM51990161984233AAA05	199	16	MMS
28.9.1984	LM52000161984272AAA03	200	16	MMS
19.7.1987	LM52000161987200AAA04	200	16	MMS
13.8.1987	LM51990161987225AAA03	199	16	MMS
13.8.1987	LT51990161987225XXX02	199	16	TM
21.9.1987	LM52000161987264AAA03	200	16	MMS
8.9.1988	etp199r16_4t19880908	199	16	TM
21.5.1989	LT52000161989141KIS00	200	16	TM
24.7.1989	LT52000161989205KIS00	200	16	TM
26.9.1989	LT52000161989269KIS00	200	16	TM
8.7.1994	LT51980161994189KIS00	198	16	TM
31.7.1994	LT51990161994212XXX01	199	16	TM
6.8.1999	elp199r016_7t19990806	199	16	TM
6.8.1999	LE71990161999218SGS00	199	16	ETM+
7.9.1999	LE71990161999250SGS00	199	16	ETM+
16.9.1999	LE71980161999259SGS00	198	16	ETM+
18.4.2000	LE71990162000109SGS00	199	16	ETM+
25.4.2000	LE72000162000116SGS00	200	16	ETM+
13.5.2000	LE71980162000134SGS00	198	16	ETM+
27.5.2000	LE72000162000148SGS00	200	16	ETM+
5.6.2000	LE71990162000157SGS00	199	16	ETM+
30.7.2000	LE72000162000212SGS01	200	16	ETM+
31.8.2000	LE72000162000244SGS00	200	16	ETM+
25.9.2000	LE71990162000269SGS00	199	16	ETM+
2.10.2000	LE72000162000276SGS00	200	16	ETM+
20.10.2000	LE71980162000294SGS00	198	16	ETM+
21.4.2001	LE71990162001111SGS01	199	16	ETM+
28.4.2001	LE72000162001118SGS00	200	16	ETM+
7.5.2001	LE71990162001127SGS00	199	16	ETM+
25.7.2001	LT52000162001206MTI00	200	16	TM

2.8.2001	LE72000162001214SGS00	200	16	ETM+
12.9.2001	LE71990162001255SGS00	199	16	ETM+
21.10.2001	LE72000162001294SGS01	200	16	ETM+
23.10.2001	LE71980162001296SGS01	198	16	ETM+
2.6.2002	LE72000162002153SGS00	200	16	ETM+
19.6.2002	LT51990162002170MTI00	199	16	TM
13.7.2002	LE71990162002194SGS00	199	16	ETM+
5.8.2002	LE72000162002217SGS00	200	16	ETM+
23.8.2002	LE71980162002235SGS00	198	16	ETM+
23.8.2002	p198r016_7x20020823	198	16	ETM+
22.9.2002	LE72000162002265SGS00	200	16	ETM+
1.10.2002	LE71990162002274SGS00	199	16	ETM+
8.10.2002	LE72000162002281SGS00	200	16	ETM+
18.4.2003	LE72000162003108ASN00	200	16	ETM+
13.5.2003	LE71990162003133ASN00	199	16	ETM+
29.6.2003	LT52000162003180MTI01	200	16	TM
15.7.2003	LT52000162003196MTI01	200	16	TM
9.8.2003	LT51990162003221MTI01	199	16	TM
18.8.2003	LT51980162003230MTI01	198	16	TM
31.5.2004	LE71990162004152ASN01	199	16	ETM+
9.7.2004	LE72000162004191ASN01	200	16	ETM+
3.8.2004	LE71990162004216ASN01	199	16	ETM+
10.8.2004	LE72000162004223ASN01	200	16	ETM+
16.4.2005	LE71990162005106ASN00	199	16	ETM+
25.4.2005	LE71980162005115ASN00	198	16	ETM+
31.8.2005	LE71980162005243EDC00	198	16	ETM+
5.5.2006	LE71990162006125ASN00	199	16	ETM+
6.6.2006	LE71990162006157ASN00	199	16	ETM+
30.6.2006	LT51990162006181KIS00	199	16	TM
15.7.2006	LE72000162006196ASN00	200	16	ETM+
16.7.2006	LT51990162006197KIS01	199	16	TM
23.7.2006	LT52000162006204KIS01	200	16	TM
1.9.2006	LE72000162006244ASN00	200	16	ETM+
11.10.2006	LT52000162006284MOR00	200	16	TM
1.6.2007	LT51990162007152MOR00	199	16	TM
10.6.2007	LT51980162007161MOR00	198	16	TM
28.9.2007	LT52000162007271MOR00	200	16	TM
29.9.2007	LE71990162007272ASN00	199	16	ETM+
24.4.2008	LE71990162008115ASN01	199	16	ETM+
10.5.2008	LE71990162008131EDC00	199	16	ETM+
2.6.2008	LE72000162008154ASN00	200	16	ETM+
4.7.2008	LE72000162008186ASN00	200	16	ETM+
21.6.2009	LE72000162009172ASN00	200	16	ETM+
29.6.2009	LT52000162009180KIS00	200	16	TM
1.8.2009	LE71990162009213ASN00	199	16	ETM+

5.4.2010	LE72000162010095ASN00	200	16	ETM+
7.5.2010	LE72000162010127ASN00	200	16	ETM+
1.6.2010	LE71990162010152ASN00	199	16	ETM+
2.7.2010	LT52000162010183KIS01	200	16	TM
19.8.2010	LT52000162010231KIS01	200	16	TM
4.9.2010	LT52000162010247MOR00	200	16	TM
5.9.2010	LE71990162010248ASN00	199	16	ETM+
6.9.2010	LT51980162010249MOR00	198	16	TM
13.9.2010	LT51990162010256KIS01	199	16	TM
28.9.2010	LE72000162010271EDC00	200	16	ETM+
29.9.2010	LT51990162010272KIS01	199	16	TM
7.10.2010	LE71990162010280ASN00	199	16	ETM+
8.10.2010	LT51980162010281KIS00	198	16	TM
2.5.2011	LT52000162011122KIS00	200	16	TM
11.5.2011	LT51990162011131KIS00	199	16	TM
14.7.2011	LT51990162011195KIS01	199	16	TM
8.9.2011	LE71990162011251ASN00	199	16	ETM+
21.5.2012	LE71990162012142ASN00	199	16	ETM+
16.8.2012	LE72000162012229ASN00	200	16	ETM+
5.10.2012	LE71980162012279ASN00	198	16	ETM+

Appendix1: List of Landsat scenes and reference number

Appendix 2: Kringsollfonna debris cover in the year 2003 (Ingolf Røtvei)