Supervisor's Signature

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MASTER THESIS

Time series analyses of Ku-band scatterometer data over Greenland for retrieval of spatial and temporal patterns of winter thaw events

carried out at the
Department of Geodesy and Geoinformation
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under the guidance of
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Abstract

The ongoing global warming has high effects on the polar regions. Greenland and its ice shield has been object of numerous investigations, especially when considering spring and summer snow melt trends. Scatterometer data acquired in Ku-band from the QuikSCAT satellite have been proven to be highly applicable because of the sensitivity to snow cover thaw-freeze dynamics. Due to the higher average temperatures, the influence of the North Atlantic Oscillation (NAO), and prevailing wind systems over Greenland winter thaw is of growing importance. It affects the biological, ecological, and hydrological processes by causing ungulate mortality, increasing NO_3-N export, and leading to severe flooding. In this study, the focus was set on winter months (November-March) for the time frame from 2000 to 2008. Four different approaches were examined due to their capability of detecting thaw events.

In the first case the difference of the backscatter coefficient σ^0 based on a three-day moving window was used. In the second case the difference between two consecutive days was used. Two types of parameterization have been investigated: a constant threshold was set to 1.5 dB and a location specific noise level. For all winters thaw events were detected, however the spatially largest extent was found during late November, 2005. Compared to in-situ data from the Greenland Climate Network (temperature) and National Oceanic and Atmospheric Administration (precipitation), the results were investigated to validate if the temperature and/or precipitation were an indicator for the ongoing melt. The different approaches not only varied for date and size when detecting thaw, even spatial irregularities were found.

Zusammenfassung

Die weiter voranschreitende globale Erwärmung hat einen großen Einfluss auf die Polarregionen. Grönland und dessen Eisdecke sind Gegenstand zahlreicher Untersuchungen, speziell im Bezug auf Schneeschmelze im Frühjahr und im Sommer. Scatterometerdaten des QuikSCAT Satelliten, aufgenommen im Ku-Band, haben sich aufgrund der Sensitivität gegenüber Schmelz- und Gefrierereignissen in Schneedecken als äußerst geeignet erwiesen. Wegen höheren Temperaturen, dem Einfluss der Nordatlantischen Oszillation (NAO) sowie auf Grönland vorherrschende Windsysteme ist die Winterschmelze von wachsender Bedeutung. Es beeinflusst biologische, ökologische und hydrologische Prozesse durch Verursachen von Huftier Sterben, anwachsendem NO_3-N Export als auch dem Anstieg von starken Überschwemmungen. In dieser Arbeit wurde der Fokus auf die Wintermonate (November-März) gelegt für die Jahre 2000 bis 2008. Vier verschiedene Ansätze wurden verfolgt und auf ihre Fähigkeit Schmelzereignisse zu detektieren untersucht.

Im ersten Fall wurde jeweils die Differenz des Rückstreuungskoeffizienten σ^0 basierend auf einem drei-Tage-vorher, drei-Tage-nachher Algorithmus berechnet. Im zweiten Fall wurde die Differenz zweier aufeinander folgender Tage untersucht. Zwei Ansätze der Parametrisierung wurden geprüft: ein konstanter Wert von 1.5 dB und ein standortbezogener noise Grenzwert. Für jeden Winter konnten Schmelzereignisse detektiert werden, das flächenmäßig größte Ereignis aber war in den letzten Novembertagen im Jahr 2005 gefunden worden. Verglichen mit in-situ Daten des Grönland Klimanetzwerkes (Temperatur) und der Nationalen Ozean- und Atmosphärenbehörde (Niederschlag) konnten die Ereignisse untersucht werden um abzuschätzen ob die Temperatur und/oder Niederschlag für das Ergebnis verantwortlich war. Die Unterschiede der Ansätze variierten nicht nur in zeitlicher und umfangmäßiger Erfassung sondern auch in ihrer räumlichen Ausprägung.

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Chapter 1

Introduction

1.1 Statement of the problem

Albeit the whole planet is affected by extreme weather conditions, the Arctic warming has exceeded that of lower latitudes in the recent decades (Forbes et al. 2016). When speaking of global warming, the consequence is not only the increase of temperature. Global warming is also a term for the increase of the frequency of intense weather events like heat waves, droughts, and heavy rainfalls (Hansen, Isaksen, et al. 2014). In the circumpolar Arctic melting and refreezing is an ongoing development. New phenomenona like rain-on-snow (ROS) events are being focused because of their influence on the ecosystem. They appear sporadic and mostly last merely days but have an important biological, hydrological, and ecological impact (Semmens et al. 2013). Because no reliable trend of the frequency of ROS can be detected (Cohen, Ye, and Jones 2015), it is not predictable when and where the phenomenon will appear (Putkonen, Grenfell, et al. 2009). In situ measurements are not able to capture snow changes all over Greenland at once and beyond that only selective whereas spaceborne instruments provide comprehensive measurements and a high temporal resolution. Using the microwave region of the spectrum, the data collection is possible during night and day, it is not affected by clouds, and the supplied information provides material which is beyond human perception as the data is a result of geometric and dielectric properties of the surface (Wagner 2010). It depends on the wavelength, whether the sensor retrieves information about the water content, the estimation of the depth or even the amount of liquid water in a snow pack (Jensen 2000). "Infiltrating water can have a significant impact on the thermal regime of permafrost" (Westermann et al. 2011, p. 1). Thus, the investigation of melt events, eventually caused by ROS and/ or higher temperatures are very interesting. Over glaciated and unglaciated areas, the impact on the formation of basal ice layers may differ a lot, causing various results over the current areas (Westermann et al. 2011). The SeaWinds scatterometer onboard the QuikSCAT satellite was operating in the Ku-band (13.4 GHz, 2.1 cm wavelength) from 1999 to 2009 (Bartsch 2010). Sensors which perform in this spectral region are highly sensitive to changes in snow and to snow wetness (Bartsch 2010; Ulaby and Long 2017). Although ROS events are typically short lived, the effects on the ecosystem may last for years (Rennert et al. 2008). In the northern arctic region, herding is often the basis of existence (Bartsch, Kumpala, et al. 2010). Due to ROS events the snowpack properties change and build ice crystals which act as an impenetrably layer for ungulates (Bartsch, Kumpala, et al. 2010; Putkonen, Grenfell, et al. 2009; Putkonen and Roe 2003; Semmens et al. 2013; Wilson et al. 2013; Westermann et al. 2011) that collect their food by digging through the snow (Bartsch, Kumpala, et al. 2010). In 2003, a ROS event was responsible for the death of approximately 20,000 muskoxen on Banks Island (Putkonen, Grenfell, et al. 2009), and in 2013 a starvation of 61 000 reindeer shrunk a herd on the Yamal Peninsula, Siberia (Forbes et al. 2016). Because of this negative effect on the population of ungulates among other things, the phenomenon of snow thaw during winter is a growing problem. Its frequency will raise as the global warming will proceed and cause warmer and wetter winters, but still less is known about this trend of appearance and the empirical evidences are limited (Hansen, Aanes, et al. 2011; Hansen, Isaksen, et al. 2014). Temporal analysis for melt detection events are applied, but glaciated areas are usually excluded. Although glaciers play an important role in climate change, less is known about the ROS events and the effect on them. It has been shown that microwave remote sensing can be used to detect rain-on-snow events. Microwave measurements are highly suitable because of the orientational polarization behaviour of liquid water and the high sensitivity of microwave backscatter due to changing water amount in snow layers.

1.2 Microwave Remote Sensing

Since the possibility of leaving the Earth's ground to soar into the sky, people did not only put themselves up in the air, but also instruments to capture the Earth from above. With the first airborne picture taken from Earth in a tethered balloon in 1858, the French photographer Gaspard Felix Tournachon (Jensen 2000) started a new era of observing the planet. However, the moving force behind the aerial photography was initially the military. To spy and observe the enemy without being noticed and putting oneself in danger was a tremendous advantage.

In the 1860s, James Clerk Maxwell developed the wave theory which said that light was a form of high-frequency electromagnetic waves, which paved the way for all generations to come (Jensen 2000; Wagner 2010). One of the most preeminent persons was Heinrich Hertz, who produced and detected electromagnetic waves which proofed Maxwell's theory (Wagner 2010). During World War II, the knowledge about electromagnetic waves and their interaction with objects was used in a spectral region beyond humans understanding. A system which utilized the microwave spectrum to trace and chase objects, respectively opposing airplanes and ships. This system was called RADAR (= Radio Detection And Ranging) and nowadays, not only the military uses this technique even in everyday life there are lots of points of contact. This technology helps to locate, navigate, or observe, be it in case of an airplane finding its route or in case of satellites collecting data all around the world.

To be able to monitor the whole Earth is a huge advantage. This way, even parts that are inaccessible due to the area's topography can be recorded, presenting a global coverage. By using different spectral regions it is possible to investigate the Earth under various aspects and receiving answers about e.g. temperature, soil moisture content, or snow melting events (Jensen 2000). With the satellite's recorded data, a huge amount of information is available which helps to make forecasts and presumptions of how the Earth will change.

The Microwave sensors can be divided into two classes: passive and active. Passive sensors, known as radiometers, detect the thermal emission of microwaves which are produced by the observed object itself (Ulaby and Long 2017). Active sensors, known as radar, create their own signal, scan the object of interest and receive the backscattered radiation. Within these classes, different approaches of instruments exist. Radar devices can either be of a real aperture radar (RAR) or a synthetic aperture radar (SAR) (Ulaby and Long 2017). The difference between the two approaches is the antenna. Whereas the real aperture system depends on the beamwidth determined by the antenna's installation length, the synthetic aperture depends on the proper motion of the platform. It also depends on the processed signal to achieve a much narrower beamwidth in the along-track direction than it would be possible without this synthesized antenna (Jensen 2000; Ulaby and Long 2017).

Band Designations	**Wavelength (λ) in cm**	**Frequency (ϑ) in GHz**
Ka	0.75-1.18	40.0-26.5
K	1.19-1.67	26.5-18.0
Ku	1.67-2.4	18.0-12.5
X	2.4-3.8	12.5-8.0
C	3.9-7.5	8.0-4.0
S	7.5-15.0	4.0-2.0
L	15.0-30.0	2.0-1.0
P	30.0-100	1.0-0.3

Table 1.1: Radar Wavelengths and Frequencies Used in Active Microwave Remote Sensing Investigations (source: Jensen 2000).

1.2.1 Radar Principles

Instead of focusing the area of interest with lenses like in the optical range, in the microwave region the field is scanned with an antenna. The region encompasses wavelengths from about 1mm to 1m but usually when referring to microwaves so-called 'bands' are used. The common bands for radar are given in Table 1.1. The band names are vestiges of the original but secret work with radar remote sensing.

Jensen defines the wavelength "as the mean distance between maximums (or minimums) of a roughly periodic pattern" and the frequency as "the number of wavelengths that pass a point per unit time" (Jensen 2000, p. 30). The frequency is inversely proportional to the wavelength (Jensen 2000) and their relationship can be described as $c = \lambda\vartheta$ with c as the speed of light. Electromagnetic waves move in a vacuum at the speed of light, c, which is after Ulaby and Long (2017):

$$c = 2.998 \times\ 10^8\ \approx 3 \times 10^8\ ms^{-1} \tag{1.1}$$

Whether it be in visible or in microwave range the electromagnetic radiation can be described by waves (Wagner 2010). Coherent (micro-)waves consist of two fluctuating fields, one magnetic and one electric, which are orthogonal to each other as well as perpendicular to the direction of travel (Jensen 2000, p. 31) (Fig. 1.1).

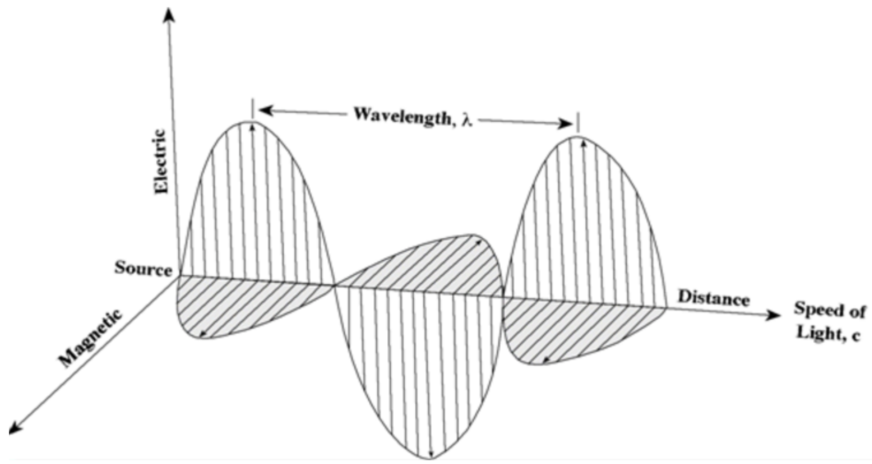


Figure 1.1: An electromagnetic wave is composed of both electric and magnetic vectors that are orthogonal to one another (source: Jensen 2000).

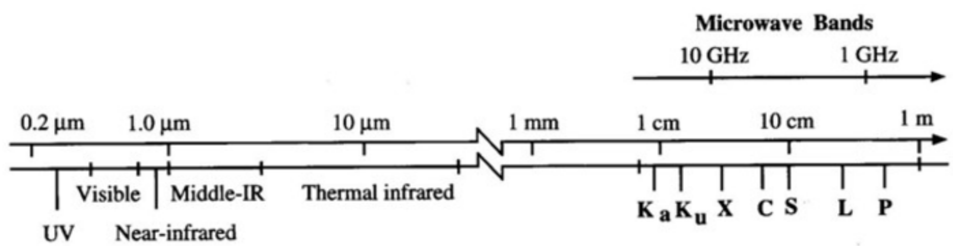


Figure 1.2: Electromagnetic Spectrum (source: Jensen 2000).

The two fields are described by Maxwell's equations after Ulaby and Long (2017):

$$\nabla \cdot \mathbf{E} = 0 \tag{1.2}$$

$$\nabla \cdot \mathbf{H} = 0 \tag{1.3}$$

$$\nabla \times \mathbf{E} = \text{-}j\omega\mu\mathbf{H} \tag{1.4}$$

$$\nabla \times \mathbf{H} = j\omega\varepsilon\varepsilon_0\mathbf{E} \tag{1.5}$$

E and **H** are the electric (in V/m) and magnetic field intensity (in A/m). Each medium has two specific properties that characterize its electromagnetic behaviour. One is the electric permittivity ε and the other is the magnetic permeability μ. The permittivity is given by

$$\varepsilon = \varepsilon_r i \varepsilon_0 \tag{1.6}$$

and is usually in the region between $1 < \varepsilon_r < 100$ (Wagner 2010). The ε_r is dependent on the frequency and is calculated with:

$$\varepsilon_r = \varepsilon'_r + i\varepsilon''_r \tag{1.7}$$

The real part ε'_r conforms to the dielectric constant without loss, whereas the losses are expressed by the imaginary part ε''_r (Wagner 2010). The real part ϵ'_r is linked with the polarization of the medium and governs the propagation velocity of the wave whilst the imaginary part ϵ''_r is associated with the conductivity of the medium and also the radar signal attenuation.
The magnetic permeability μ is of lower importance in the field of remote sensing and is usually given with:

$$\mu = \mu_0 \tag{1.8}$$

The fundamental Radar equation is given by Woodhouse (2005):

$$P_r = \frac{P_t G_t A_r}{(4\pi)^2 R^4}\sigma \tag{1.9}$$

P_r is the received power, P_t is the power which is transmitted towards the target, G_t is the income of the antenna in the direction of the target, R is the distance from the transmitter to the target, σ is the effective backscatter area of the target, and A_r is the area of the receiving antenna (Jensen 2000).

The backscatter coefficient, also known as sigma zero (σ^0), is normalized and calculated by a function which considers the frequency, the polarization, and the illumination direction of the signal (Wagner 2010). It can be obtained after Woodhouse (2005):

$$\sigma^0 = \frac{d\sigma}{dA} \tag{1.10}$$

The backscatter coefficient is actually a unitless value, but often expressed with a logarithmic function, the amount can be given in decibel [dB] after Wagner (2010):

$$\sigma^0[dB] = 10\ log_{10}(\sigma^0)[m^{-2}m^2] \tag{1.11}$$

The waves are either emitted by the sun or produced by a localized source. They have to travel from the source through the atmosphere to the object of interest and all the way back. By passing the atmosphere, the waves get attenuated due to changes of density. Because of different densities, the waves experience refraction. Refraction causes the bending of light when it passes from one medium to another and can be described by Snell's law:

$$n_1 sin\theta_1 = n_2 sin\theta_2 \tag{1.12}$$

The amount of refraction is a function of the angle made by the vertical (θ), and the index of refraction (n) calculated from the ratio of the speed of light (c) to the speed of light in a substance (c_n) (Jensen 2000). The waves are getting slower in a medium where the index of refraction (n) is higher, respectively where density of the medium is higher.

Besides the refraction, the scattering effect plays an important role. Due to small material particles (aerosols) in the atmosphere, parts of the electromagnetic waves are redirected. How much the waves are affected by scattering depends on the one hand on the radiation's wavelength and on the other hand on the size and shape of the particles. If the air molecules are many times smaller than the wavelength of the incident electromagnetic radiation, the effect is called *Rayleigh scattering.* This effect is responsible for the blue appearance of the sky because shorter wavelengths are more scattered than the longer ones. If gas molecules, dust particles, or water vapor are in the size of the wavelength it is named *Mie scattering* and noticeable at orange and red sunsets. If particles are greater than the wavelength the *Non-selective scattering* becomes operative. This type of scattering is causing the clouds to appear white (Jensen 2000). Further on, the absorption is another issue which affects the radiation. It absorbs and converts the radiant energy into other forms of energy. The atmospheric absorption is caused by various substances, e.g. water (H_2O), carbon dioxcide (CO_2), oxygen (O_2), ozone (O_3), or nitrious oxide (N_2O) (Jensen 2000). Therefore, the atmospheric opacity, called atmospheric windows, are important to consider when operating with remote sensing systems. Some of the wavelengths are almost completely absorbed by the atmosphere, whereas others can pass it with nearly no interference. An advantage of microwaves is that the atmosphere is almost translucent and the effects of extinction (term for the effects of scattering and absorption) is negligible (Albertz 2009).

The way a radar system captures the Earth is dependent on different aspects. One main aspect are the parameters of the recording system. This includes the wavelength of the radiation, its polarization as well as the depression angle. To distinguish between the different wavelength bands (Tab. 1.1) is necessary, because the interaction between radiation and objects is different for each band.

Polarization is a wave phenomena that can only be applied on transverse waves. Microwaves transmitted by the antenna can either be vertical (V) or horizontal (H) polarized (Albertz 2009). The polarization always effects the electric field, not the magnetic field, because the most interaction of the electromagnetic radiation is caused by the electric field (Wagner 2010). Furthermore, not only the outgoing but also the incoming radiation can be polarized. There are four possible combinations of how it can be set: HH, VV, HV, and VH. As a reference for the polarization, the horizon is used.

The depression angle defines the angle between the horizontal plane of the recording system and the beam to a specific recorded object (Albertz 2009). The supplement of the angle to 90° is called incidence angle. It influences immediately the resolution of the system across the flight direction.

The parameters of the surface form another significant aspect in collecting data. This includes the surface roughness, the surface shape, and the electrical property of the materials (see formula 1.7). The surface roughness plays an important role for the behaviour of the reflection of electromagnetic waves. If the surface roughness is small compared to the size of the incoming wavelength, the electromagnetic waves are scattered in specular direction. In this case the operating system is not receiving any information because no backscattered signal arrives at the unit. It occurs as a black area (Albertz 2009) in the radar picture. If the surface roughness is in the size of the wavelength, the area acts as a diffuse reflector and induces part of the incoming microwaves to travel back to the sensor.

The surface shape causes some geometric distortions in almost every radar image. According to the slope and height of the terrain, some areas are more illuminated than others, resulting in relief displacements in the picture. The effects are foreshortening, layover, and shadow. Higher objects which are closer to the antenna are recorded sooner than their bottom and cause a foreshortening and/or layover. If an area is not ascertained by the wave front it cannot be recorded. In the picture it causes a shadow for that part of the terrain (Jensen 2000).

The permittivity is an essential parameter for the propagation of electromagnetic waves as mentioned before. High reflection occurs on objects with a metallic structure as well as on materials with a high dielectric constant (= high moisture content). As the dielectric constant decreases, so does the reflectivity, whereas the penetration depth increases. Thus, the backscattered signal depends on the thickness of the layer, which has its own effect called volume scattering.

Figure 1.3 shows the behaviour of Ku-band radar backscatter at an incidence angle of 54° and VV-polarized (Rawlins et al. 2005). The upper chart shows an increasing radar extinction and a corresponding decrease of the penetration depth into snow due to the increasing amount of liquid water. The lower chart draws the main influences on total backscatter from snow under wet snow conditions, called the backscatter from the snow surface and the volume backscatter from within the snow itself (Rawlins et al. 2005).

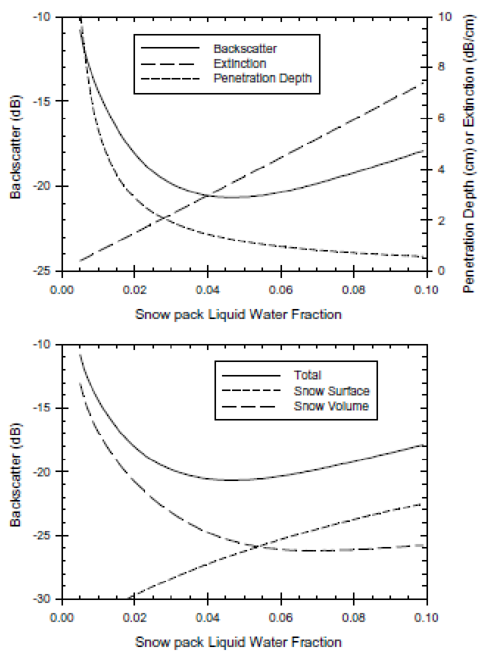


Figure 1.3: Ku-band radar backscatter with increasing snow wetness. It shows VV-polarized backscatter behaviour at an incidence angle of 54° over tundra snow. The top chart illustrates increasing radar extinction and a corresponding decrease in radar penetration into the snow as the amount of liquid water in the snow increases. This gives rise to a pronounced decrease in backscatter for wet snow relative to drier snow. The bottom chart shows the two dominant contributions to the total snow backscatter for wet snow, namely the backscatter from the snow surface and the volume scatter from within the snow itself. As wetness increases, the contribution of the volume backscatter diminishes while the surface scattering contribution becomes more pronounced. (source: Rawlins et al. 2005).

1.2.2 Backscatter from ice and snow

The radar backscatter depends on the wavelength and on the depression angle (Jensen 2000). According to the wavelength, it is possible to estimate the depth, the water content and the amount of liquid water in the snow pack (Jensen 2000). The permittivity of an object, defined by Jensen as "a measure of the ability of a material (vegetation, soil, rock, water, ice) to conduct electrical energy" (Jensen 2000, p. 311) is not easily described for snow. It depends highly on the water content. The more liquid water in the snow layer, the more specular reflection, and the poorer the backscatter towards the operating system. The dielectric constant ε_r for water itself is very high with about 80 compared to dry surface material with 3 to 8 (Jensen 2000). Because liquid water shows orientational polarization, water holds an important role in remote sensing in the microwave region (Wagner 2010) and affects the amount of backscattered energy tremendously.

Ice has a quite stable real part ε_r' over the microwave region with $\varepsilon_r' = 3.17 \pm 0.03$ (Wagner 2010; Ulaby and Long 2017). When the frequency is below 10 GHz the imaginary part ε_r'' is less than 0.001. These negligible losses facilitate the penetration depth and enable microwaves to get through ice in the order of meters to tens of meters (Wagner 2010). However, snow is a mixture of water droplets, air, and ice particles according to temperature (Wagner 2010). The real part ε_r' for dry snow is less than 1.7 whereas the imaginary part ε_r'' is in the ice's order. If the temperature reaches up to zero degrees, the dielectric properties change rapidly due to the liquid water (Wagner 2010). With increasing water content, the penetration depth quickly decreases.

Microwaves at shorter wavelengths are best suited for detecting snow processes due to the increased scattering albedo (Rawlins et al. 2005). As shown in Figure 1.3, the Ku-band backscattered signal decreases with the increase of liquid water. This drop in backscatter is either an evidence for thaw caused by increasing temperatures and/or rain (liquid precipitation).

In general, the backscatter coefficient from snow is formed after Ulaby and Long (2017) by (a) a direct impact of the air-snow boundary, (b) a two-way attenuated contribution from the snow-ground boundary, (c) the backscatter from the snow volume, and (d) some indirect contributions due to the interaction between the snow volume and either or both boundaries of the snow layer.

1.3 Time series analysis for snow melt detection

For snow melt detection in winter a "three-day window has been found to be sufficient as backscatter does not change much before and after events" (Bartsch, Kumpala, et al. 2010, p. 5). This change detection approach considered and observed the days before as well as after a melt event (Semmens et al. 2013). "Change detection is the foremost methodology for large-scale detection of changes in snow due to thaw based in Ku-band scatterometer" (Bartsch, Kumpala, et al. 2010, p. 5). Rawlins et al. (2005), Kimball et al. (2004) and Wang, Derksen, and Brown (2008) however used a five-day window to detect melt events.

Several approaches have set different thresholds that must be exceeded by sigma zero to mark a location as a melt event. In Bartsch (2010) the threshold was defined as 1.5 dB due to validation from observations on the Yamal Peninsula in Russia on unglaciated ground during mid-winter. Another approach from Bhattacharya et al. (2009) declared that sigma zero needed to be decreased by 3 dB to be labelled as a melt onset. Bhattacharya et al. (2009) based the model on Ashcraft and Long (2006) who suggested that within a wet snow layer with about 3.8 cm thickness and approximately 1% of liquid moisture content would led to a backscatter decrease of 2.7 dB on glaciated terrain during winter. Kimball et al. (2004) calculated a minimum backscatter threshold from the "absolute value of twice the standard deviation of daily radar backscatter differences from a moving window average of the previous 5-day period during fall (September 1-November 30) and spring (March 1-May 31)" (Kimball et al. 2004, p. 6).

1.4 Objectives

The aim of this thesis was to investigate the changes of the backscatter coefficient σ_0 received from the SeaWinds scatterometer aboard the QuikSCAT satellite. It focused on the area of Greenland and examined spatial and temporal patterns of winter melt events during the years 2000-2008 on glaciated and unglaciated areas. By defining the winter months from November until March, the algorithm only finds thaw events that should be explained by temperature increase or rain-on-snow, and not by unrelated summer melt. Further, the algorithm was used to perform a sensitivity analysis which involved the noise aspect of the data from the Ku-band. This considered the specific value of noise to the corresponding backscatter value for each grid point to be a very helpful aspect in finding melt events. Instead of setting one threshold for all the backscatter coefficients that needed to be exceeded in order to detect thaw, each backscatter quantity is connected with its specific amount of noise.

Also, the suitability of the algorithms for detecting events above glacier and not only along the unglaciated coastal line was investigated.

The data from the Greenland Climate Network (GC-Net) and from the National Oceanic and Atmospheric Administration (NOAA) were used to approve that the shown melt events are related to increased temperature and/or to precipitation.

1.5 Structure overview

The thesis is divided into seven chapters. *Chapter 1* gives a short overview about microwave remote sensing, explains the statement of the problem as well as describes the objectives of this research work.

Chapter 2 takes a look at the area of interest with its (2.1) geography and the (2.2) climate. It also describes the phenomenon of rain-on-snow (2.3) and the characteristic surface winds (2.4) on Greenland and especially the predominant katabatic winds (2.4.1).

Chapter 3 describes the data which is utilized to solve the objectives. The important role is the backscatter data from the scatterometer onboard the QuickSCAT satellite (3.1).

Chapter 4 considers the methodology of how the data was processed and how the four different approaches were built.

Chapter 5 shows and discusses the results for the different approaches as well as the validation for the detected melt events.

Chapter 6 summarizes the main findings of the research work, a conclusion of the thesis regarding to the initial objectives, and an outlook for future work.

Chapter 2

Study area and the rain on snow phenomenon

Greenland covers an area of 2.2 million square kilometres and is the largest island on Earth. Seen from the political side, Greenland is an autonomous constituent country within in the Kingdom of Denmark, but from continental side it belongs to the North American Plate. Kalallit Nunaat, the greenlandic word for the island, means ”land of the people” although it has one of the lowest population density worldwide. Because 80% of the area is covered in ice and snow due to the continental ice shield, the population of about 57 000 people settles on the remaining part of 20%, which is primarily along the coast. The capital city is Nuuk and is located in the south-western part of Greenland. The country is divided into four municipalities as well as the unincorporated fifth area, the Northeast Greenland National Park, which is the largest protected land surface on Earth. The island reaches out over three time zones that is UTC+0, UTC-2, and UTC-3.

2.1 Geography

The northern part is very close to the North American continent, separated only by a narrow more or less ice-filled sea. The north pole is only 700 km away which makes Greenland the closest country to the north pole. To the east side the island is surrounded by the Greenland Sea and the Denmark Strait, to the west side borders the Davis Street and the Baffin Bay. From the North to the South it stretches over 2600 km and from the East to the West it is more than 1400 km. Because the island reaches from Cape Farvell at 59°46’28”N to Cape Morris Jesup 83°37’39”N (Demhardt 2016), the main part lies above the polar circle which is at 66°33’55”N. Due to the axial tilt of the Earth and depending on the latitude, the duration of the lengths of day and night change reversely the further going northwards.

The ice sheet that covers Greenland, is at some point up to 3400 m high (Demhardt 2016) and caused a subsidence of the continental crust. Hence, the lowest point in Greenland lies below the sea level at around 300 m depth. The highest point is also the highest mountain of the Arctic region, namely the Gunnbjorns Fjaeld which is about 3800 m high (Semmens et al. 2013). Together with the Antarctic ice sheet, the Greenland ice shield contains more than 99% of the freshwater on Earth. In light of the fact of global warming, for many years Greenland’s ice shield is under severe observation. If the Greenland ice sheet would melt utterly, the sea level would rise more than 7m (Hanna et al. 2008; *Quick Facts on Ice Sheets* 2017).

2.2 Climate

Greenland is part of the Arctic, which is commonly defined by the area above the polar circle, although there is no strict geographic boundary (Serreze and Roger 2014).

Because Greenland shows big differences in temperature and precipitation behaviour depending on the latitude, longitude and especially because of the topography, Cappelen divides Greenland into seven weather and climate regions (see Figure 2.2), and provides further detailed information for climate.

> *South Greenland* is often affected by lows from the southwestern to the northeastern part. The amount of precipitation is large compared to other regions. The summer temperature are warmer inside the country but lower the closer to the coast. The winter differ from year to year and is very changeable due to the crossing lows from the southwestern to the northeastern part. When there is a stationary low at the south of Greenland, easterly directed Foehn winds may occur and bring temperatures up to 10°C or more. If the stationary low is located near to Iceland, it causes northwesterly winds bringing frost and snow showers. The part of *Southwest Greenland* has relatively mild winters at the coastal zone, but with coolish summers. The winters are colder inside the fjords, whereas the summers are warmer.

The precipitation is usually large in the south but is getting less the further to the north. Also, going from the coast inwards the amount of snow decreases. Areas of low pressure that passes the Davis Strait bring lots of precipitation and wind from the south. When the wind is combined with the Foehn effect, the temperature can rise in winter up to 10-15°C. The weather in summer is usually stable with temperature of 20°C for the inner fjords. *Northwest Greenland* has less unstable but colder winters than the southwest part of Greenland. Because of storms, in summer as well as in winter the winds bring large amount of precipitation. The *North of Greenland* has often clear and calm weather. The summers are short but sunny and warm at the inland, although passing cyclones can cause snowfalls even during that time. The coastal areas are often affected by clouds and fog. The precipitation is sparse and unevenly spread. In *Northeast Greenland* the winters are very cold because there is no open sea. In summer the coastal zone is affected by fog, but the fjords inside are warm and sunny with sparse precipitation. Mostly the winds blow from the ice cap and can be very strong when reaching the fjords. The winds and the precipitation in the area of *Southeast Greenland* are highly affected by cyclonic activities around Iceland. There is lots of precipitation, especially when a regime of warm easterly winds blow to the north of a low pressure system which is stationary over South Greenland or over the sea to the south of Greenland. If this situation takes place, it is possible that even during winter the precipitation is liquid. The temperature is throughout the year close to zero degrees as the region is affected by the East Greenland Polar Sea Current. The biggest part of the seven climate regions after Cappelen is the *Greenland Ice Sheet*. It is one of the most arid regions on Earth. Because of the altitude and the high albedo, melting only takes place along the edge. During winter the temperature can reach till -60°C. Because the surface is colder than the air above, the surface drains the heat from the lowest layer of the air which results in an inversion. This inversion layer is the cause of the katabatic winds on Greenland. Particularly in winter the katabatic winds are very strong. Even if a passing cyclone affects the local wind system on Greenland and causing a break down, the wind pattern is quickly re-established.

The map of Fausto et al. (2009) shows the mean annual temperature which was calculated for the time span of 1996-2006 (Fig. 2.1). It presents the near-surface air temperature which was calculated with parameterization. The parameterization is depending linearly on altitude, latitude and longitude, which is based on the study by Ritz, Fabre, and Letréguilly (1997) (cited in Fausto et al. 2009). The map shows also the location of the stations from which Fausto used the in-situ data, for instance the Greenland Climate Network (GC-Net) and the automatic weather stations (AWS) of the Danish Meteorological Institute (DMI).

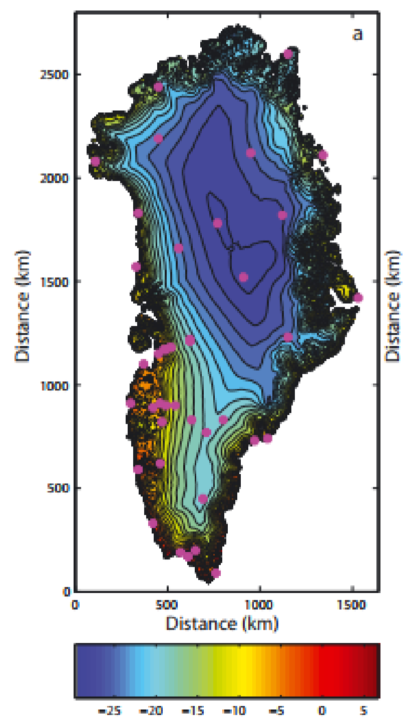


Figure 2.1: Mean annual temperatures in degrees. Dots show the location of the used weather stations (source: Fausto et al. 2009)

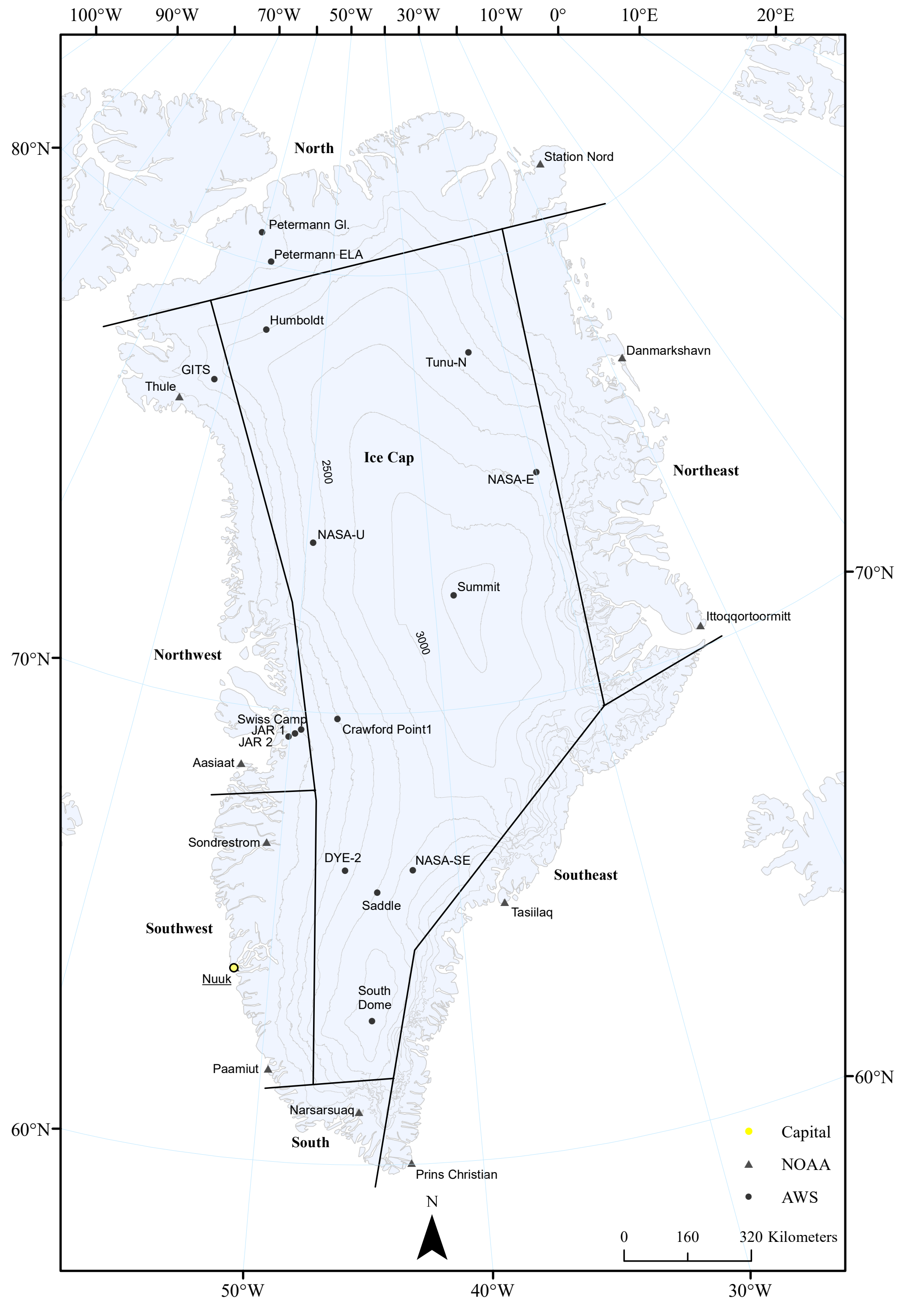


Figure 2.2: Greenland climate zones after Cappelen with weather stations for temperature (AWS) and precipitation (NOAA) (source contour lines: derivated from GETASSE30; source country lines: World Countries (Generalized) by ESRI).

2.3 Wind

Due to its size and height Greenland has an enormous impact on the movement of air in the lower part of the troposphere. This causes the wind to blow mainly along the coast (Cappelen 2013) as seen in Fig. 2.3. These so-called *barrier winds* are blowing clockwise oriented to the land and can be very strong. According to Mote (1998), the topography of the ice sheet also plays a huge role in controlling cyclones that approach from North America. Either they are shoved eastward to the Icelandic low or are pushed westward through Davis Strait into Baffin Bay (Mote 1998). Cyclones along Greenland's coast produce a force of pressure drop that accelerates the drain of cold air from the summit and magnifies katabatic winds (Mote 1998).
Although, strong winds are usually connected with passing cyclones, there are also wind regimes that are occasioned by local conditions (Cappelen 2013). Winds over Greenland are especially strongest in winter, which is primary caused by surface radiative cooling (As, Fausto, and Steffen 2014).

In Gorter et al. (2014) the Greenland ice sheet boundary is described as a surface temperature inversion layer that is especially strong during winter. The inversion is primarily caused by the highly reflective ice sheet, resulting in absorbing only a little bit of the incoming radiation. Because of this high albedo, the surface is not getting warmer and the air temperature close to the ice sheet stays very low and results in a negative surface radiation balance (Gorter et al. 2014). The cold air wants to move down (Figure 2.4) and is influenced by the surrounding weather conditions, especially the weather conditions around the coast. Since the downward going movement of the cold air is governed by the surface and the topography, causing canalization and an extremely high wind velocity, the outgoing air is warmed up with 1°C every 100 m of altitude change. This effect is called *Foehn* and is very common on Greenland. Especially during winter there is a strong daily temperature variability that is associated with katabatic winds (Serreze and Roger 2014). The wind speed is affected due to three main factors (GEUS):

- the influence of the topography
- the pressure gradient associated with cyclones and anticyclones
- the static stability of the air near the surface

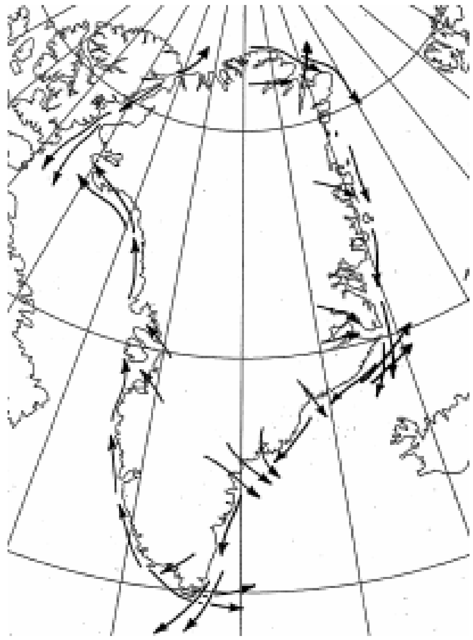


Figure 2.3: Predominant wind directions over Greenland (source: Cappelen 2013).

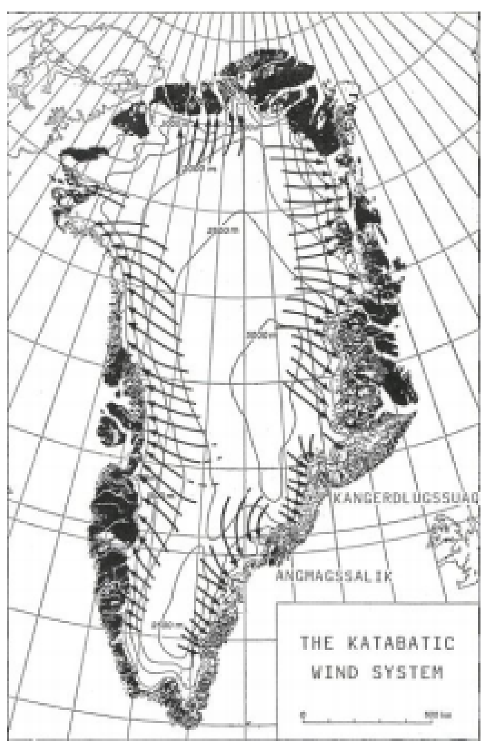


Figure 2.4: The katabatic wind system over Greenland (source: Cappelen 2013)

Foehn winds are of importance during the winter, because in fjords they may bring warm temperatures. With these warm winds, it is possible that even in winter the temperatures climb above zero degrees or even higher and induce snow melt and ice break (Cappelen 2013). Although this does not sound threatful but for the life of the inhabitants, this phenomenon can create a difficult situation. If the air temperature increase above zero degrees changes in the ice and snow pack may occur. But not the liquid state is the problem, it is the refreezing one. For ungulates the refrozen ice layer is an obstacle when searching for food under the layers of snow.

In the past the connection between the North Atlantic Oscillation (NAO) was investigated and Mote (1998) found out that more than the half of the melt extent of the ice sheet between 1979 to 1989 was attributed to the NAO. The NAO is a covariability of the Icelandic low and the Azores high, "the two "centers of action" in the atmospheric circulation of the North Atlantic" (Serreze and Roger 2014, p. 13). The NAO is in its positive phase, if the Icelandic low and the Azores high both are strong. In contrast, if both pressure systems are weak, the NAO is in its negative phase. When the Icelandic low is weak, it tends to be shifted to the southwest, wherefore the winds over Greenland are weaker and may cause positive temperature anomalies (Serreze and Roger 2014).

2.4 Rain on snow

The amount of precipitation is not an easy quantity to measure in the Arctic region (Denmark and Greenland accessed: 2017-08-30; Liston and Hiemstra 2011). At the eastern part of Greenland the orographic uplift of moisture air amplifies the precipitation whereas it is low in the northern part due to the low humidity (Denmark and Greenland accessed: 2017-08-30). A big influence of the precipitation over Greenland is the North Atlantic Oscillation (NAO) (Calder, Craigmile, and Mosley-Thompson 2008; Cohen, Ye, and Jones 2015; Mosley-Thompson et al. 2005). Especially on the west-central side of Greenland the NAO modulation of accumulation is very strong (Mosley-Thompson et al. 2005). Thus, the spatial behaviour of the distribution of precipitation is associated to the NAO variability which is influenced by the global, respectively the Arctic warming of the 20th century (Mosley-Thompson et al. 2005). These "variations in the distribution of atmospheric mass between the Arctic and the suptropical Atlantic [are] characterized by an index calculated as the difference in mean monthly surface pressure anomalies between Iceland and the Azores" (Mosley-Thompson et al. 2005, p. 1). When the NAO is in its positive phase the southwesterly flow is reduced by the westerlies which causes a decrease of accumulation. Contrarily, when the NAO is in its negative phase the atmospheric flow from the southwest brings more humidity, particularly to the southern region (Mosley-Thompson et al. 2005). The results of Mosley-Thompson et al. (2005) conclude, that when there are warmer temperatures in the northern latitudes, the influence of the NAO on the precipitation over Greenland gets attenuated along the west-central side of the ice cap and gets enhanced along the southeastern side.

Because of the global warming, rain on snow (ROS) events during winter will increase in the future (Semmens et al. 2013). Even if the event is not causing any change in the snow depth, it occasionates an ice layer in the snow pack which impedes foraging for ungulates. "Extensive winter mortality in reindeer, caribou, and muskoxen populations can result from ice-crust formation that prevents access to winter food" (Liston and Hiemstra 2011, p. 16). Thus, ROS events have negative consequences for the reindeer population growth rates (Hansen, Aanes, et al. 2011; Westermann et al. 2011), influences on the hydrological, terrestrial, and ecological cycles, but still ROS events are studied very little (Ye, Yang, and Robinsons 2008).

Chapter 3

Data

Microwave remote sensing systems can be divided into active and passive systems. The passive sensors only detect the thermal emission of objects, whereas the active systems scan the objects by transmitting and receiving the backscattered coefficient. For this thesis data from the QuikSCAT SeaWinds scatterometer, which is an active system, was used because of its high sampling rate and sensitivity to the phenomenon (Bartsch 2010; Drinkwater, Long, and Bingham 2001; Kimball et al. 2004; Nghiem and Tsai 2001; Rawlins et al. 2005; Tedesco 2007). In addition, climate data from the Greenland Network (GC-Net) and from the National Oceanic and Atmosphere Administration (NOAA) was used.

3.1 The SeaWinds scatterometer

The SeaWinds scatterometer onboard the QuikSCAT satellite was launched on June 19th, 1999 (Bartsch 2010; Rennert et al. 2008). NASA's Quick Scatterometer antecedent mission was to collect data for the ocean surface winds but is also highly suitable for snowmelt studies (Bartsch 2010; Semmens et al. 2013). The investigation of scatterometers using the Ku-band of the microwave region (2.1 cm wavelength, 13.4 GHz) began with the NASA scatterometer $NSACT$ aboard the Advanced Earth Observation Satellite (ADEOS-I) in 1996 (Bartsch 2010; Rawlins et al. 2005). Scatterometers are real-aperture radars (RAR) which measure the Radar backscatter coefficient quantitatively and are used for climate research studies, especially in the polar regions (Ulaby and Long 2017).

Because the ADEOS-I operating mission ended unforeseen in 1997, the QuikSCAT satellite

Parameter	Inner beam	Outer beam
Incidence Angle [°]	46	54
Polarization	HH	VV
Frequency [GHz]	13.4	13.4
Swath [km]	1400	1800

Table 3.1: Parameters of the SeaWinds scatterometer for inner and outer beam.

was its follow-up with the same kind of scatterometer onboard. Data collected by scatterometers are of highly use for hydrological modeling (Bartsch, Kidd, et al. 2007), and particularly the Ku-band is able to detect snow cover freeze and thaw dynamics (Kimball et al. 2004). Because of its sensitivity to changes in the dielectric properties of the scanned area (Kimball et al. 2004), the Ku-band is very effective to detect ice and snow facies in the top few meters (Drinkwater, Long, and Bingham 2001). Due to the short wavelength of the Ku-band the scatterometer is highly sensitive to snow wetness (Hall et al. 2009). When the amount of the backscatter coefficient changes, a transformation of the snow layer which results in a modification of the scattering behaviour can be noticed (Bartsch, Kidd, et al. 2007). The change from volume scattering to surface scattering can affect the backscattered signal up to 6 dB (Bartsch, Kidd, et al. 2007). Due to Drinkwater, Long, and Bingham (2001), the Ku-band provides a good balance between the penetration and the snow grain scattering, when expecting a polar snowpack having mean grain radii of approximately 0.5 mm. The QuikSCAT satellite was operating from June 1999 till November 2009 and had a polar, sun-synchronous orbit. The satellite provides a daily coverage of the Earth of 90% with four measurements at 55°N and up to ten measurements for the region towards 75°N (Bartsch, Kidd, et al. 2007). This high temporal resolution is achieved by the fast circumnavigation (of the earth) each 101 minutes and is a big advantage for the study to detect short thawing periods. At an altitude of 803 km, the rotating, conically pencil-beam antenna collects backscatter measurements at two constant incidence angles, the inner beam at 46° and the outer beam at 54° (Bartsch 2010; Huddleston and Spencer 2001). This dual spot beam scatterometer has two polarization modes. The inner beam permanently operates at horizontal (HH), covered a swath of 1400 km, and the outer beam permanently at vertical (VV) polarization, covered a swath of 1800 km (Drinkwater, Long, and Bingham 2001). The SeaWinds scatterometers is a non-imaging Radars with a dual-rotating beam (Bartsch 2010; Ulaby and Long 2017) which has a scanning dish antenna that operated at 13.4 GHz (2.1 cm wavelength). The collected data needed to be preprocessed to be able to work with it further on, "the scatterometer image reconstruction (SIR) resolution enhancement algorithm [is one way] to generate images of the surface backscatter characteristics" (Drinkwater, Long, and Bingham 2001, p. 3). The SIR algorithm from the Brigham Young University (BYU) Microwave Earth Remote Sensing (MERS) Laboratory uses a combination of multiple passes to extract information for resolution improvement. In the end, there are two backscatter products which differ in size and shape (Hall et al. 2009). The resulting SIR images are either of the *egg* or of the *slice* format. Each footprint is given by eight 'slices' with eight corresponding backscatter coefficients. When the eight slices are combined the result is called 'egg'. The spatial resolution for the slice data is approximately 6 x 25 km and for the egg data 37 x 25 km (Rawlins et al. 2005). Albeit the 'egg' data has a lower resolution than the 'slice' data, it is less sensitive to calibration errors (Bhattacharya et al. 2009; Long and Hicks 2005; Wang, Derksen, and Brown 2008). The technical specifications of the data products can be found in Long and Hicks (2005).

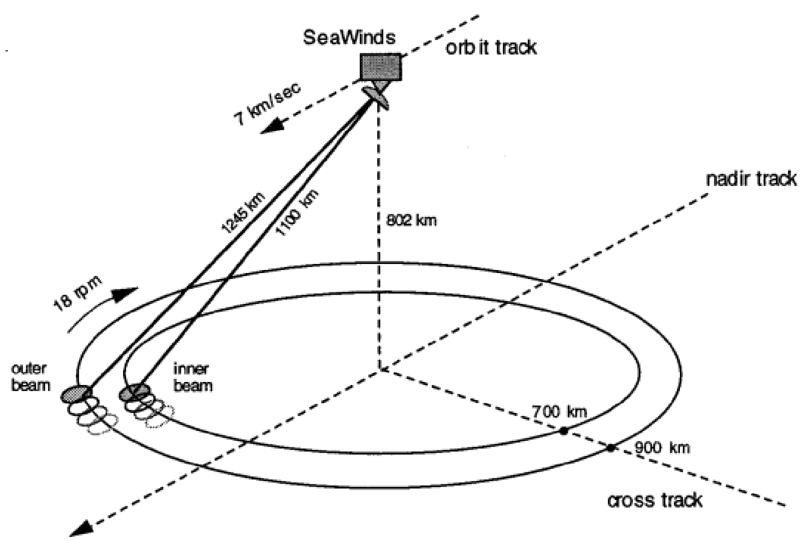


Figure 3.1: SeaWinds measurement geometry (source: Long and Spencer 2000).

In this work however, the QuikSCAT data was preprocessed by the TUW (Vienna University of Technology) model. The backscatter was regridded into 10 x 10 km rectangular cells using a 12.5 km large search radius (Bartsch, Kidd, et al. 2007). In case for the QuikSCAT data "the sampling characteristics over one grid point change substantially from acquisition to acquisition, both in terms of the number and distribution of the measurements and the respective azimuthal viewing directions. The number of measurements is highest when the grid point is close to the edge of the satellite swath and lowest close to the sub-satellite track" (Bartsch, Kidd, et al. 2007, p. 4). A visualization of the TUW assignment is shown in Figure 3.2.

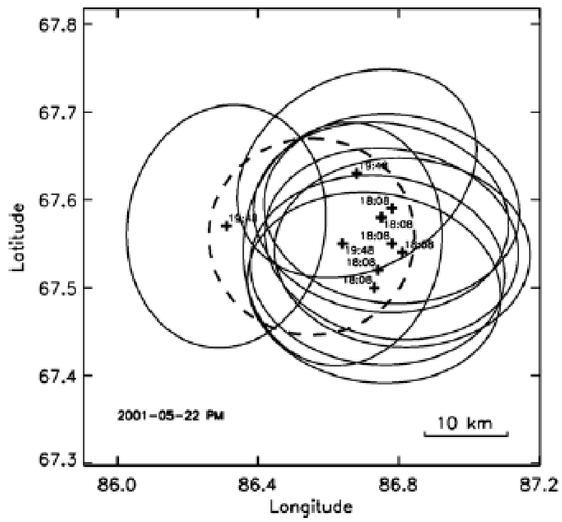


Figure 3.2: Distribution of footprints and their time-stamp. For each grid point the search area (delimited by dashed circular lines, radius 12.5 km) backscatter response from the SeaWinds antenna inner beam is averaged. For the evening measurements of 22nd of May: The grid point falls at the periphery of the scatterometer swath, resulting in numerous footprints with similar azimuthal orientation. Three footprints are registered one orbit later and this have a different orientation (source: Bartsch, Kidd, et al. 2007).

The dashed circular line has a radius of 12.5 km and represents the search area for each grid point. The spatial resolution of the scatterometer is 25 x 25 km and the relative accuracy of the backscatter measurements is 0.25 dB (Kimball et al. 2004; Rawlins et al. 2005).

3.2 Auxiliary data

3.2.1 The Greenland Climate Network

In this work, in-situ data is used from the Greenland Climate Network (GC-Net), which consists of 18 automatic weather stations (AWS) which are allocated all along the ice shield of Greenland (Steffen and Box 2001) as seen in Figure 2.2. The stations are conducted by the Cooperative Institute for Research in Environments Science (CIRES) and are equipped with several instruments. The AWS measure hourly, daily, or annual and interannual changes the accumulation rate, the surface energy and its climatology. After Nghiem, Steffen, et al. 2005 each AWS is able to detect changes in surface height with high temporal resolution, radiation balance as well as air temperature (at 2 m height) and snow temperature (at 10 different levels), humidity and wind velocity and wind direction (at 2 m height). The battery is placed below the station in the snow which is charged due to solar panels on top of the station. Unfortunately, sometimes there are losses, like Summit for the year 2008. The details of the AWS are given in Table 3.2.

Name	**Latitude**	**Longitude**	**Elevation [m]**	**Start Year**
Swiss Camp	69°35'53"N	49°16'51"W	1176	1990
Crawford Point 1	69°52'42"N	46°59'48"W	2022	1995
NASA-U	73°50'29"N	49°30'25"W	2334	1995
GITS	77°08'16"N	61°02'24"W	1869	1995
Humboldt	78°31'36"N	56°49'50"W	1995	1995
Summit	72°34'46"N	38°30'19"W	3199	1996
Tunu-N	78°00'59"N	33°50'00"W	2052	1996
DYE-2	66°28'50"N	49°16'59"W	2099	1996
JAR 1	69°29'42"N	49°42'14"W	932	1996
Saddle	65°59'59"N	44°30'06"W	2467	1997
South Dome	63°08'56"N	44°49'02"W	2901	1997
NASA-E	75°00'02"N	29°59'50"W	2614	1997
NASA-SE	66°28'30"N	42°29'55"W	2373	1998
JAR 2	69°24'53"N	50°05'34"W	507	1999
Petermann Gl.	80°41'01"N	60°17'35"W	37	2002
Petermann ELA	80°04'59"N	58°04'22"W	965	2003

Table 3.2: List of automatic weather stations on Greenland with their latitude, longitude, elevation, and the starting year of recording data (source: GC-Net CIRES). For location of stations see Fig. 2.2.

For more information of the data products please have a look at GC-Net CIRES.

In this work only the temperature data was used. The requested data was for the time from the year 2000 till 2008. For the temperature data the maximum for each day was calculated.

3.2.2 Circumpolar Arctic Region Bioclimate Subzones Map

The Circumpolar Arctic Vegetation Map (CAVM) at a scale of 1:7 500 000 was the first vegetation map of a global biome. The basis for the map was delivered by an Advanced Very-High Resolution Radiometer (AVHRR) by the US Geological Survey (USGS) Alaska Geographical Science Office, which provided high-resolution false color-infrared images of the circumpolar region (Walker et al. 2002). The image is represented by pixels with a resolution of 1 km x 1 km. For each pixel the highest value of the Normalized Difference Vegetation Index (NDVI) was used (Walker et al. 2002). For the calculation of the NDVI, the time period from April to October for the years 1993 and 1995 was considered, because "these periods cover the vegetation green-up-to-senescence period during two relatively warm years when summer-snow cover was at minimum in the Arctic" (Walker et al. 2002, p. 2). The southern border of the vegetation map was aligned to the tree line, while the approach for the CAVM is resting upon visual photo-interpretation of the AVHRR images (Walker et al. 2002). Because there was no predecessor for this kind of map, the information about the vegetation was gathered from plant communities and experts (Walker et al. 2002). Walker divides the bioclimatic zonation as shown in Figure 3.3 in six areas, which are characterized as follows.

> The *Zone A*, also known as herb zone, includes mostly fog-shrouded islands but also coastal fringe of the northernmost Greenland. The temperatures in summer are near freezing point and the area shows permanent ice covers over large areas of land. Sedges are rare and plants are confined between hummocks. *Zone B*, the prostrate dwarf-shrub zone, is found in the much of the Peary Land in Greenland. This zone has scattered creeping dwarf shrubs on zonal soils with a mean July temperature of approximately 5°C. The hemiprostrate dwarf-shrub zone, *Zone C*, is among others located at the west coast of Greenland and has a mean July temperature of 7°C. *Zone D*, the erect dwarf-shrub subzone covers most of the southern Greenland. The mean temperature in July is 9°C and the area is generally covered by vascular plants. *Zone E* is the warmest part of the Arctic Tundra Zone with the mean temperature in July of 10-12°C and a vegetation dominated by low shrubs.

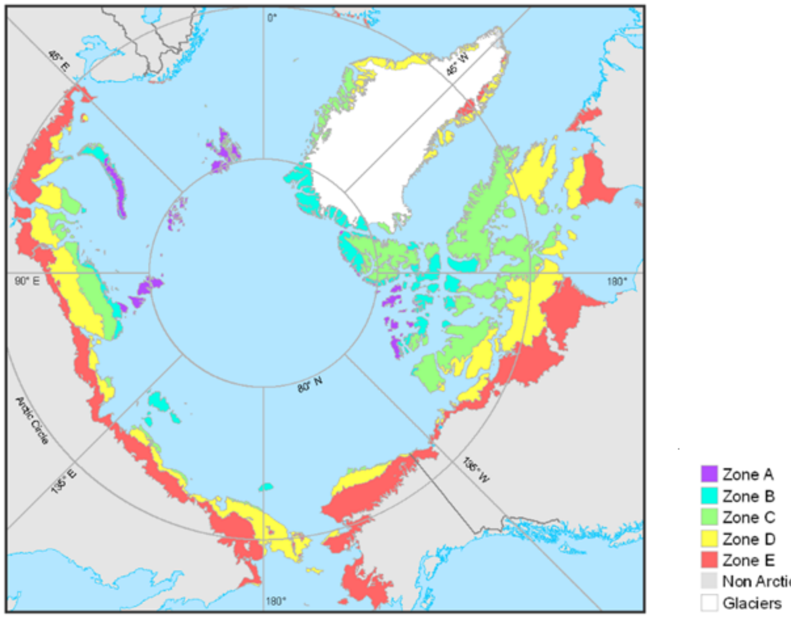


Figure 3.3: The Circumpolar Arctic Region Bioclimate Subzones Map illustrates the occurrence of the different zones in the north polar regions (Zone A: mean July temp: 0-3°C, dominant plants: cushion forbs; Zone B: mean July temp: 3-5°C, dominant plants: prostrate dwarf shrubs; Zone C: mean July temp: 5-7°C, dominant plants: sedges; Zone D: mean July temp: 7-9°C, dominant plants: erect dwarf shrubs; Zone E: mean July temp: 9-12°C, dominant plants: tussock sedges (source: Alaska Geobotany Center).

By connecting the data of the bioclimate zones with the backscatter data from QuikSCAT, for each grid point it was possible to retrieve the associated zone. This was necessary to distinguish between points which were situated on the ice shield and which were not.

3.2.3 GETASSE30 Digital Elevation Model

The Global Earth Topography And Sea Surface Elevation (GETASSE) is a composite of a Digital Elevation Models (DEMs) with a resolution of 30 arc seconds. "It is using the SRTM30 dataset, the Altimeter Corrected Elevations (ACE) dataset, Mean Sea Surface (MSS) data and the EGM96 ellipsoid as sources. The resulting GETASSE30 dataset represents the Earth Topography And Sea Surface Elevation with respect to the WGS84 ellipsoid" (Riazanoff et al. 2005, p. 62). The GETASSE30DEM was used to create contour lines for Greenland to receive an impression of the topography and the surface of the study area.

3.2.4 National Oceanic and Atmospheric Administration precipitation data

Because the automatic weather stations did not deliver data for precipitation, the information was obtained by the National Oceanic and Atmospheric Administration (NOAA). This organization provides free access to global historical weather and climate data. The stations which were used for the precipitation data are shown in Table 3.3.

Name	**Latitude [DD]**	**Longitude [DD]**	**Elevation [m]**
Narsarsuaq	61,1667°	-45,4167°	27
Thule	76,5166°	-63,8333°	77
Sondrestrom	67,0166°	-50,8°	50
Ittoqqortoormiit	70,4831°	-21,95°	70
Prins Christian	60,033°	-43,117°	19
Station Nord	81,6°	-16,6497°	36
Aasiaat	68,7°	-52,85°	41
Nuuk	64,1667°	-51,75°	80
Tasiilaq	65,5997°	-37,6331°	50
Danmarkshavn	76,77°	-18,67°	12
Paamiut	62,0167°	-49,6667°	36

Table 3.3: List of the used NOAA precipitation stations with information about latitude, longitude, and elevation (source: NOAA). For location of stations see Fig. 2.2.

Chapter 4

Methodology

Previous methods have shown that the use of scatterometer data, especially in the Ku-band, are highly applicable to determine information about snow and ice transformations (Bartsch 2010; Hall et al. 2009; Nghiem and Tsai 2001). Thermal conditions of snow influence the snow wetness, which affect the microwave backscatter behaviour (Nghiem and Tsai 2001), because "in wet snow, liquid water has an imaginary part of about 38 ε_0, [and] is approximately 19,000 times larger than that of nonmelting ice" (Hall et al. 2009, p. 2). In case of snow melt, the backscatter coefficient σ^0 rapidly decreases due to the melting snow surface which acts like a water surface causing specular reflection (Bartsch 2010; Kidd, Bartsch, and Wagner 2005; Semmens et al. 2013; Rawlins et al. 2005).

In this work, the detection of snow melt events during winter (November-March) was investigated with different approaches for sensitivity analysis with varying thresholds applicable to temporal analysis. One aspect was to examine the effect of noise on the amount and appearance of the detected events. The different approaches of sensitivity analysis are either based on a constant threshold or on an adaptive one. Bartsch (2010) already distinguished between different forms of land cover types and their influence on the backscatter coefficient σ^0. It has been pointed out that the noise effect has only been considered for spring snow melt, but not for rain on snow events, which is an interesting aspect also for winter thaw on glaciers.

4.1 Noise

In literature, the noise term of the QuikSCAT scatterometer often is considered with just one constant value of threshold (Bartsch, Kidd, et al. 2007; Bartsch 2010; Nghiem, Steffen, et al. 2005;

Semmens et al. 2013). The following equations based on Wagner (2010) and Bartsch, Kidd, et al. (2007) give an overview how noise n_σ, respectively its standard deviation s_σ, can be obtained. Each backscatter measurement σ^0 is a sum of the 'true' physical value σ_t^0 of the grid point and a noise term n_σ which accounted instrument noise, speckle and azimuthal effects as well as irregular sampling.

$$\sigma^0 = \sigma_t^0 + n_\sigma \tag{4.1}$$

As an assumption the noise of σ^0 is normally distributed in the logarithmic way with its standard deviation s_σ. An estimation of s_σ, which is based on QuikSCAT observations, can be made with the usage of multiple backscatter measurements within one overpass.

$$\vartheta = \sigma_i^0 - \sigma_j^0 = (\sigma_t^0 + n_\sigma) - (\sigma_t^0 - n_\sigma) = n_\sigma - n_\sigma \tag{4.2}$$

The variance s_ϑ^2 of ϑ is

$$s_\vartheta^2 = 2s_\sigma^2 \tag{4.3}$$

from which follows the standard deviation with

$$s_\sigma = \frac{s_\vartheta}{\sqrt{2}} \tag{4.4}$$

Usually the principle of the 3σ-rule is taken to calculate a static threshold (after Bartsch, Kidd, et al. (2007) and Kidd, Bartsch, and Wagner (2005). The 3σ-rule is a way to analyze data and implies that if the data has a normal, Gaussian distribution, around 99% of the data lies within the three-times standard deviation 3σ.

$$\Delta\sigma^0 - 3\sigma_\Delta > 0dB \tag{4.5}$$

4.2 Work flow

Figure 4.1 gives an overview of the different steps to obtain the results for the different approaches. The backscatter data was merged to one big file and clipped to land covered area. After calculating the daily mean of the backscatter coefficient σ^0, the first distinction between the approaches was to use either a three-day moving window or the difference between two consecutive days. Within these two approaches another distinction was made due to the threshold that needed to be exceeded by sigma zero. This results in four approaches which further were investigated.

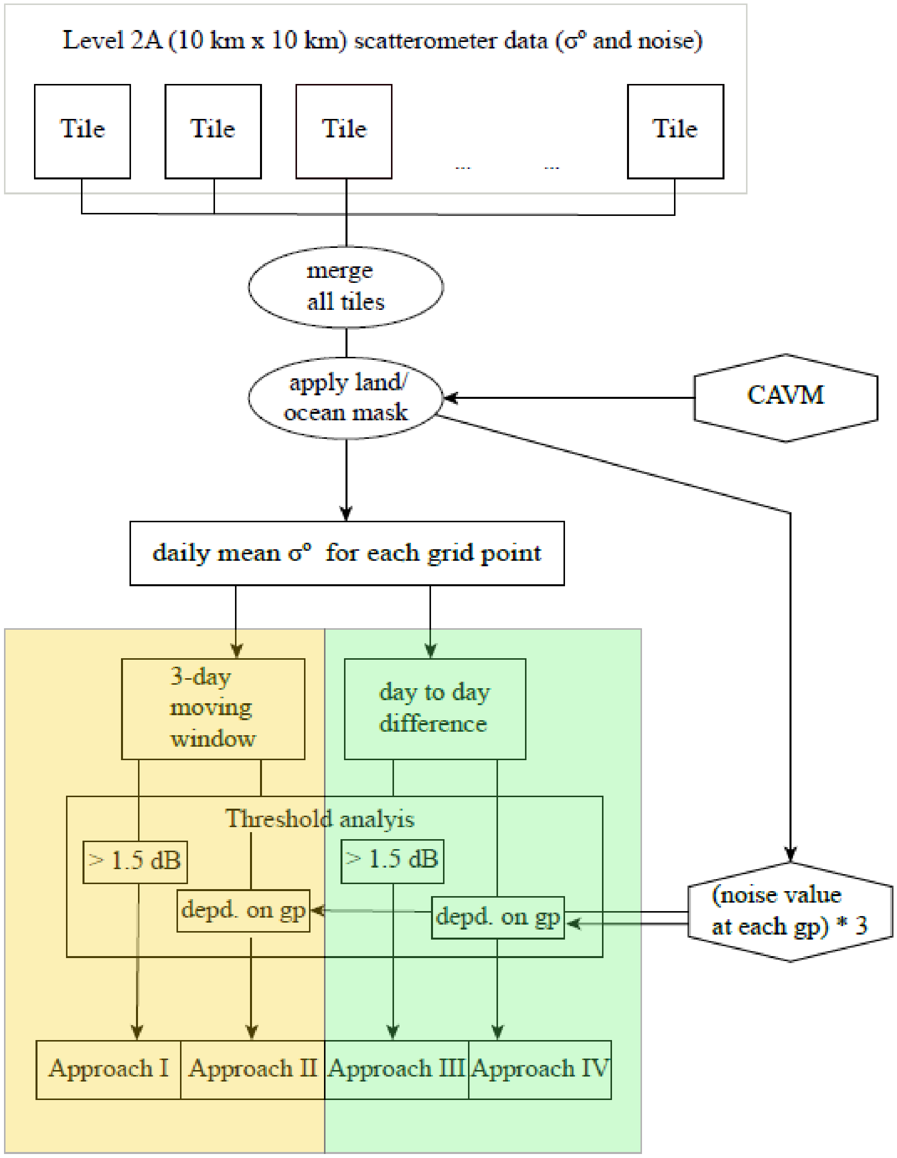


Figure 4.1: Work flow of the processed backscatter data from starting with separate tiles to merge them and applying the land/ocean mask by using the CAVM outlines. When calculated the daily mean of σ^0 for each grid point both two approaches investigated the data either over a three-day moving window or with the difference of consecutive days. Within these approaches σ^0 needed to exceed either a constant noise-threshold of 1.5 dB or a location dependent calculated noise-threshold for each grid point. The four results are named approach I, approach II, approach III, and approach IV.

4.3 Time series analysis

For this work, the inner beam data of the scatterometer was used which operated at a constant incidence angle of 46° and was horizontal like-polarized (HH). The data was provided by the Jet Propulsion Laboratory (JPL) as a Level 2A product and represents the backscatter measurements as an elliptical antenna footprint area (Bartsch, Kidd, et al. 2007). After this methodology, "the backscatter data are extracted and reformed into time series that are allocated to unique, regular, grid points, with a 10 km by 10 km grid spacing using a 12.5 km large search radius" (Bartsch, Kidd, et al. 2007). Greenland is covered by 44 tiles of the scatterometer data, but due to lack of time, in this work two tiles were not processed and therefore not included (tile 3132 and tile 3232, marked with a brown rectangle in Fig. 4.2).

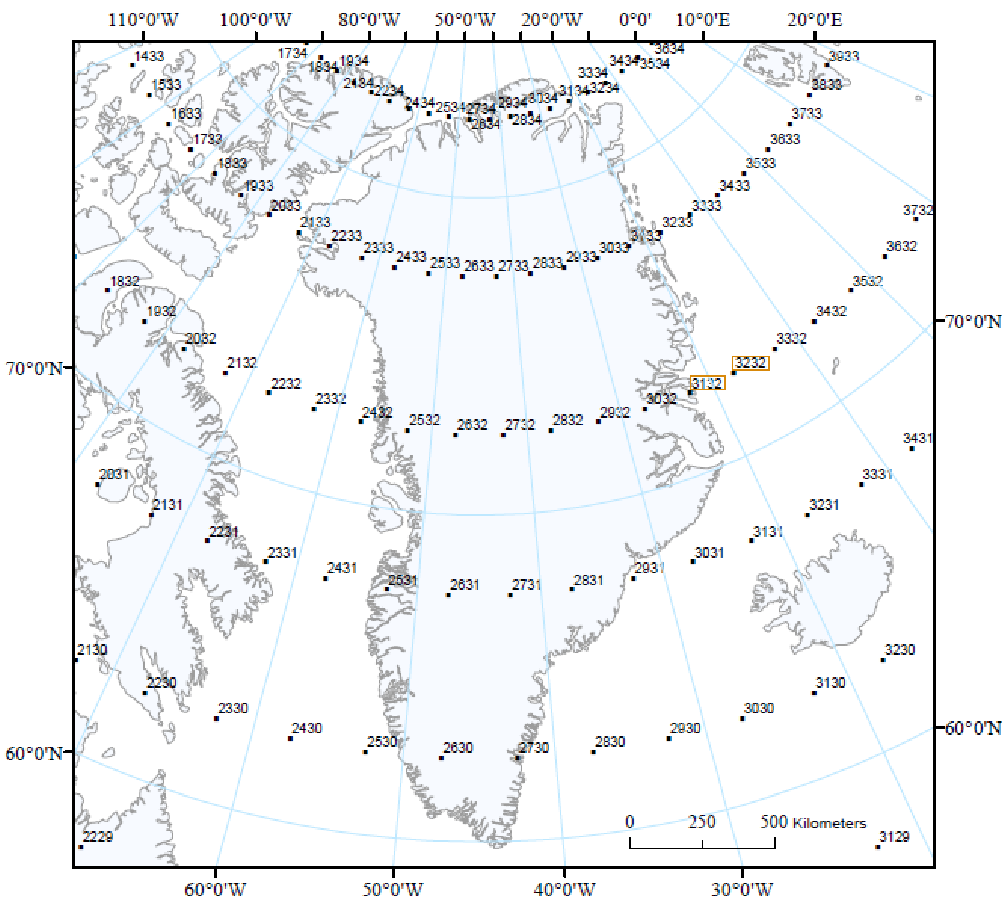


Figure 4.2: Greenland covered by tiles with the missing tiles marked with a brown rectangle (source country lines: World Countries (Generalized) by ESRI), projection: NSIDC Sea Ice Polar Stereographic North.

First of all, the data was transformed into a comma-separated values (csv) format. With the programming language Python and its library package Pandas, the huge amount of data was processed. For each grid point, backscatter values as well as corresponding noise values have been available. The amount of backscatter measurements for each grid point can be more than 20 measurements per day, whereas there was just one noise value belonging to each grid point. In this study, no distinction was made between to the collection time of the data in case of day and night, so for the further algorithms the daily mean backscattered amount for each grid point was calculated and used.

In course of this study, four different approaches were developed to investigate thaw events during winter. For each grid point the daily mean backscatter coefficient σ^0 was calculated. The algorithm needed to be able to calculate the mean for each day, although the backscatter measurements not always were from the same amount. This required the consideration of the date the measurements were taken to be able to calculate the mean of it. In the *first approach* a constant threshold of 1.5 dB was set that needed to be exceeded by the σ^0 value. A moving window algorithm over three days was used. With this three-day moving window approach based on Bartsch (2010), the average of three days before and three days after an event were considered. The difference of the three-days-before-average and the three-days-after-average needed to be of a higher amount than the defined threshold of 1.5 dB. If so, the day was marked as a melt event. The threshold of 1.5 dB "equals approximately three times the typical estimated standard deviation of noise s_σ" (Bartsch 2010, p. 8). This *first approach* was build upon the approach from Bartsch (2010) who investigated snow melt products i.a. from the QuikSCAT satellite utilizing long-term noise for snowmelt applications in high latitudes (>60°N). This can be seen as the 'original' one on which the further approaches are based on. The *second approach* also used the three-day moving window step but as a threshold not a constant quantity was used that needed to be out valued, but an accordingly adjusted threshold for each grid point which is based on the related noise signal. The noise signal was multiplied three times as suggested in Bartsch (2010) and if the σ^0 is higher a melt event was detected. Because the noise effects for the QuikSCAT backscatter signal which were caused by the satellite's instrument due to land cover heterogeneity, azimuth effects, and irregular sampling are generally of minimal amount (Bartsch, Kidd, et al. 2007; Semmens et al. 2013), this approach was thought of being more sensitive and provided better adapted change detection of backscatter values. Noise is usually reduced when averaging the backscatter value over several days, but still needs to be examined. Table 4.1 gives an overview of the estimated standard deviation of noise s_σ

depending on land cover after Bartsch (2010) in [dB].

GlobCover class	**Min**	**Max**	**Mean**
mixed broad leaved and needleaved forest	0.45	0.97	0.50
needle leave deciduous or evergreen forest	0.45	1.17	0.49
sparse vegetation (less than 15%)	0.46	1.66	0.59
water	0.48	2.46	1.98
permanent snow and ice	0.48	2.20	0.87

Table 4.1: Minimum, maximum and mean of estimated standard deviation of noise s_σ for the predominant major land cover classes (source: Bartsch 2010).

As an alternative access, the *third approach* and the *fourth approach* both were not based on the moving window average but instead used the difference between two consecutive days. In the *third approach* a constant threshold of again 1.5 dB was defined and the *fourth approach* utilized the strategy from the second approach, where σ^0 needed to exceed the amount of three times the noise value belonging to each grid point. Table 4.2 summarizes the diverse parameters which were used in the different approaches.

	Threshold [dB]	**Time Period**
Approach I	1.5	moving window over 3 days
Approach II	three times location specific noise	moving window over 3 days
Approach III	1.5	difference to the next day
Approach IV	three times location specific noise	difference to the next day

Table 4.2: Parameters of the different approaches with their used time period and chosen threshold of noise.

4.4 Post processing for event detection

As an interim result, the four algorithms presented four separate files which contained for each grid point the detected melt events with the corresponding date. On these four files the further investigations were based on.

One way to deal with the data was to filter the grid points. For each grid point the frequency was calculate. By grouping the data depending on the grid point number and counting the amount of recorded events, the commonness of occurrence for each point was found. Figure 5.4 shows the result for the frequency of each grid point for the time frame of 2000 to 2008. Figure 5.5 illustrates the amount of events for each grid point in one averaged year.

Another way to investigate the four results was to filter by date. Thus, for each day of event the amount of affected grid points was calculated. Based on these results, for each approach the date and its spatial extents could be found and compared (e.g. Tab. 5.4).

4.5 Pre-processing of auxiliary data

4.5.1 Temperature data

The temperature data which was used from the Automatic Weather Stations (AWS) from the Greenland Climate Network (GC-Net) first needed to be transferred from Julian Date format to Gregorian Date. Based on the date it was possible to calculate the maximum temperature for each day. In this work, the temperature data from the sensor TC Air 2 H Air Temperature in [degC] was used. Unfortunately there are sometimes gaps in the measurements, for example at station Swiss Camp there were gaps with data missing e.g. from March 24th, 2004 until September 5th, 2004 or from July 31st, 2005 until May 12th, 2006. In this case, there is no in-situ data available for validation of the results of the change detection algorithms. In total there are 16 stations from which the temperature data was used. The location of the AWS can be seen in Figure 2.2 and the specific location coordinates were summarized in Table 3.2.

4.5.2 Bioclimate Subzones

The circumpolar data for bioclimate subzones were downloaded from the webpage of the *Alaska Geobotany Center* as shapefile loaded into ArcMap. By converting the shapefile into a raster it was possible to do further calculations of how much area was affected by melt events. With the already defined zones (as seen in the legend of the map of Fig. 2.2) requests were made via SQL statements, so the algorithm results were investigated with this CAVM data to see in which zones melt events took place.

4.5.3 Precipitation data

The precipitation data from the NOAA was already delivered in Gregorian date format as well as calculated in [mm] for each day. The stations which were used on Greenland were also visualized in Figure 2.2 and the concrete information of the coordinates were given in Table 3.3.

4.5.4 Validation

For investigations of the results which were obtained by the four different algorithms, the temperature data and the precipitation data was examined.

Melt events change the composition of snow layers when increasing the amount of liquid water content. These changes can be seen in the backscatter coefficient behaviour (Fig. 5.7). The general acceptance is that snow melt is induced by warmer temperatures, at least temperatures above 0°C. For clarifying whether the temperature was a pivotal factor, the grid points that were located closest to the AWS were investigated. But only three out of sixteen stations directly experienced thaw events. The stations with melt events were Swiss Camp, JAR 1, and JAR 2. All three stations are located on the northwestern side upon the glacier (Fig. 4.3).

For investigating the NOAA stations (Tab. 3.3) and the recorded amount of precipitation, each station was examined due to the appearance of precipitation on grid points which were detected for melt events. Again as done for the AWS, the closest grid point was investigated. Eleven stations were used, however five of them did not have a melt event. The remaining six stations are listed in Tab. 5.6. All stations are located along the coastal line all around Greenland (Fig. 4.3). Referring to Cappelen (2013), the amount of precipitation in the south of Greenland is large. In this area the station Narsarsuaq is located. In winter precipitation is mostly in form of snow, but also rain can be possible. The stations Paamiut and Sondrestrom are in the southwestern area, which also experiences larger amounts of precipitations. Even during winter when wind from the south combined with a Foehn effect brings up the temperature liquid precipitation can occur. The station Aasiaat lies in the northwestern area but close to the border to the southwest. For this station the precipitation is also expected to be of a higher amount. Tasiilaq in the southeast is strongly affected by cyclones around Iceland. Although the amount of precipitation is usually rare, due to winds from the north or the south it is possible to have liquid precipitation even in winter. Unfortunately, the recorded data had gaps. Sometimes there was no data recorded over months. Moreover, the data of precipitation did not distinguish between rain and snow. This aggravates the conclusion that the detected precipitation is in form of rain and that the detected events are rain-on-snow events.

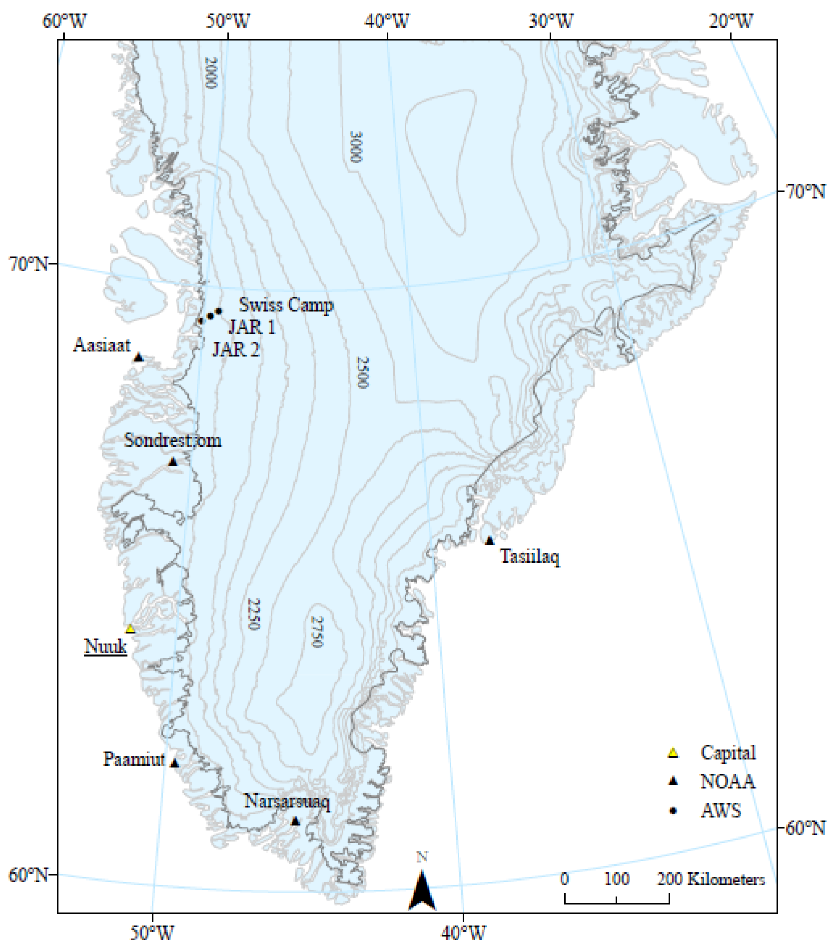


Figure 4.3: Locations of the stations of the AWS (•) and NOAA (△) which experienced melt events (source contour lines: derivated from GETASSE30; source country lines: World Countries (Generalized) by ESRI), projection: NSIDC Sea Ice Polar Stereographic North. For information about latitude, longitude, and elevation of stations see Tab. 3.2 for AWS and Tab. 3.3 for NOAA.

Chapter 5

Results and Discussion

5.1 Daily average backscatter

The common approach for investigating snow melt is to examine the backscatter coefficient. Backscatter drops with inreasing amount of water content in snow layer which can be an indicator for temperature above zero degrees. Looking closer at specific grid points with their observed backscatter radiation different behaviour was noticeable. Depending on the location and the height, diverse backscatter patterns can be found. Grid points on lower, unglaciated area along the coastal line had more variations in backscattered radiation over the year than points on higher, glaciated areas. Figure 5.1 illustrates the backscatter behaviour at four different grid points during the year of 2005. The year of 2005 revealed the melt event with the highest amount of affected grid points. For all four approaches (Tab. 4.2) the thaw event in late November 2005 had the spatially largest extent.

Figure 5.1 shows the backscatter coefficient at four different grid points during 2005. The behaviour of σ^0 differed greatly for each grid point. The lowest point was at a height of 58 m in the Northwest region. The following three points are lined in a row (Fig. 5.2). The first point was located on non glaciated area whereas the three others were on Greenland's ice shield. Moving from the lowest point to the highest, the different grid points were at a height of 58 m, 860 m, 1220 m, and 1552 m. The blue record (Fig. 5.1) for the first point showed that the backscatter coefficient varied over the whole year. While during winter time staying between -8 db to -14 dB in summer backscatter dropped down to -13 dB to -16 dB. For the second grid point σ^0 in general is higher.

In winter it stayed around -6 dB to -9 dB except when some isolated melt appeared. Again, in summer the backscatter strongly decreased to -16 dB. The third, grey path showed less backscatter variations during winter than the two before, having usually a constant σ^0 of -6 dB. However, in summer it decreased rapidly down to -16 dB, in June even reached -19 dB. In August σ^0 already increased up to -10 dB and in September stabilized again at -6 dB. The biggest change however took place at the end of November when σ^0 fell from -5 dB to -15 dB within one day. Illustrated in yellow, the backscatter of the fourth grid point rarely changed during winter months. The amount of σ^0 was between -3 dB to -5 dB showing no bigger changes at all. Albeit, in late November one strong backscatter decrease was observable. Seen this immense drop before at the third grid point, again within one day σ^0 decreased for more than 7 dB from -4 dB to -11 dB. In addition, during summer the backscatter dropped to -12 dB to -18 dB, in July even reached -21 dB.

Even though the backscatter behaviour at each of these four grid points differed a lot, similarities were also found. Because of their location, some being closer to the coastal line than others or being at higher ground than others, the amount of backscattered radiation during winter months always differed immense compared to the amount of backscatter during summertime. Especially when closer to the sea, the backscatter coefficient is highly influenced by wind and weather conditions. This results in unstable, ongoing backscatter transitions but at the same time attenuates the range of σ^0 over the year. Going up the ice shield backscatter got calmer for winter months but with steep backscatter decrease during summer. Because there is no generally valid number that needed to be exceeded when searching for change detection within in the backscatter, the 3σ-rule was used (Bartsch 2010).

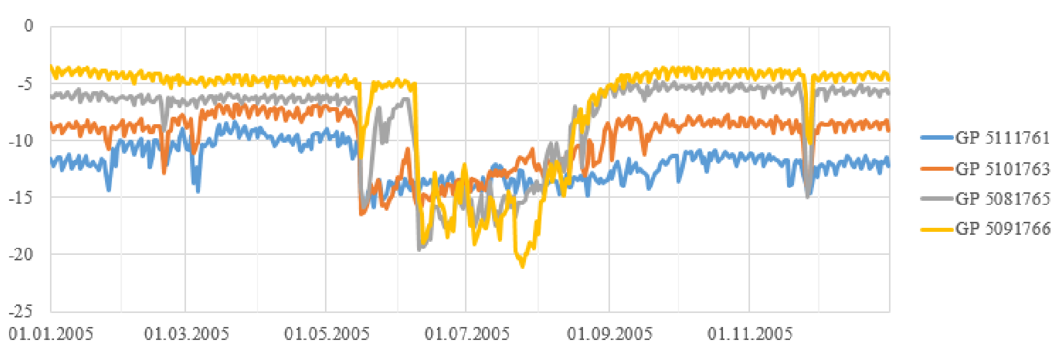


Figure 5.1: The backscatter coefficient at four different grid points for 2005: GP 5111761 at a height of 58 m, GP 5101763 at 860 m, GP 5081765 at 1220 m, and GP 5091766 at 1552 m. For location of the grid points see Fig. 5.2.

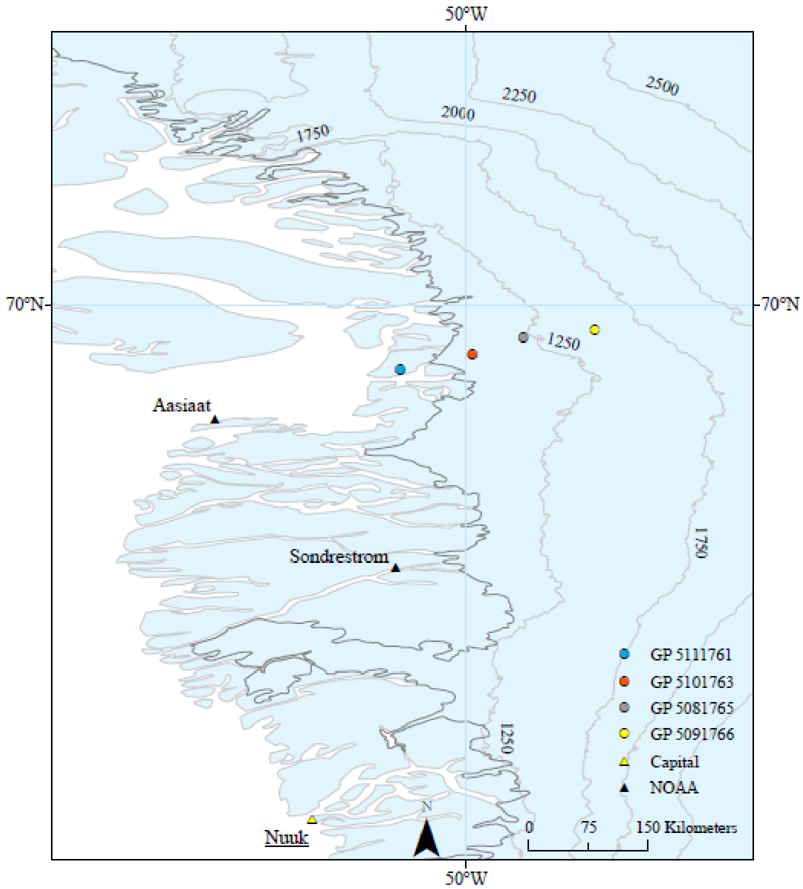


Figure 5.2: Location of the four grid points whose backscatter coefficient was investigated in Fig. 5.1 and the surrounding NOAA stations (Tab. 3.3) (source contour lines: derivated from GETASSE30; source country lines: World Countries (Generalized) by ESRI), projection: NSIDC Sea Ice Polar Stereographic North.

5.2 Sensitivity analysis of melt events

The amount of detected melt events was different for each approach. The threshold that needed to be exceeded in the *first approach* was set to a constant value of 1.5 dB. In the *second approach* each noise value was adjusted for each grid point. Both approaches were based on a three-day moving window. For the *third approach* the threshold was again a constant value of about 1.5 dB and in the *fourth approach* once again each noise value was calculated independently for each grid point, but both were working with the difference of σ^0 of two consecutive days.

The overall amount of detected thaw events were summarized in Tab. 5.1. Both approaches I and III which used a constant threshold of 1.5 dB captured more melt events compared to the approaches II and IV which took an individual, grid point based threshold.

	Detected melt events
Approach I	78 873
Approach II	28 173
Approach III	40 230
Approach IV	11 465

Table 5.1: Amount of all detected winter melt events of the different approaches (2000-2008).

The amount of affected grid points by melt events during winter months January-March and November-December for 2000-2008 were further investigated (Fig. 5.3). There was already made a distinction referred to the location of the grid points. With the bioclimate zones from the circumpolar arctic vegetation map it was possible to assign each grid point to a bioclimate area. Hence, a differentiation was executed to examine whether the grid points were located on the ice shield or not (Fig. 5.3).

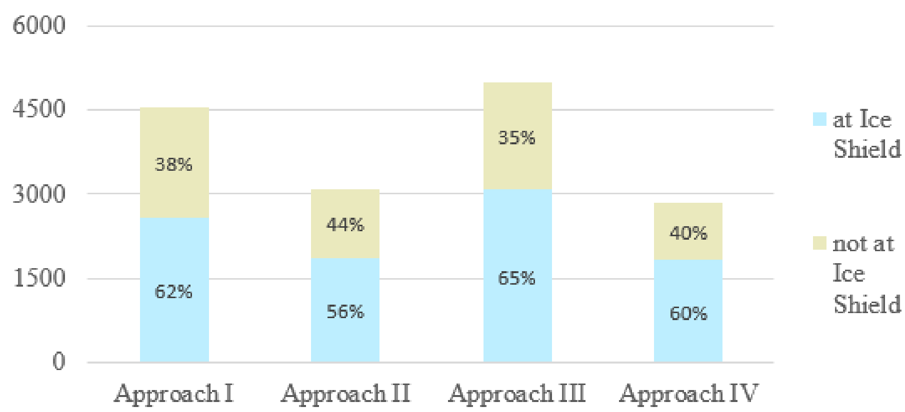


Figure 5.3: The amount of grid points which experienced winter melt events during the years of 2000 to 2008. For each approach a differentiation due to the location of the grid points were made with the circumpolar arctic vegetation map. The blue part contains the amount of affected grid points which lay on glaciers ground, the beige part contains the grid points which lay on unglaciated terrain.

The results indicated that the approaches with a predefined threshold detected considerably more melt events than the approaches with an adapted threshold. It also showed that more melt events are detected on the glacier's area than on not glaciated field (Tab. 5.2).

The visualization in Fig. 5.4 illustrated the frequency for each grid point of winter melt events between 2000-2008 with the outline of the Greenland ice sheet. The highest amount of melt events for one grid point were 171 events detected by the third approach. Nine classes with the same intervals were defined. The occurrence of thaw events showed a great coincidence with the prevailing wind directions (Fig. 2.3 and 2.4). For all approaches the highest frequency of melt events were found at the southwestern part (Fig. 2.2), which matches with the statement of Cappelen (2013) who characterized this region by mild winters especially at the coastal zone.

Another investigation was made by calculating the percentage of pixel with melt events. So far, the amount of affected grid points of melt events was higher at glaciated area compared to unglaciated area. However, regarding to the circumpolar arctic bioclimate map, Greenland is covered by 79.12% with glaciated and 20.88% with unglaciated area. The spatial distribution showed that much more area was affected by thaw events which was not covered by glacier than area along the ice shield. The first approach found over more than 50% of unglaciated area was

	Affected glaciated area	**Affected unglaciated area**
Approach I	4.7%	54.6%
Approach II	3.5%	33.9%
Approach III	5.7%	53.0%
Approach IV	3.4%	27.8%

Table 5.2: Percentage of affected area with melt events during winter months.

affected by thaw events, whereas it barely reached 5% on glacier. For all approaches the amount of affected unglaciated area was higher than of glaciated area (Tab. 5.2).

By dividing the results of the different approaches by nine years, Fig. 5.5 gives an overview of the average of melt events for each winter. The map key (Fig. 5.5(e)) shows that the highest amount of thaw events in one (averaged) year was 19 events. Again, this was detected in the third approach in the southwestern region.

One of the basic ideas behind the approaches was that the detection of thaw differs between unglaciated and glaciated areas. As seen in the visualization of the frequency for each grid point (Fig. 5.4), approach I and II barely found melt above 2000-2250 m. In contrast, approach III detected thaw events up to a height of 2500-2750 m. Also approach IV found few thaw events at that height, but not that many and not that contiguous as approach III.

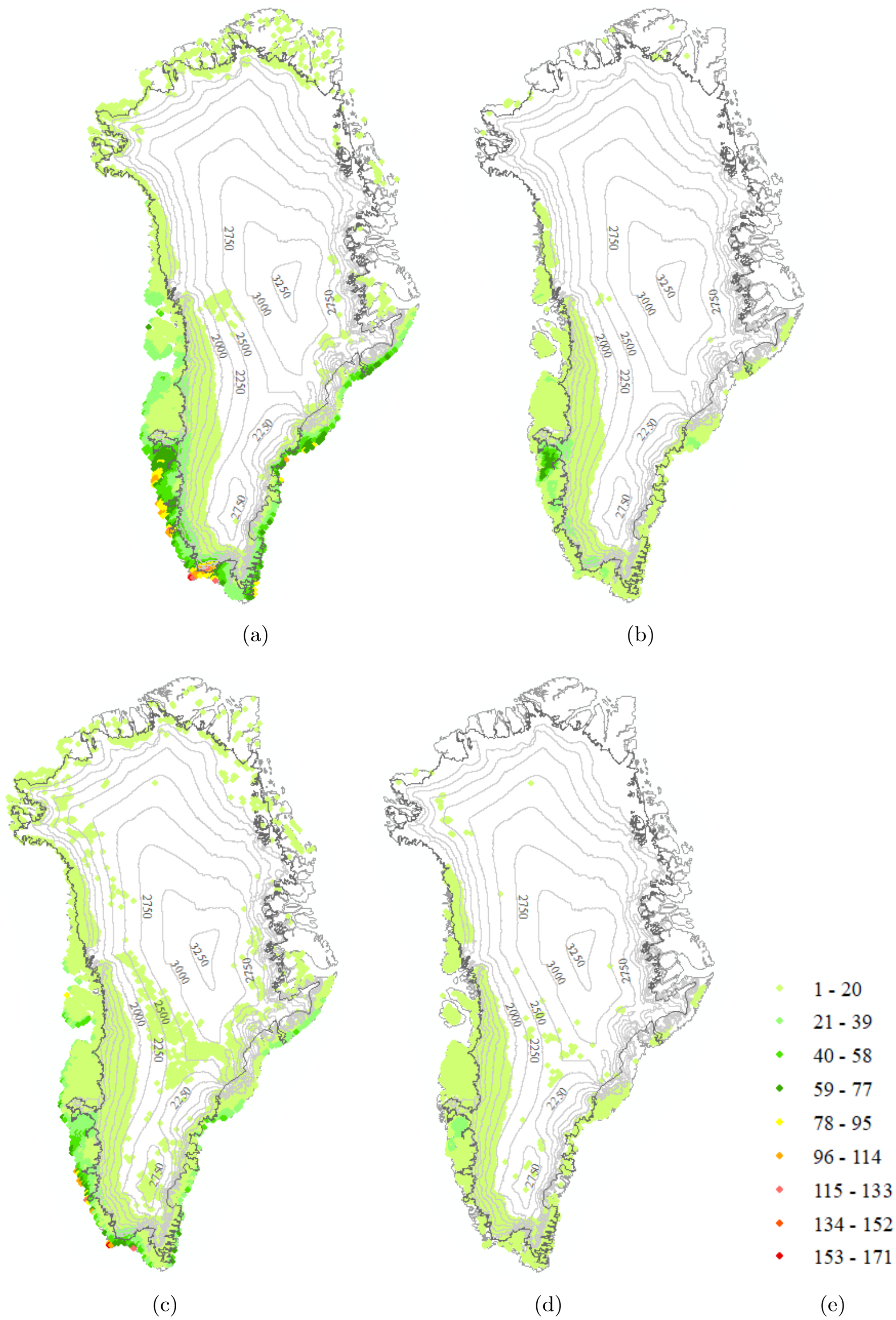


Figure 5.4: Frequency at each grid point: (a) frequency for approach I; (b) frequency for approach II; (c) frequency for approach III; (d) frequency for approach IV; (e) legend.

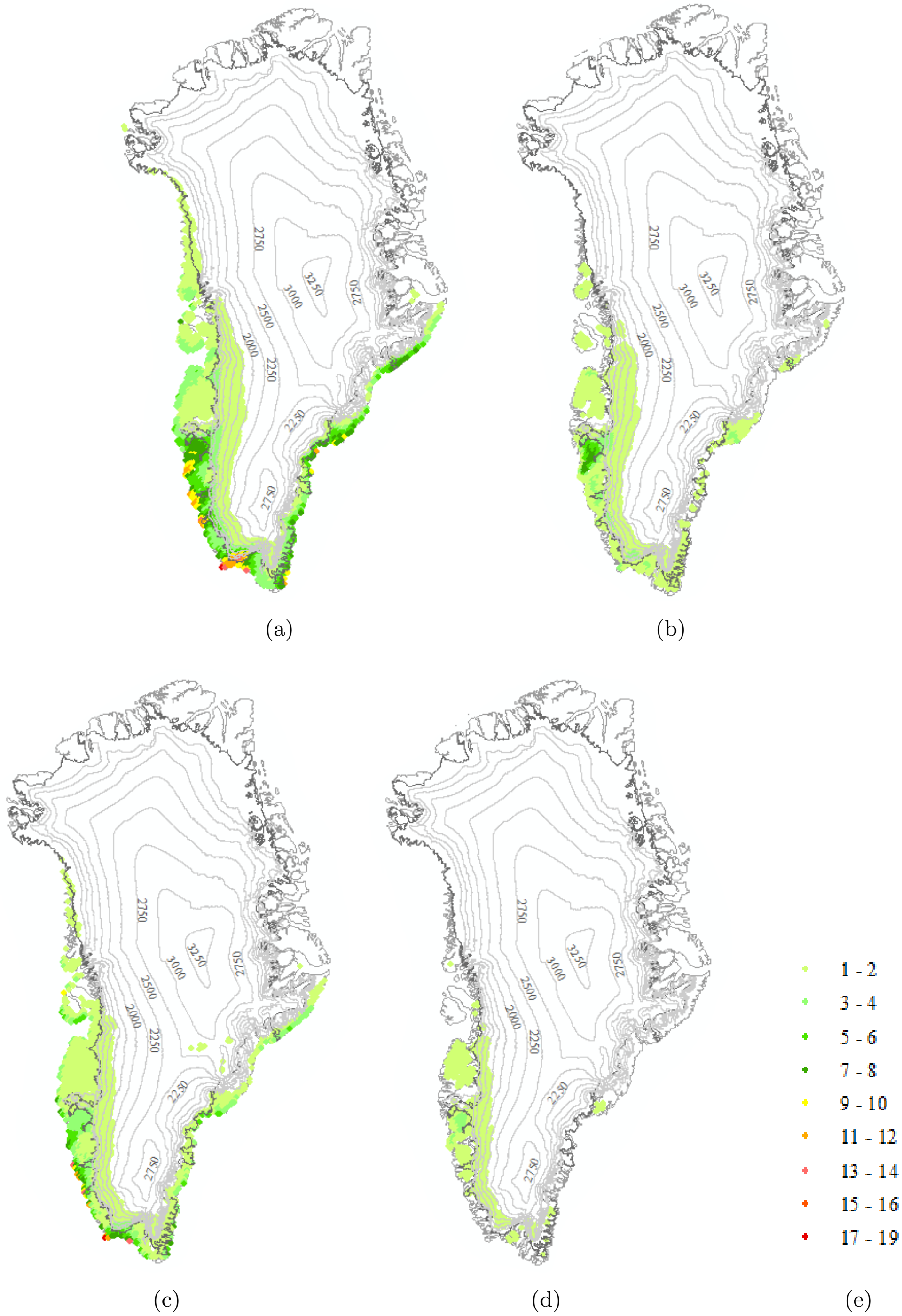


Figure 5.5: Average number of thaw-refreeze events for each winter (Nov–March) in Greenland from 2000 to 2008: (a) Approach I; (b) Approach II; (c) Approach III; (d) Approach IV; (e) legend.

5.3 Spatio-temporal analysis of melt events

As an overview of the affected grid points which experienced melt during the years 2000 to 2008, Figure 5.6 gives and overview for each approach. For all of them the highest amount of grid points with thaw events was the year of 2005.

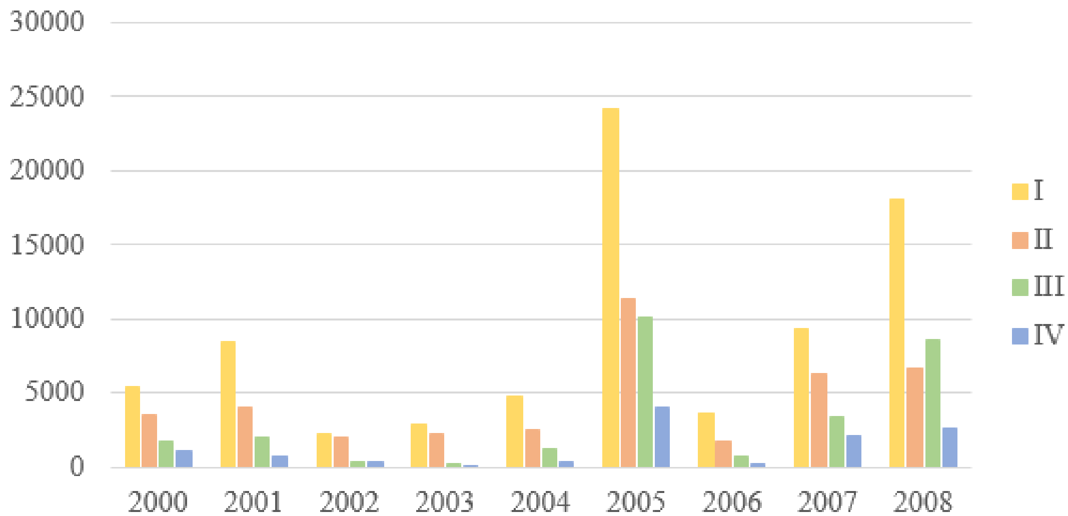


Figure 5.6: Affected grid points of melt events for each year during the time frame 2000-2008 for all approaches. The year of 2005 had the highest amount of grid points which experienced thaw events for all approaches.

By comparing the temporal results, the third approach which used the difference of two consecutive days that needed to be higher than the defined constant threshold of 1.5 dB detected the most days with melt events. It identified almost twice as much days with melt events compared to the first approach which were based on the three-day moving window (Tab. 5.3). Although the first approach detected more affected grid points when considering the spatial extent of melt events, the third approach noticed more days of thaw when considering the temporal aspect.

	Approach I	Approach II	Approach III	Approach IV
Approach I	**724**	237	645	144
Approach II	237	**241**	228	100
Approach III	645	228	**1116**	180
Approach IV	144	100	180	**181**

Table 5.3: The detected amount of days with melt event for each approach. The third approach found the most days with thaw events with 1116 days. Each detected day for each approach was compared with the other approaches to examine how many days are in common.

Observing the results for the first approach, the event with the greatest distribution was taken place on November 28th, 2005. Over 2221 grid points were affected. That was the highest amount of grid points involved in this work. The time of event also showed up in the second approach which involved 1549 grid points and was the second biggest melt event for that case. For the second approach the largest event was on November 2nd, 2008 with more than 1555 grid points. The third and the fourth approach both had the highest amount of affected grid points on November the 27th, 2005. This event in the last days of November 2005 was also one of the biggest melt appearance for all approaches (Tab. 5.4). By visualizing the spatial extent of this event the distribution shows differences in the allocation depending on the date (Fig. 5.8).

	11/26/2005	11/27/2005	11/28/2005	11/29/2005	11/30/2005
Approach I	36	1462	2221	2207	1646
Approach II	1	948	1549	1457	763
Approach III	948	1826	406	158	75
Approach IV	664	1245	100	32	1

Table 5.4: Affected grid points on melt events in November 26th-30th, 2005. Approach I and II both have the highest amount of affected grid points two days earlier than the approaches III and IV.

Comparing the numbers of affected grid points, approach I and II have their peak at least one or two days later than approach III and IV. When investigating the daily backscatter coefficient σ^0 for these days on grid point 05311754 (see location in Fig. 5.8(a)) it showed that the calculated daily mean of σ^0 decreased around November 23rd-24th, 2005 (Fig. 5.7). After the 26th the backscatter coefficient increased until it reached around the 28th its original level of approximately -7 dB. The loss of σ^0 over three consecutive days implies that there was specular reflection which reduced the amount of backscattered radiation. Specular reflection occurs when the illuminated area acts like a smooth surface, like over areas of water. This in turn suggested that the amount of liquid water in the snow pack was increasing, as it is the case when snow is melting (Jensen 2000; Ulaby and Long 2017).

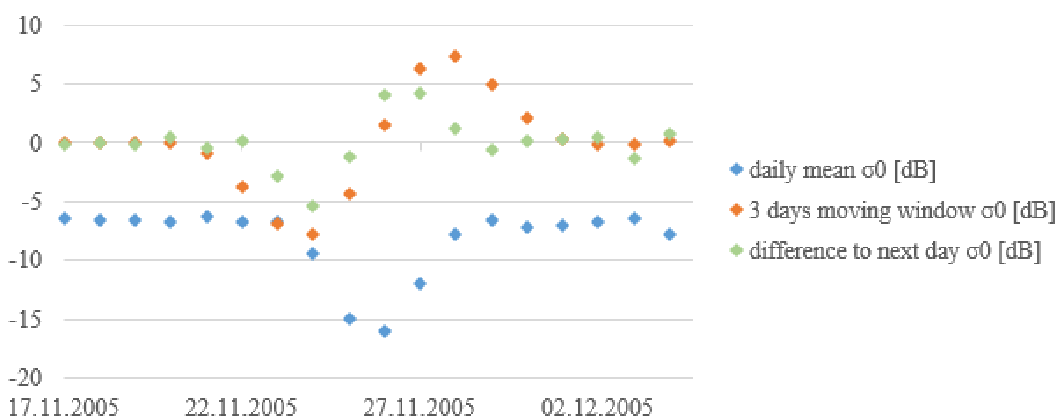


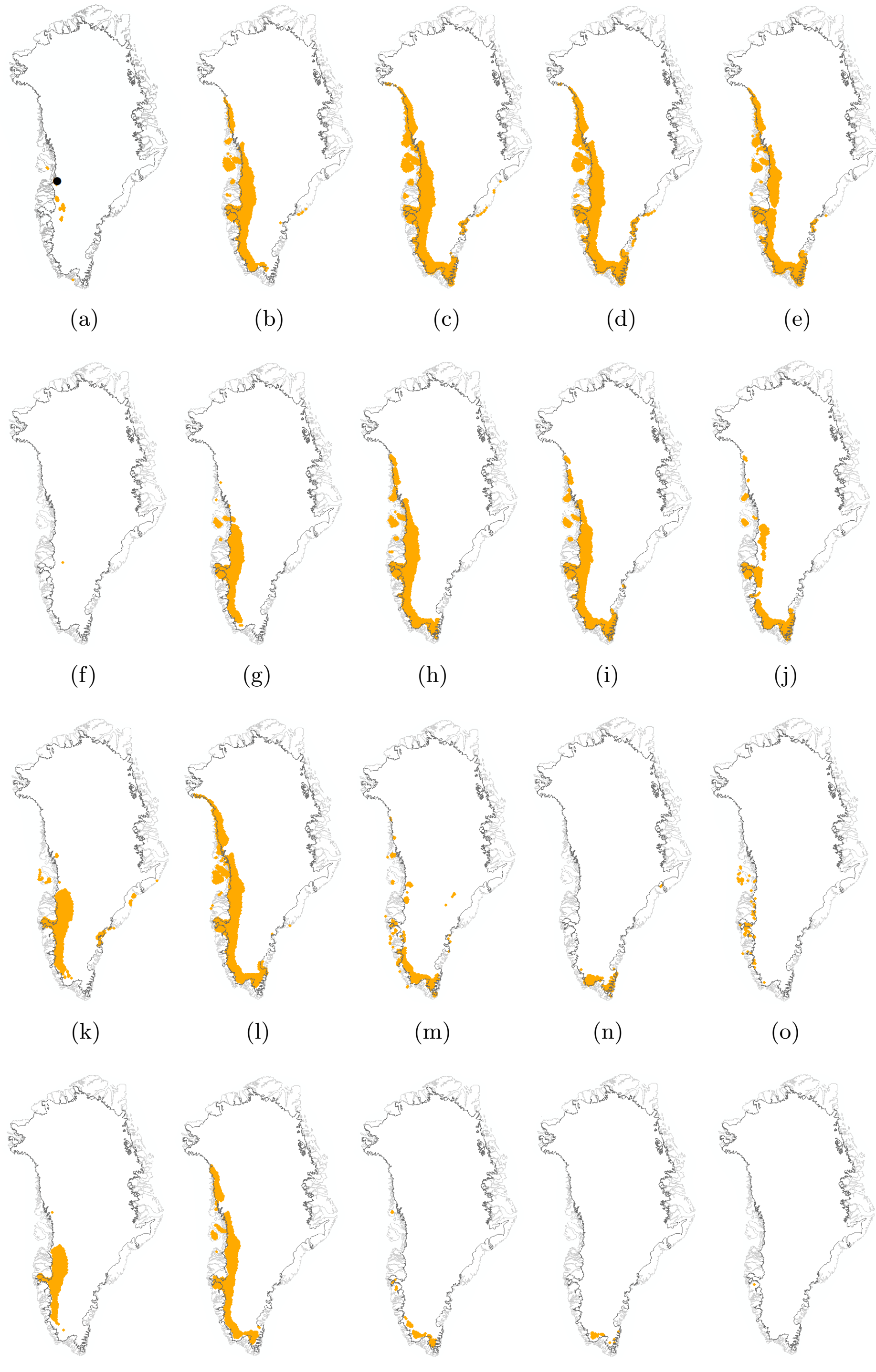
Figure 5.7: The backscatter coefficient σ^0 from November 17th to December 4th, 2005. The melting took place from November 24th-26th as the blue ⋄ decreases from -6.8 dB on the 23rd to -9.5 dB to -14.9 dB to -16 dB on November 26th, 2005. From the 26th to 29th σ^0 increased again.

The approaches I and II, which used the three-day moving window, reveal larger discrepancies when compared to the daily mean backscatter as the approaches III and IV. Because of the calculated average over three days the backscatter decrease is shifted towards earlier days. In this case the backscatter coefficient already dropped around November 22nd, 2005 and started to increase on November 24th, 2005. Moreover, the increase of σ^0 from November 24th, 2005 until November 28th, 2005 last five days, whereas the increase of backscatter for the daily mean of σ^0 took around three to four days. Also the daily mean of σ^0 leveled out at its previous amount of -7 dB on November 29th, 2005 the three-day moving window calculation needed three more days to settle down at its usual range. In contrast, approach III and IV which were not based on the three-day moving window but on the difference of the backscatter coefficient σ^0 of two consecutive days, seemed to be more qualified for detecting that events. The graph showed better adaption when considering the amount of days of decreased or increased backscatter. Although σ^0 started to drop on November 22nd, 2005 it decreased until November 24th, 2005. From November 24th, 2005 until November 26th, 2005 σ^0 increased with staying one day at 4 dB. During November 27th and 28th it leveled back to reach on November 29th, 2005 its averaged value.

The approaches taking the difference of two consecutive days showed more correspondence in duration of melt events and impact on the backscatter coefficient σ^0 data than the three-day moving window approach. The three-day moving window approach showed a three days earlier backscatter decrease and also a longer time frame when backscatter increased. The difference of two days seemed to be more suitable because of its closer behaviour to the ones of daily mean backscatter coefficient. Because the three-day moving window expands melt events over more days than the event was actually happening, the temporal pattern for this approach is considerably longer and of wider influence.

Not only the temporal appearance of melt events differed for each approach, sometimes even the spatial appearance was distorted. As an example the event of March 10th-13th, 2005 was investigated (Fig. 5.9). Whereas the first and second approach detected thaw events along the eastern part of Greenland on March 10th, 2005 the third approach detected less and the fourth approach did not even detected any ongoing melt at all. On March 12th, 2005 the first approach recorded increasing thaw event towards the south of Greenland moving on March 13th around the edge upwards on the southwestern side until it reached on March 14th its largest extent for that melt event all along the coastal zone. The melting took place almost entirely on glaciated area as well as on the mid-western located Disko island and upwards north along the unglaciated coastal zone. The behaviour of the second approach was similar to the first one but in attenuated dimension. The third approach was detecting some melt on March 10th and 11h, 2005 also along the eastern coast but reached its biggest expansion on March 12th when it was mainly found on the southwestern coastal region. The event already weakened on March 13th and vanished completely on the southeastern side. The fourth approach did not found any thawing on March 10th, 2005 and barely on March 11th when only three grid points on the southeastern part detected thaw. On March 12th, 2005 exclusively on the southwestern side the major melt event for this approach was detected. On March 13th almost no melting was revealed and only some isolated points showed thawing. However all approaches had in common that melting was concentrated over glaciated area. Sparse events were just along the unglaciated coastal area and Disko island.

The second biggest melt event for approach I as well as for approach II was during the first couple of days in November, 2008. In contrast, approach III hardly showed any affected grid points and approach IV was not recording any ongoing melt at all. Although this event was one of the largest for approach I and II, the approaches III and IV barely detected anything (Fig. 5.10). For approach III and IV the second biggest event was around November 18th, 2007 (Fig. 5.11). Again approach I and II recorded approximately two days later the melt onset compared to approach III and IV. Although one of the largest melt event for approach III and IV, it did not reach greater spatial extent than approach I and II.



(a) (b) (c) (d) (e)

(f) (g) (h) (i) (j)

(k) (l) (m) (n) (o)

(p) (q) (r) (s) (t)

Figure 5.8: Melt events from November 26th to 30th, 2005: Approach I (a)-(e) with grid point location in (a) of 05311754 (•), Approach II (f)-(j), Approach III (k)-(o), Approach IV (p)-(t).

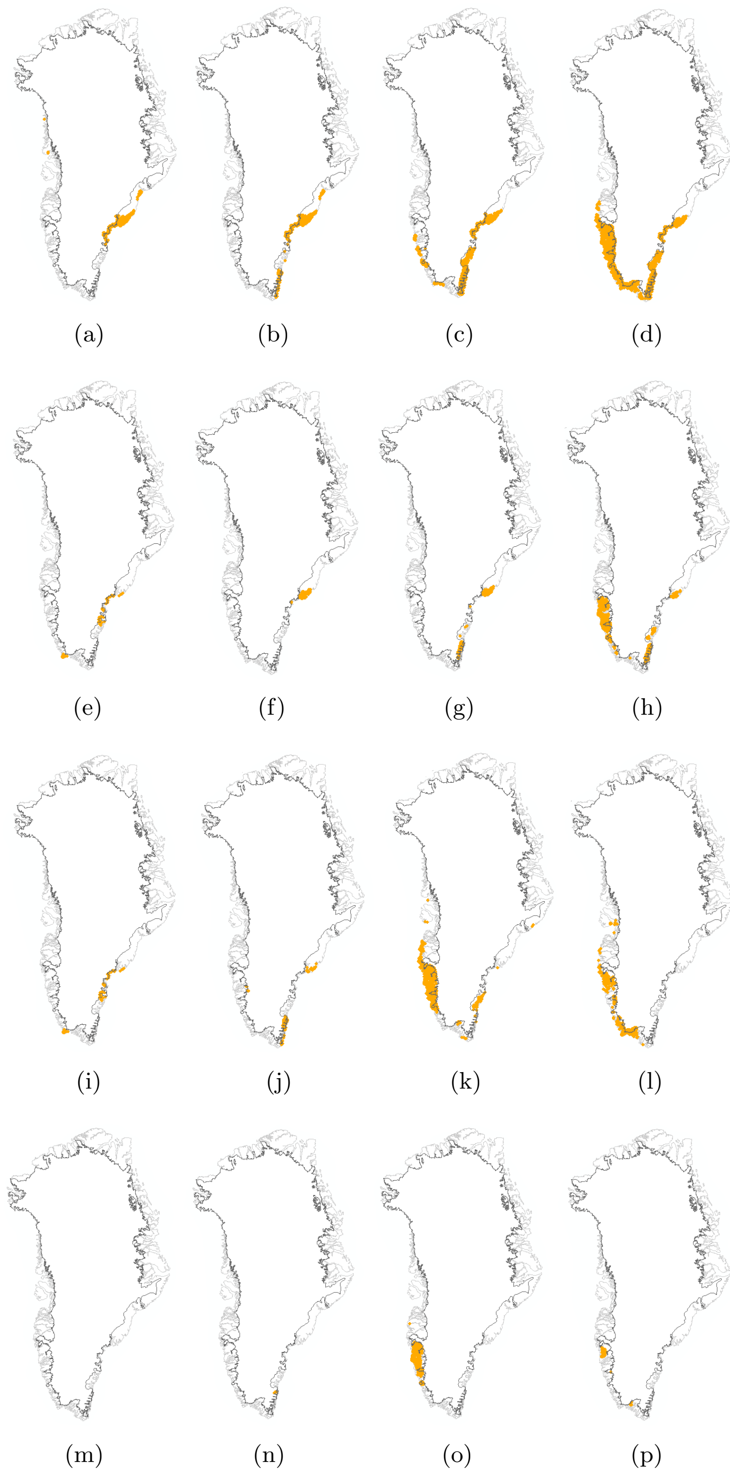


Figure 5.9: Melt events from March 10th to 13rd, 2005: Approach I (a)-(d), Approach II (e)-(h), Approach III (i)-(l), Approach IV (m)-(p).

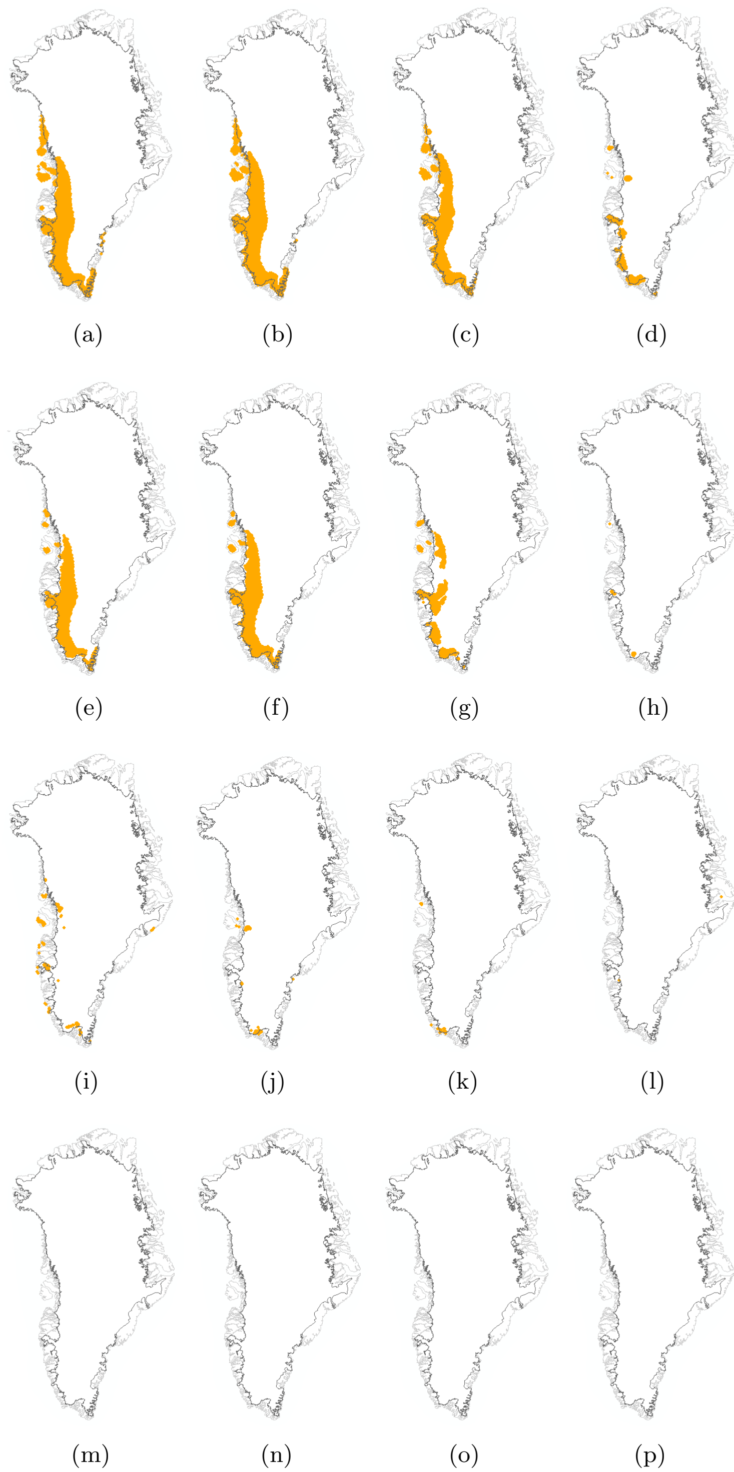
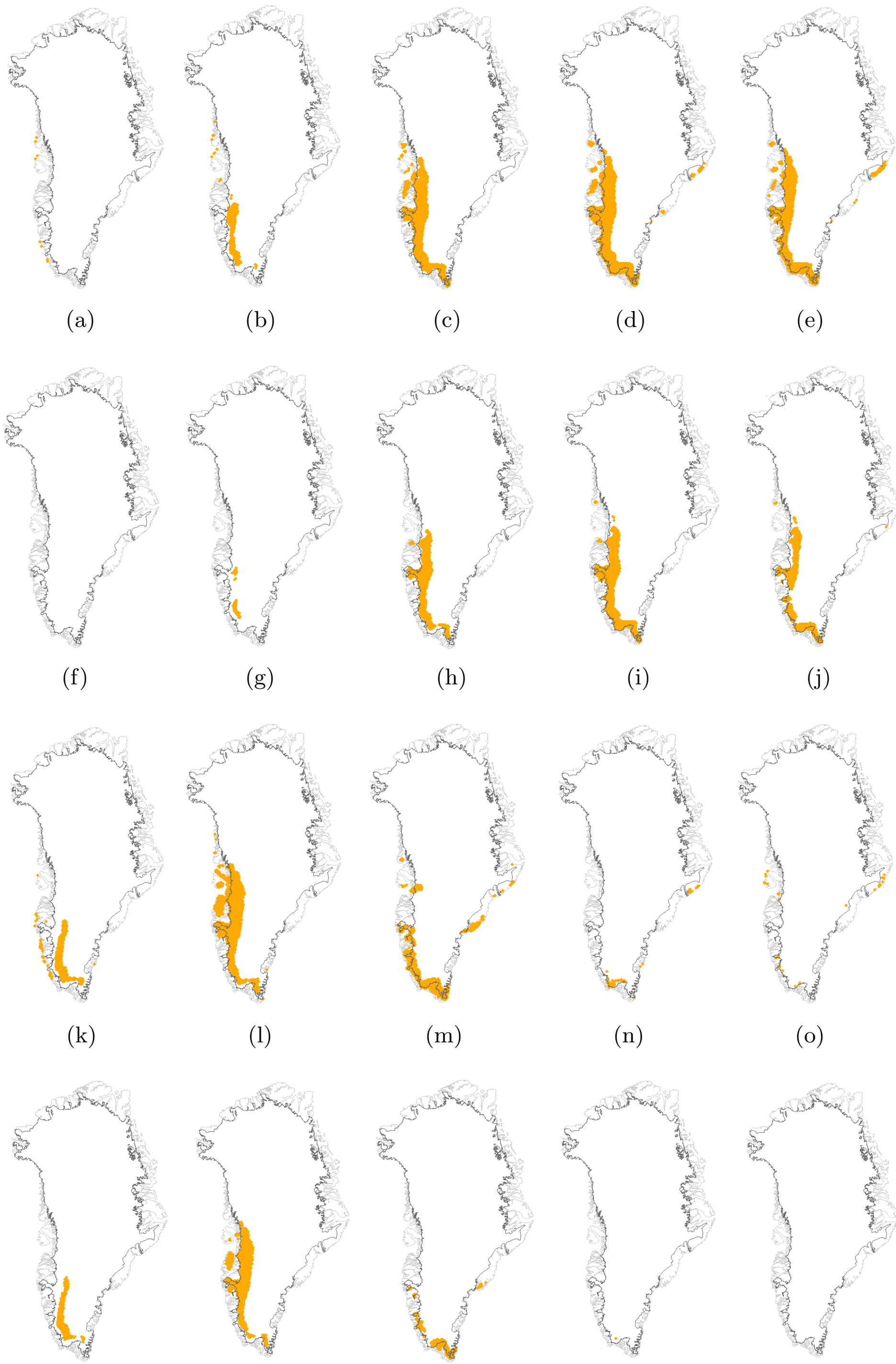


Figure 5.10: Melt events from November 1st to 4th, 2008: Approach I (a)-(d), Approach II (e)-(h), Approach III (i)-(l), Approach IV (m)-(p).



(a) (b) (c) (d) (e)

(f) (g) (h) (i) (j)

(k) (l) (m) (n) (o)

(p) (q) (r) (s) (t)

Figure 5.11: Melt events from November 17th to 21st, 2007: Approach I (a)-(e), Approach II (f)-(j), Approach III (k)-(o), Approach IV (p)-(t).

5.4 Validation

To examine if the melt events were influenced by warmer temperatures, grid points at the AWS were investigated. The stations which experienced thawing were Swiss Camp, JAR 1, and JAR 2 (Fig. 4.3). The closest grid points to the stations were taken to explore how many melt events happened on the stations and if the temperature was above zero degrees or not.

AWS	Approach	total days	days with -°C	days with +°C	no °C data
Swiss Camp	I	11	3	1	7
	II	8	2	1	5
	III	5	1	0	4
	IV	2	-	-	2
JAR 1	I	14	11	3	0
	II	5	4	1	0
	III	8	5	4	0
	IV	2	1	1	0
JAR 2	I	26	11	10	5
	II	3	1	2	-
	III	11	4	6	1
	IV	1	-	1	-

Table 5.5: Melt events at the three automated weather stations Swiss Camp, JAR 1, and JAR 2 which experienced melt events. For location information of stations see Fig. 4.3 or Tab. 3.2.

Unfortunately, at Swiss Camp there are days with detected melt events but without temperature data. For all approaches, more than 60% of days did not have available temperature records for that station. At JAR 1 the temperature balanced each other at the approaches III and IV, whereas for the approaches I and II around 80% of days the temperature was below zero degrees. Most melt days were found at the station JAR 2. But again, 10-20% of days did not have temperature data for approach I and III. The lack of continuous temperature data aggravated any serious declaration. Albeit it followed, that on days with melt sometimes the temperature were positive, but most of the time tended to be of a negative number. For further investigations it would be helpful to have additional temperature data from stations which are not located upon the ice shield, too.

By investigating explicitly the time around November 28th, 2005, the temperature at the automated weather station JAR 2 was recognizably increased (Fig. 5.12). The station (Fig. 4.3) recorded increasing temperature between November 25th and 27th, 2005 reaching more than 7°C. The warmer temperature above zero degrees lasted until November 28th, 2005. This covered the time frame at which the thaw event appeared. JAR 2 is located on Greenland's ice shield at a height of 507 m (Fig. 3.2). It implied that if on glaciated ground the temperature is that warm moving downwards to the coastal area it might be the same temperature if not even warmer.

To investigate melt events at the NOAA stations, grid points which were lying next to them were examined. Stations at which thaw was detected were Aasiaat, Sondrestrom, Nuuk, Paamiut, Narsarsuaq, and Tasiilaq (Fig. 4.3). Some events matched with the occurrence of precipitation, some did not. Again, for more precise statements, the lack of recorded precipitation data was a problem.

Also the precipitation at the NOAA station Aasiaat was examined for the time in late November 2005. The Aasiaat station was the closest precipitation recording station to JAR 2. It showed that there was some precipitation around two to three days before thawing was detected. This can be seen as an evidence for a ROS event. However, the precipitation data did not separate the condition of aggregation. This means that there is no distinction between liquid precipitation in form of rain or solid precipitation in form of snow. Investigating the amount of backscatter coefficient for that time (Fig. 5.7), it showed that $sigma^0$ did not increased that much after the thaw event, that it had exceeded the amount of backscatter before the melt. This would have been an sign that the melt was a rain-on-snow event.

NOAA	Approach	total days	days with [mm]	days with no [mm]	no data
Aasiaat	I	30	12	2	16
	II	3	-	-	3
	III	27	12	3	12
	IV	2	2	-	-
Sondrestrom	I	14	4	10	-
	II	11	4	7	-
	III	9	2	7	-
	IV	7	2	5	-
Nuuk	I	54	31	23	-
	II	8	3	5	-
	III	30	22	8	-
	IV	1	-	1	-
Paamiut	I	71	6	6	59
	II	-	-	-	-
	III	108	18	7	83
	IV	-	-	-	-
Narsarsuaq	I	39	15	24	-
	II	11	3	8	-
	III	9	8	1	-
	IV	2	2	-	-
Tasiilaq	I	56	18	19	19
	II	15	1	9	5
	III	29	14	5	10
	IV	1	1	-	-

Table 5.6: NOAA stations which experienced melt events. For location information of stations see Fig. 4.3 or Tab. 3.3.

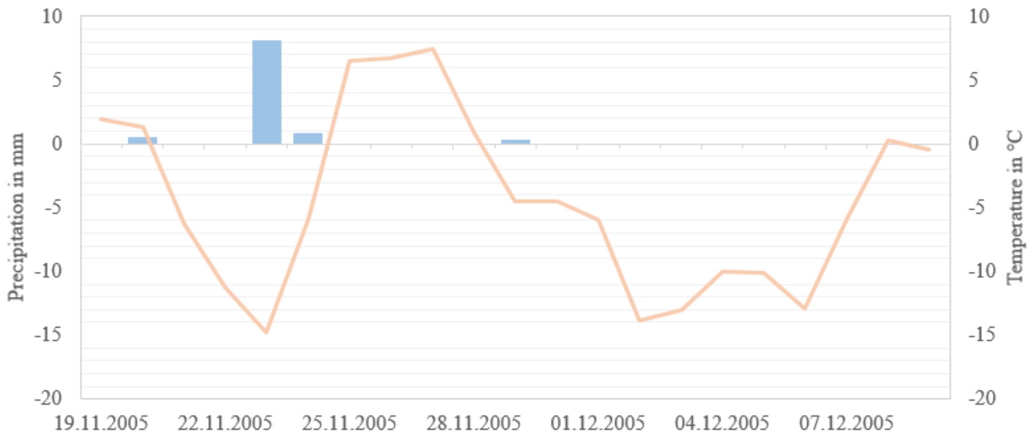


Figure 5.12: Temperature at JAR 2 on November 26th-30th, 2005 with precipitation from Aasiaat.

Investigating one of the biggest melt event for approach III and IV the temperature at station JAR 1 (932 m) and DYE-2 (2099 m) and the precipitation at Prins Christian (19 m), Narsarsuaq (27 m), and Nuuk (80 m) were examined (Fig. 5.13). At DYE-2 the temperature rose above zero degrees on November 18th and 19th. JAR 1 recorded -0,3°C for November 19th and 20th. This matched with the detected date of thaw. The precipitation at the station Prins Christian was highest for November 19th with more than 25 mm. At Nuuk the most precipitation was on the 20th with 11 mm. By far the most amount of precipitation fell at Narsarsuaq with over 73 mm on November 19th. The temperature as well as the precipitation suggested that the detected event was initiated by rain-on-snow. Moreover, it was recognizable the event was placed majorly on the ice shield and hardly noticed at the unglaciated coastal area.

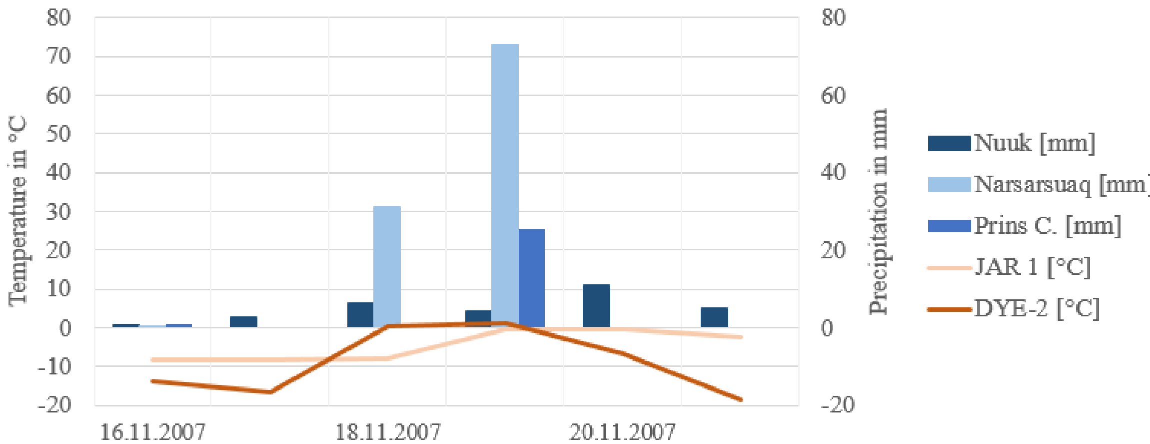


Figure 5.13: Temperature at JAR 1 and DYE-2 on November 17th-21st, 2007 with precipitation at Prins Christian, Narsarsuaq, and Nuuk.

Based on the prevalent wind systems on and around Greenland (Fig. 2.3), the assumption that the major occurrence of events were detected on the east as well as on the west side, but most of the time restricted to the latitude in between of 60 - 70°N could be verified. Because the southern part of Greenland in particular is strongly influenced by weather conditions that is connected with the North Atlantic winter cyclones, the northern part at Davis Strait has the lightest winds because of the alleviating effect of high pressure systems (Denmark and Greenland accessed: 2017-08-30). In the southern part the highest amount of frequency at grid points were found (Fig. 5.4). However the area around the capital Nuuk and the city Paamiut were also often detected for having melt events.

5.5 Suitability of methods

Although the air temperature was not always above zero degrees when detecting a thaw event, it needs to be mentioned that the temperature data were recorded at a level of 2 m and therefore were not an exact indication of surface temperature. However, the majority of thaw events were detected when the temperatures were initially below zero degrees. It was also noticeable that with increasing elevation the appearance and in addition the frequency of melt events decreased. McCabe, Martyn, and Hay (2007) mentioned for this aspect, that at higher elevation the temperature has less effect because of the already low temperature. The approaches I and III with a constant threshold of 1.5 dB detected overall more melt events than the ones with the a noise-dependent threshold (Tab.

5.1). The highest amount of melt events was during the year 2005. For all approaches the most affected grid points were detected during that time.

In addition, the third approach detected by far more events over glaciated area than the others. The approaches II and IV which calculated the thresholds separately for each grid point had the fewest melt detections. This may be because the threshold was usually very high compared to the constant value of 1.5 dB. Albeit for each grid point the individual noise was considered, the final threshold was three times higher than the actual amount of noise. Eventually, this was set too high when detecting melt events. In Tab. 4.1, Bartsch (2010) defined for areas with permanent snow and ice a maximum threshold of 2.20 dB. This amount was often overstepped, when calculating in II and IV the threshold being three times the noise value. Perhaps this approach could be investigated in further studies. Up till now in literature when considering the noise value it was calculated as seen in Bartsch (2010). However, contemplating for each grid point the corresponding noise amount seemed to make the melt detection more sensitive. Nevertheless, the third and fourth approach seemed to fit better when considering the original daily average backscatter coefficient. Taking the difference between two consecutive days matched the duration of melt more efficient than the approaches I and II which used the three-day moving window (Fig. 5.14).

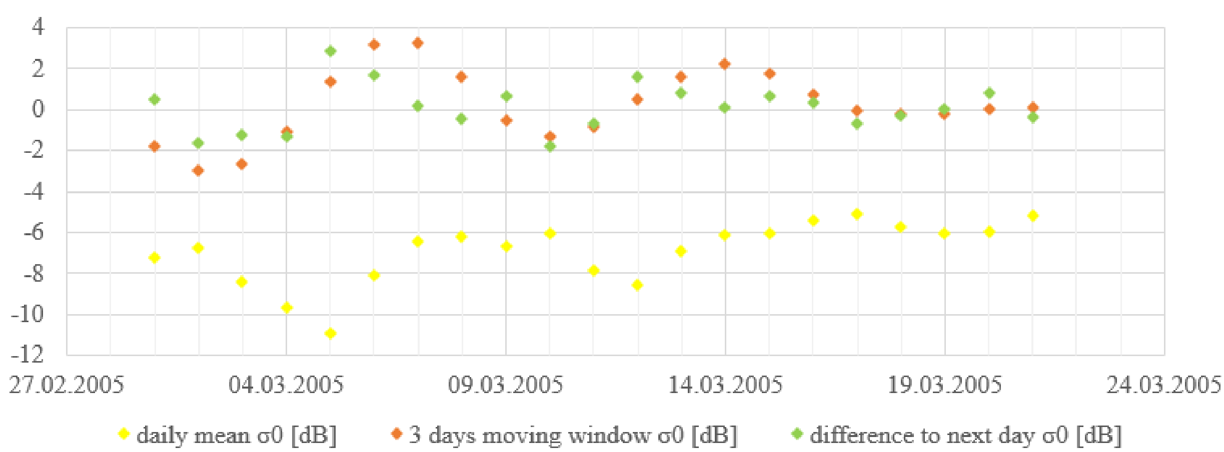


Figure 5.14: Backscatter coefficient for daily σ^0 (yellow), for 3-day moving window σ^0 (red), and for the difference of two days σ^0 (green) The approach of the difference of consecutive days matches better with the original daily backscatter amount than the three-day moving window approach.

Chapter 6

Conclusion

The advantages of scatterometer data recorded in the Ku-band were the continuous record of microwave radar backscatter and its sensitivity to snow wetness for detecting melting areas. From decreasing backscatter coeffient σ^0 the onset of thaw was assumed. The investigation of thaw events, particularly the observation of rain-on-snow events during winter months over Greenland is important because of its biological and hydrological effect on unglates and nature (Semmens et al. 2013). ROS events have a huge effect on the thermal structure of snowpack (Putkonen and Roe 2003). However its appearance is growing throughout the Arctic (Liston and Hiemstra 2011), less is known about the pattern of frequency, intense, and occurrence. For each approach thawing was detected in every year. In 2005, the highest amount of melt events were found.

A major focus of this investigation was to determine the ability of the approaches for detecting thaw events over glaciated area. Whereas the first and second approach used the difference of daily averaged σ^0 over a three-day moving window, the third and fourth approach used the difference of σ^0 between two consecutive days. The utilization of difference between days detected more thawing over glacier than the three-day moving window approach. This also fitted properly to the daily σ^0 backscatter behaviour considering the amount of days of thawing and refreezing. Not all detected melt events were associated with temperature above zero degrees, but for each thaw an increase in temperature was found. In addition, for the majority of events increase of precipitation was observable. However, the precipitation data did not distinguish between solid and liquid precipitation.

A future objective could be to use the approach of the difference of consecutive days with a grid point depending noise threshold, but not that high as it was tested within this study. It also would be interesting to distinguish backscatter coefficient data during day and night. Another future aspect could be to investigate if the distance of the grid points which are used for the backscatter radiation plays an important role or not. In this work, there was not set a spatial limitation for the grid points which compiled the value of the backscatter coefficient σ^0 . Albeit, melt events and especially rain-on-snow events are short-lived, when thinning out the data important information could get lost.

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Appendix A

List of melt events 2000-2008

Date	I	II	III	IV
01.01.2000				
02.01.2000				
03.01.2000				
04.01.2000				
05.01.2000			24	
06.01.2000	1			
07.01.2000			7	
08.01.2000			4	
09.01.2000	1		11	
10.01.2000	2			
11.01.2000			6	
12.01.2000				
13.01.2000	1		9	
14.01.2000	6		14	
15.01.2000	13	1	17	
16.01.2000	15		9	
17.01.2000	15		8	
18.01.2000	11		19	2
19.01.2000			67	12
20.01.2000	1		637	255
21.01.2000	42	1	50	21
22.01.2000	263	65	12	
23.01.2000	674	251	1023	656
24.01.2000	831	361	212	51
25.01.2000	860	339	100	
26.01.2000	732	226	3	
27.01.2000	181	3	29	1
28.01.2000	37			
29.01.2000	19		21	
30.01.2000	10		2	
31.01.2000	4		11	
01.02.2000				
02.02.2000			8	
03.02.2000			4	
04.02.2000			9	
05.02.2000				
06.02.2000			10	
07.02.2000			2	
08.02.2000			12	
09.02.2000			3	
10.02.2000			8	
11.02.2000				
12.02.2000			10	
13.02.2000				
14.02.2000			4	
15.02.2000			1	
16.02.2000			5	
17.02.2000			3	
18.02.2000			3	

Date	I	II	III	IV
19.02.2000			1	
20.02.2000			3	
21.02.2000			1	
22.02.2000			9	
23.02.2000	1		2	
24.02.2000			14	
25.02.2000				
26.02.2000			1	
27.02.2000				
28.02.2000			11	
29.02.2000			1	
01.03.2000			6	
02.03.2000				
03.03.2000			6	
04.03.2000			14	
05.03.2000	6		7	
06.03.2000	7		1	
07.03.2000	4		6	
08.03.2000	1		1	
09.03.2000	1		2	
10.03.2000			2	
11.03.2000			7	
12.03.2000				
13.03.2000			5	
14.03.2000			1	
15.03.2000			5	
16.03.2000				
17.03.2000			3	
18.03.2000			2	
19.03.2000			11	
20.03.2000				
21.03.2000			1	
22.03.2000	1		3	
23.03.2000	1		8	
24.03.2000				
25.03.2000			1	
26.03.2000			4	
27.03.2000			8	
28.03.2000			2	
29.03.2000	1		2	
30.03.2000	7		3	
31.03.2000			5	
01.04.2000				
02.04.2000				
03.04.2000				
04.04.2000				
05.04.2000				
06.04.2000				
07.04.2000				

Date	I	II	III	IV
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24.05.2000				
25.05.2000				
26.05.2000				

Date	I	II	III	IV
27.05.2000				
28.05.2000				
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30.05.2000				
31.05.2000				
01.06.2000				
02.06.2000				
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04.06.2000				
05.06.2000				
06.06.2000				
07.06.2000				
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28.06.2000				
29.06.2000				
30.06.2000				
01.07.2000				
02.07.2000				
03.07.2000				
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08.07.2000				
09.07.2000				
10.07.2000				
11.07.2000				
12.07.2000				
13.07.2000				
14.07.2000				

Date	I	II	III	IV
15.07.2000				
16.07.2000				
17.07.2000				
18.07.2000				
19.07.2000				
20.07.2000				
21.07.2000				
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26.07.2000				
27.07.2000				
28.07.2000				
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31.07.2000				
01.08.2000				
02.08.2000				
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Date	I	II	III	IV
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05.01.2003	11		5	
06.01.2003	1			
07.01.2003	9		56	
08.01.2003	22		35	
09.01.2003	43		59	1
10.01.2003	74	7	44	1
11.01.2003	122	10	76	1
12.01.2003	117		3	

Date	I	II	III	IV
13.01.2003	67		15	
14.01.2003	16		5	
15.01.2003	7		6	
16.01.2003	5		4	
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18.01.2003	1			
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21.01.2003	1		16	
22.01.2003	1		2	
23.01.2003			11	1
24.01.2003			5	
25.01.2003			7	
26.01.2003			3	
27.01.2003			2	
28.01.2003	2		3	
29.01.2003	1		79	5
30.01.2003	40	1	270	32
31.01.2003	269	30	17	3
01.02.2003	290	44	5	
02.02.2003	88	1		
03.02.2003	8		4	
04.02.2003	2		7	
05.02.2003	1		10	
06.02.2003	1		2	
07.02.2003	1		5	
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10.02.2003				
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14.02.2003	1		1	
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16.02.2003			19	
17.02.2003	4		8	
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20.02.2003	9		3	
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22.02.2003			2	
23.02.2003			5	
24.02.2003			2	
25.02.2003			6	
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27.02.2003			3	
28.02.2003			4	
01.03.2003	6		15	
02.03.2003	19		17	

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09.03.2003			2	
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11.03.2003	1		1	
12.03.2003			7	
13.03.2003	1			
14.03.2003			7	
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23.03.2003	50	4	5	
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25.03.2003	5			
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27.03.2003				
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29.03.2003			1	
30.03.2003			1	
31.03.2003			2	
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15.09.2003				
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Date	I	II	III	IV
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06.11.2003			4	
07.11.2003			3	
08.11.2003	1		3	
09.11.2003	1		12	
10.11.2003			7	
11.11.2003			2	
12.11.2003			13	
13.11.2003	5		17	
14.11.2003	40		15	
15.11.2003	59		16	
16.11.2003	27			
17.11.2003	8		16	
18.11.2003	1		1	
19.11.2003	3		25	
20.11.2003	43	3	4	
21.11.2003	49	14	18	
22.11.2003	50	4	14	
23.11.2003	11	1	9	
24.11.2003	10	1		
25.11.2003			2	
26.11.2003			2	
27.11.2003			17	2
28.11.2003			2	
29.11.2003			13	
30.11.2003			2	
01.12.2003	2		29	1
02.12.2003	21	3	27	1
03.12.2003	26		8	
04.12.2003	8		12	
05.12.2003	4			
06.12.2003	11		19	1
07.12.2003	20	1	16	
08.12.2003	14		4	
09.12.2003	7			
10.12.2003			3	
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12.12.2003			39	
13.12.2003				
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15.12.2003	40	1	28	
16.12.2003	48	3	20	
17.12.2003	8		41	5
18.12.2003	3		199	30
19.12.2003			2	
20.12.2003			30	1
21.12.2003			11	1

Date	I	II	III	IV
22.12.2003	49	10	136	4
23.12.2003	134	26	30	
24.12.2003	144	22	16	
25.12.2003	89	1	18	
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27.12.2003			1	
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30.12.2003				
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01.01.2004	1		3	
02.01.2004	3		21	
03.01.2004	28	5	16	1
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07.01.2004	1		3	
08.01.2004	1		6	
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15.01.2004	1		2	
16.01.2004			5	
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08.02.2004			2	

Date	I	II	III	IV
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15.02.2004	7		30	
16.02.2004	38		15	
17.02.2004	66	12	33	1
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28.02.2004	555	235	131	18
29.02.2004	519	215	21	
01.03.2004	399	144	49	3
02.03.2004	252	81	37	
03.03.2004	139	29	6	
04.03.2004	65		2	
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07.03.2004	1		41	4
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16.03.2004	112	4	12	
17.03.2004	81		12	1
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20.03.2004	7		7	
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23.03.2004			36	10
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27.03.2004	43	4		
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Date	I	II	III	IV
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17.05.2004				
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04.11.2004	2		6	
05.11.2004			22	
06.11.2004	2		24	
07.11.2004	44	1	35	2
08.11.2004	122	19	11	
09.11.2004	93	4	48	
10.11.2004	47		9	
11.11.2004			5	
12.11.2004			6	
13.11.2004			12	
14.11.2004			4	
15.11.2004	2		1	
16.11.2004	5		27	
17.11.2004	6		3	
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19.11.2004			12	
20.11.2004			10	
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22.11.2004			6	
23.11.2004			2	
24.11.2004			9	
25.11.2004				
26.11.2004			8	1
27.11.2004	15		180	
28.11.2004	93	23	204	44

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29.11.2004	190	62	9	
30.11.2004	191	59	33	7
01.12.2004	58	18	5	
02.12.2004	10		20	2
03.12.2004			1	
04.12.2004			18	
05.12.2004	3			
06.12.2004	11		13	
07.12.2004	8		7	
08.12.2004	1		2	
09.12.2004			2	
10.12.2004			5	
11.12.2004			3	
12.12.2004			2	
13.12.2004			2	
14.12.2004	2		1	
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27.12.2004	8		15	
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30.12.2004			14	
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12.01.2005			6	
13.01.2005	1		3	
14.01.2005			11	
15.01.2005	1		2	
16.01.2005			4	

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20.01.2005			1	
21.01.2005			10	
22.01.2005			2	
23.01.2005	1		11	1
24.01.2005	1		81	
25.01.2005	4		2	
26.01.2005	83	13	313	155
27.01.2005	408	109	348	49
28.01.2005	551	119	105	21
29.01.2005	443	99	23	
30.01.2005	187	23	3	
31.01.2005	19	23	54	8
01.02.2005	89	65	82	15
02.02.2005	114	64	23	
03.02.2005	113	27	1	
04.02.2005	95	3	6	
05.02.2005	52		22	
06.02.2005	3		5	
07.02.2005			7	
08.02.2005			1	
09.02.2005				
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13.02.2005	33	2	204	52
14.02.2005	301	73	95	13
15.02.2005	296	67	41	
16.02.2005	1		1	
17.02.2005			10	
18.02.2005	4			
19.02.2005	41	2	962	519
20.02.2005	559	120	417	125
21.02.2005	947	323	261	51
22.02.2005	1278	519	238	52
23.02.2005	810	376	195	38
24.02.2005	651	277	63	
25.02.2005	420	97	130	2
26.02.2005	211	33	44	1
27.02.2005	129	13	9	
28.02.2005	82	2	24	
01.03.2005	19		195	54
02.03.2005	1		44	9
03.03.2005	3		14	
04.03.2005	10		110	28
05.03.2005	164	54	293	94
06.03.2005	646	302	585	284

Date	I	II	III	IV
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08.03.2005	698	305	72	1
09.03.2005	277	45	33	
10.03.2005	135	33	39	
11.03.2005	173	41	53	3
12.03.2005	331	71	403	182
13.03.2005	806	309	214	29
14.03.2005	809	373	96	
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Date	I	II	III	IV	Date	I	II	III	IV
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21.11.2005	19		14	
22.11.2005	19		12	
23.11.2005	11		2	
24.11.2005	12		105	11
25.11.2005	9		83	9
26.11.2005	35	1	948	664
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29.11.2005	2207	1457	158	32
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Date	I	II	III	IV	Date	I	II	III	IV
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08.11.2006	1		4	
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11.11.2006	10		5	
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17.12.2006	9	1	5	
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27.01.2007	213	54	25	
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29.01.2007	293	115		
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04.11.2007			13	
05.11.2007			17	
06.11.2007			21	1
07.11.2007	7		13	
08.11.2007	15		1	
09.11.2007	21		58	11
10.11.2007	16		5	
11.11.2007	2		36	

Date	I	II	III	IV
12.11.2007			5	
13.11.2007			4	
14.11.2007				
15.11.2007			39	
16.11.2007	3		7	
17.11.2007	8		390	260
18.11.2007	295	51	1440	1038
19.11.2007	1267	747	669	195
20.11.2007	1581	1030	56	1
21.11.2007	1328	672	27	
22.11.2007	333	48	37	2
23.11.2007	66	3	55	
24.11.2007	26		65	
25.11.2007	13		90	1
26.11.2007	109	4	237	21
27.11.2007	167	7	186	20
28.11.2007	180	14	125	8
29.11.2007	75	2	27	
30.11.2007	13		1	
01.12.2007	1		1	
02.12.2007			5	
03.12.2007				
04.12.2007			1	
05.12.2007	1		2	
06.12.2007			85	2
07.12.2007			27	
08.12.2007			7	
09.12.2007	1		2	
10.12.2007			3	
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13.12.2007			2	
14.12.2007			3	
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17.12.2007			19	
18.12.2007	3		22	
19.12.2007	4			
20.12.2007			3	
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22.12.2007	12		2	
23.12.2007	8			
24.12.2007	7		1	
25.12.2007			4	
26.12.2007			1	
27.12.2007			3	
28.12.2007			1	
29.12.2007			8	
30.12.2007	2		3	

Date	I	II	III	IV
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23.01.2008			2	
24.01.2008	1			
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03.02.2008				
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06.02.2008	2		1	
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08.02.2008			1	
09.02.2008			23	
10.02.2008			5	
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19.03.2008	35		5	
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21.03.2008	9		6	
22.03.2008			159	77
23.03.2008	275	56	1304	825
24.03.2008	1326	769	580	235
25.03.2008	1510	1041	177	19
26.03.2008	1365	776	15	
27.03.2008	626	201	24	
28.03.2008	279	26	2	
29.03.2008	130		19	
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01.11.2008	1983	1367	102	
02.11.2008	2111	1558	43	
03.11.2008	1548	653	16	
04.11.2008	294	15	2	
05.11.2008	121		11	
06.11.2008	34		3	
07.11.2008	11		9	
08.11.2008	2		1	
09.11.2008	1		41	
10.11.2008	3		1	
11.11.2008			4	
12.11.2008	2		9	
13.11.2008	4		6	
14.11.2008	7		5	
15.11.2008	6		2	
16.11.2008	1		4	
17.11.2008	1		498	252
18.11.2008	75	1	678	323
19.11.2008	201	100	151	24
20.11.2008	222	128	12	
21.11.2008	82	14	731	528
22.11.2008	503	183	211	88
23.11.2008	629	359	183	40
24.11.2008	701	415	105	26
25.11.2008	1071	420		
26.11.2008	543	165		
27.11.2008	338	75		
28.11.2008	227	15	497	14
29.11.2008	319	13	13	
30.11.2008	49		80	
01.12.2008	76	2	202	58
02.12.2008	228	73	203	54
03.12.2008	289	60	25	
04.12.2008	222	39	50	
05.12.2008	73		6	
06.12.2008	26		50	1
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Date	I	II	III	IV
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13.12.2008			2	
14.12.2008	1		21	
15.12.2008	1		3	
16.12.2008			1	
17.12.2008				
18.12.2008			1	
19.12.2008			3	
20.12.2008				
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23.12.2008			2	
24.12.2008				
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26.12.2008				
27.12.2008			18	
28.12.2008	20		26	
29.12.2008	66		64	
30.12.2008	95			
31.12.2008	76	9	52	1