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Thermokarst thaw lakes in Polar regions - Evaluating the need for pan-Arctic monitoring of periglacial environments

A Master's Thesis submitted for the degree of
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Dipl.-Geogr. Dr. Annett Bartsch

Anna Maria Angelica Trofaier MPhys

0827914

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Affidavit

I, **Anna Maria Angelica Trofaier**, hereby declare

1. that I am the sole author of the present Master's Thesis, "Thermokarst thaw lakes in Polar regions – Evaluating the need for pan-Arctic monitoring of periglacial envrionments", 71 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master's Thesis as an examination paper in any form in Austria or abroad.

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Signature

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Abstract

The necessity of implementing an appropriate operational monitoring system for thermokarst lakes in the Arctic is considered by analysing time series of microwave images of these periglacial features. Thermokarst lakes in Central Yakutia, Siberia and the Mackenzie Delta, Northwest Territories, Canada are examined using radar data from the European ENVISAT and the Japanese ALOS satellites. ENVISAT ASAR Wide Swath (C-band; spatial resolution 150 m) are compared to ALOS PALSAR (L-band; spatial resolution 12.5 m) data.

The importance of thermokarst lakes lies in their implications for greenhouse gas emissions as they are related to atmospheric methane exchange. Therefore, monitoring and recording their dynamics play an important role in future climate predictions as has been established by the UNFCCC's GCOS initiative.

This study evaluates the need for a pan-Arctic monitoring system by analysing discrepancies that arise due to the different microwave sensors. It is found that ENVISAT ASAR WS provides sufficient data for such a monitoring system, despite its lower spatial resolution to ALOS PALSAR.

Pixel count differences between the two sensors range from 3 - 10 % depending on region. PALSAR's potential lies in resolving small lakes. However, statistical analysis of water density zones shows that lake sizes are within the same order of magnitude for both sensors, indicating ASAR's effectiveness in monitoring thermokarst lakes.

Furthermore, the international community's challenges, as well as milestones, in establishing a spaceborne monitoring system are considered all of which are pointing in a similar direction: The implementation of operational monitoring of thermokarst lakes is an issue that is being tackled through various EO coordination initiatives.

KEY WORDS: Permafrost; thermokarst; tundra; active microwave remote sensing

Preface

The Arctic is a highly complex ecosystem that contains a vast wealth of natural resources. Recently, these northern areas have been increasingly present in the public eye as news of climatic warming has sparked both fear and opportunity. The latter are due to the newly emerged numbers defining the quantity of undiscovered oil and natural gas that lie below the Arctic waters. According to recent studies these amount to 13% and 30%, respectively (Borgerson, 2009). In the past, these resources would not have been attainable due to the Arctic Ocean's ice cover, however, this ice cover is rapidly deteriorating and therefore the situation is turning out to be a profitable one, which has not gone unnoticed. The governments of the Arctic nations have started to engage in a race for territorial rights to ensure its resources for themselves. It is a highly conflicting stance. On the one hand, global warming and the prevention of environmental deterioration are important parts of governmental policies and on the other hand, making the most of the situation by exploiting the natural resources of the Arctic has aroused the interest of many countries and the hydrocarbon industry.

In recent years, the understanding of the geophysical dynamics of sea ice has tremendously progressed. Remote sensing methods for mapping sea ice have provided data that contribute to the enhancement of computer simulations and our knowledge of sea ice properties (Bravo and Rees, 2006). It is according to these simulations that predictions of an ice-free Arctic have been made. In particular, the *Arctic Climate Impact Assessment* (ACIA) has given insight to the political and commercial relevance of the Arctic. This report was commissioned in 2000 by both the Arctic Council and the International Arctic Science Committee (IASC), a NGO dedicated to scientific research that provides experts offering advise for political decision-making without having any political interests of its own (Bravo and Rees, 2006). The ACIA deals with many issues concerning the Arctic, regionally as well as the impacts on a global level.

One of these issues is the opening up of sea routes in the Arctic due to the melting ice cover of the Ocean. Apart from capital hungry energy firms, shipping companies too are pleased at the thought of a melting Arctic.

The necessity will arise to legally regulate the transit of these ships through the Arctic waters, and once more sovereignty issues emerge. This stresses afresh the need for cooperation in the Arctic, since pan-Arctic coordination will safeguard the environmental interests of all Arctic states (Borgerson, 2008).

Tensions in the Arctic have been increasing over the past few years, environmentally but also politically. Remilitarisation of the Arctic, by NATO countries as well as the Russians, is underway as they struggle over territorial rights.

As the Arctic consists primarily of ocean, territorial rights and sovereignty are either established by customary international law or the United Nations Convention on the Law of the Sea (UNCLOS). However, overlapping territorial claims have resulted in political tensions. Particularly alarming are comments such as those recently issued by the Kremlin on the competition for Arctic resources and its opinion that when dealing with these problems "the use of military force cannot be ruled out" (Times, 2009), as well as Canadian Prime Minister Stephen Harper's statement of "use it or lose it", indicating that the government believes securing future welfare lies in the Arctic regions (Omestad, 2008).

It seems as if the world is slowly returning to the frosty international relations of the Cold War epoch. During Soviet times these international relations between West and East were very much in accordance with the Realist view of Self-help and Balance of Power. Each country's interest was to safeguard its own survival. The West's fear of the menacing USSR, and the Soviet Union's determination to prove its strength and hence be considered as a worthy opponent, led to an arms' race that was on the verge of ending in catastrophe. It was fortunate that this possible disaster did not come about and from the beginning of the 1990s onwards the world saw the links between countries increase and globalisation pick up at a greater speed. Trade has resulted in an interconnectedness between states that makes governments think twice before any actions are taken. However, the prospect of securing energy resources has put a strain on international relations that could have an effect on finding appropriate solutions for all Arctic issues.

The issues in the Arctic are, though, not just of political nature. Environmental protection of the Arctic has always been a great concern. In the past, it was the fear of oil spills (such as the tragic *Exxon Valdez* disaster in 1989 (Howard, 2009)) that caused outrage from environmental pressure groups and in fact led to the formation of the Arctic Environmental Protection Strategy (AEPS) in 1991.

Nowadays, the environmental focus lies on the effects of rising temperatures. One of these effects of global warming is the deterioration of permafrost.

In the high North, communities rely on the existence of frozen ground. As soon as the permafrost starts to thaw, the infrastructure in the Arctic collapses. Roads turn into boggy sludge routes, mud- and rockslides as well as avalanches become more frequent and inadequate house constructions start to crumble (Hassol, 2004). These are serious problems that are starting to affect the inhabitants of the northern regions.
The underlying concern is the strain global warming has on three factors: Air temperature, snow cover and vegetation and their links to other parameters such as precipitation and soil moisture. All three of these variables contribute to the degradation of permafrost. Vegetation is a particularly interesting element as the changes in vegetation due to global warming influence the permafrost in a reciprocal manner. The more the vegetation suffers due to solar radiation, the more will the permafrost thaw, which in turn will deteriorate the vegetation further (Hassol, 2004).

Another issue is the emission of CO_2 and methane by peatlands, fens and shallow surface water bodies (Bartsch et al., 2008a). It is highly likely that the process of photosynthesis by the slowly deteriorating plant population will no longer be able to compensate for the rate at which organic matter is decomposing and hence increased amounts of carbon will be emitted into the atmosphere. Furthermore, permafrost deterioration due to rising temperatures can lead to thaw lake creation which in turn will result in methane emissions as these are oxygen depleted shallow water bodies where chemical redox reactions cannot take place. Both greenhouse gases, carbon dioxide from decomposing organic matter and methane emitted from thaw lakes, will then contribute further to global warming (Hassol, 2004). It is a reiterative process and the strains on the environment are starting to show.

The importance of monitoring water bodies in the Arctic is apparent. Their dynamics are still not very well understood and their implications for greenhouse gas accounting are crucial. It is therefore the intention of this thesis to investigate the need and possibilities for a continuous monitoring system of these Arctic thaw lakes.

Analysing the conflicting policies in the Arctic goes beyond the scope of this thesis. Nevertheless, a brief insight into the different programmes and organisations that are engaged in Arctic protection and are interested in a circumpolar monitoring system will be given later on. In this context, the above mentioned conflicts in the Arctic should be kept in mind since environmental policies are often overshadowed by opportunity costs and other socio-economic politics.

"Permafrost dynamics during periods of global change are increasingly recognised as an important factor in biogeochemical cycling, topographic and hydrological change [...]" (IPA, 2009).

1 Introduction

The Arctic is a highly sensitive region whose environment is coming ever more under stress due to direct as well as indirect human impact.

Recent climate projections have resulted in an ever increasing importance of the understanding of the Arctic regions and their associated environments, due to their potential of turning from a carbon sink into a net carbon source. It is thought that permafrost contains nearly double as much carbon as is already present in the atmosphere (Schuur et al., 2009). This carbon is stored in the anaerobic frozen ground by organic soil materials, histosols (Ström and Christensen, 2007). Vast amounts of methane are trapped within the permafrost. Ever increasing temperatures could result in the release of this greenhouse gas to the atmosphere. The rate at which CH_4 is emitted into the atmosphere is highly uncertain. It can, however, be said that global warming trajectories are such that these methane fluxes will result in a positive feedback (Zimov et al., 1997).

In particular, thermokarst thaw lakes play an important role with regard to greenhouse gas emissions. Increase in air temperature will result in changes to the ground thermal regime, which in turn may lead to this ground abasement feature. In particular, in ice-rich permafrost regions, the degradation of permafrost will result in ground surface subsidence, also known as thermokarst depressions (Duguay et al., 2005). These topographic abasements may fill with water to create lakes (Anderson, 2004). Anaerobic conditions within the lake sediments result in the production of CH_4, common to high latitudinal surface water bodies, whose water tables are near the surface. Oxidation of methane to carbon dioxide does not take place in these shallow, oxygen depleted lakes (French, 1996). Therefore, thermokarst thaw lakes are closely related to atmospheric methane exchange (the dominant form of greenhouse gas emission being through CH_4 ebullition (Walter et al., 2007)).

Methane is a greenhouse gas that is relatively short-lived in the atmosphere (the perturbation lifetime being 12 years. However, it has a global warming potential of 25 $CO_{2\text{-eq}}$ over a time horizon of 100 years, 72 $CO_{2\text{-eq}}$ over a time horizon of 20 years (Forster et al., 2007).

Therefore, it is evident that the dynamics of thermokarst lakes have important implications for global warming.

Water bodies have the ability to store heat which results in the degradation of the permafrost below. Often a layer of unfrozen ground, known as a talik, can hence be found below the lake beds. Therefore, water bodies are associated with geothermal disturbances and can result in a disequilibrium of the permafrost conditions (French, 1996). As such, the importance of monitoring these lakes is not to be underestimated.

Water body monitoring can be done through *in-situ* measurements or via remote sensing techniques including optical and thermal as well as microwave satellite imagery. Water's special sensitivity to microwaves, due to the polarity of the H_2O molecule, allows for

the effective application of radar sensors in hydrology.
This study aims to investigate the operational monitoring of thermokarst lakes in the Arctic using radar data from two different satellite instruments. The objective is to determine the importance of an operational satellite monitoring system for these periglacial features by analysing the discrepancies in sensors and the accompanied possible loss in information as well as by investigating the application of such a monitoring system for scientific and political user communities.

The thesis can roughly be divided into three main parts:

1. Background information on periglacial features, in particular thermokarst lakes, as well as on microwave remote sensing, focusing on synthetic aperture radar.

2. The study of thermokarst lakes in Central Yakutia, Siberia and the Mackenzie Delta, Northwest Territories, Canada.

3. Relevance of this study for international organisations and scientific communities, in order to evaluate the necessity and effectiveness of a satellite monitoring system for periglacial features.

The inclination to investigate the operational monitoring of thermokarst lakes comes at a time when satellite remote sensing has increased its importance in political decision making. Indeed, the need for empirical data to feed into climate models as input parameters has lead to an increased focus on remote sensing by the international community, a topic that is discussed below.

The need for, and the possibilities that arise from, a continuous remotely sensed monitoring system are evaluated and it is found that although some sensors are ideally suited for such a task, it is the combination of these that allows for an all encompassing, holistic monitoring system.

This study contributes to the ESA DUE Permafrost project of the IPF.
http://www.ipf.tuwien.ac.at/permafrost/

2 Geographical Background

2.1 Arctic Tundra

The world can be divided into a number of biomes, each of which cover extensive, contiguous geographic regions. One such biome is the Arctic tundra. It spans the northern edges of Russia, Canada, Scandinavia and Alaska. Its vegetation predominately consists of shrubs and lichens.

Due to the tilt of the Earth's axis, the North Pole faces the Sun in the summer and points away from it in the winter. In fact, this is the cause for the seasons, as the tilted axis regulates the solar intensity that is incident on the Earth over the course of the Earth's path around the Sun along the ecliptic plane (Withgott and Brennan, 2010). As such the climate in the Arctic is mostly determined by low solar angles. Differences between the seasons become more extreme at higher latitudes. In the high Arctic (North of Greenland, Svalbard and the Ellesmere islands) temperatures in the summer are greater than the regions located around the Arctic circle. This is due to the continuous incoming solar radiation over the period of the summer months. At lower latitudes, only once a year does the Sun remain above the horizon for 24 hours. Therefore, frost changes in the high Arctic only occur at the beginning and the end of the warmer seasons, whereas at lower latitudes there are daily frost changes in the summer months (Ahnert, 1996).

However, mean annual air temperatures deviate greatly according to geographic location, even if there is no latitudinal difference. Other climatic variables, such as ocean currents, contribute to the differences in temperatures around the globe. For instance in Greenland and the eastern Canadian Arctic southward flows of cold waters result in low temperatures allowing for polar bears and tundra to exist at a latitude of 51°N. However, the Gulf Stream that flows from the Gulf of Mexico across the Atlantic warming the northern European landmasses, allows for agricultural practice in Norway to take place at a latitude of 69°N (Callaghan et al., 2005).

The tundra is thought to be a periglacial environment, being a non-glaciated region that is subject to various cold-climate processes and landforms. The word *peri* stems from the ancient Greek word surrounding, therefore periglacial can freely be translated as "surrounding the ice" and is therefore used for all regions that are adjacent to glaciated areas (Ahnert, 1996). However, these regions are still to be seen as part of the cryosphere, due to their frozen ground conditions, also known as permafrost (French, 1996).

2.2 Arctic Permafrost

Most of the tundra is underlain by permafrost, although its extent and depth varies considerably over the whole biome.

The term permafrost has been attributed to rock and soil that have continuously been frozen for a minimum of 2 years. This thermal condition in ground materials to remain below 0 ℃ is highly climate dependent. Its abundance increases with latitude, but topographic conditions such as altitude, slope and orientation of this slope need also be considered (Duguay et al., 2005).

Permafrost exists in cold areas where temperatures nonetheless are high enough in the summer so that the snow cover can be completely melted away and no glaciated regions can be formed. Therefore, the periglacial regions of the Earth primarily lie in the Arctic (there are some islands off the coast of Antarctica as well as periglacial mountain regions) (Ahnert, 1996).

About 25% of the land surface of the Northern Hemisphere is underlain by permafrost (IPA, 2010). There is a distinction between continuous permafrost in the high North and discontinuous permafrost, which is thinner and is spatially fragmented (Anderson, 2004). The depth of permafrost varies from the centimetre range to several hundreds of metres. Although freezing commences at the surface the bottom layers remain frozen through all years. Permafrost therefore is a subsurface condition. The top layer will undergo seasonal thawing and has been termed the active layer.

Permafrost growth is related to a negative energy balance at the surface. The three most important factors to influence the thickness of permafrost are the surface energy balance, the thermal properties of the ground components (the conduction of heat will vary according to material) and the geothermal heat flow that allows the temperature to rise with increasing depth (Anderson, 2004). Therefore, the thickness of permafrost is a balance between the internal heat gain and the heat loss from the surface (French, 1996). Large thermal conductivities of the soil can ensure relatively thick active layers, which in turn allow for higher temperatures at greater depths (Duguay et al., 2005).

The upper boundary of the permafrost, where the active layer is at its maximum, is known as the permafrost table (Anderson, 2004). In most areas the seasonal frost reaches down to the permafrost table, however, there do exist regions wherein unfrozen areas between this seasonal frost and the permafrost table can be found. These are known as taliks (French, 1996). They occur due to the fact that the rate of downward freezing is not the same throughout the active layer, resulting in the creation of pockets of unfrozen ground (Anderson, 2004).

Ground ice content plays an important role in periglacial environments, as it is one of the main components of permafrost itself. Often, the amount of ice that can be found within the frozen ground is higher than the natural water content of the sediment in its unfrozen state. The thawing of permafrost can hence result in ground abasement and subsidence (French, 1996). This phenomenon is known as thermokarst and will be discussed in section 2.2.3.

2.2.1 Pingos

Isolated circular hills in the tundra which contain a central core of ice are known as pingos, a term originating from the Inuit word for hill. Pingos can vary considerably in size - their radii are from 15 to 300 m and they can be 3 to 70 m in height. The growth of the ice core often results in dilation cracks and thawing of the ice can lead to the collapse of the summit. One distinguishes between open and closed system pingos, a classification made according to the mechanism that explains their formation (Anderson, 2004).

Open system pingos are thought to develop in areas where continuous groundwater flow under artesian pressure enables the growth of ice. Large ice domes, overlain by soil and sediment, are formed. Closed system pingos are often related to the disappearance of small lakes. The heat conductivity of lakes allows for a permafrost free zone to exist beneath these. However, when lakes shrink or disappear, their insulating effect will be reduced or even cease. Permafrost will start to aggrade. The pressure associated with permafrost encroachment allows pore water to concentrate underneath the former water body, which in turn freezes creating the ice core of a pingo that eventually pushes up and expands (French, 1996). The surface freezes from the top down and exerts, due to a phase change related expansion, a cryostatic pressure on the pore water. Since the water cannot be compressed further it is pushed to the surface elevating the topmost soil layers (Ahnert, 1996).

2.2.2 Ice wedge polygons

Freezing water undergoes a phase change that results in a volumetric change. When water turns to ice, its volume expands by a tenth of its initial volume. Ice, however, contracts when temperatures continue to fall below the freezing point. This statement also holds for periglacial permafrost grounds (Ahnert, 1996).

As temperatures drop in the winter and the ground continues to freeze, the soil will contract which in turn will cause cracking. The resultant fractures create random polygonal shapes across the surface, from which they stretch, through the active layer, down to the permafrost (Anderson, 2004). Snow that has accumulated on the surface can blow into the cracks and freeze (Billings and Peterson, 1980). In addition, seasonal change causes the active layer to thaw, water will also seep into these cracks and turn to ice. The following winter contraction will once again result in more cracking and the process starts afresh. These periglacial formations are known as ice wedge polygons (Anderson, 2004). Generally, the upper surface of an ice wedge coincides with the depth of the seasonal thaw (Bosikov, 1989).

It has been established that ice wedges only form in regions where the mean annual air temperatures are ≤ -6 ℃. Active ice wedges can only be found in continuous permafrost zones, whereas ice wedges in discontinuous permafrost zones are generally thought to be inactive. Ice wedges are particularly influenced by snow cover (French, 1996). Its low thermal conductivity allows for insulation of the ground below this cover. In addition, snow has a high albedo. Much of the incoming solar radiation will be reflected. When the snow pack disappears in the summer months more radiation will be absorbed and this heat transfer will influence the thermal regime of the ground materials, leading to permafrost degradation (Duguay et al., 2005). Ice wedge cracking has a high sensitivity to various climatic conditions and is a useful method for studying climate change (French, 1996).

There is a close relationship between the polygonal tundra and thaw lakes. Ice-wedge polygons affect the thermal conditions of the ground and can lead to thermokarst depressions and thaw lakes (Billings and Peterson, 1980).

2.2.3 Thermokarsts

Thermokarst creation is related to an increase in active layer and the disruption of the thermal equilibrium of the permafrost. Heat conduction due to this increased active layer leads to ground ice ablation (Murton, 2009). The thawing of ground ice in turn results in a topographic abasement, known as thermokarst subsidence (French, 1996). Thermokarst areas are identified as a hummocky terrain with water-filled cavities, known as thaw lakes (Anderson, 2004). The surrounding mounds are usually up to 2.5 m high, although in extreme cases they may be higher than 8 m (Murton, 2009).

The magnitude of subsidence is connected to the quantity and distribution of the frozen excess ice and to the thickness of the thawed permafrost. Subsidence can occur due to thermal erosion. Flowing waters, such as rivers, but also streams that arise due to periods of rainfall and snowmelt, lead to the thawing of ground ice due to heat conduction but also through convection. Furthermore, the newly released sediment will be further eroded mechanically (Murton, 2009). This lateral stream erosion can result in the slumping of overlying material and the development of thermokarsts (French, 1996). Lastly, the aforementioned ice wedge polygons can further this thermokarst depression.

Thermal erosion can also lead to gently sloping depressions, forming beaded streams. These are a network of lakes linked to each other by short and tight channels. The formation of these channels is closely related to the thaw of individual ice wedges.

Thermokarst lakes tend to occur at ice wedge intersections. The lakes may grow in depth if their floors collapse over these intersecting ice wedges, allowing for water to flow alongside the ice wedge troughs. In addition, lakes induce permafrost thawing along the margin of the lakes themselves. This can result in bank subsidence and retrogressive thaw slumping (Murton, 2009).

Abasements with steep sides and flat floors are known as alases. These are formed from the melting of numerous ice wedges resulting in large-scale thermokarst depressions which often contain lakes (Anderson, 2004).

Water bodies store and conduct heat. Therefore, the temperature at the bottom of a lake will rise and the depth of the active layer below a thermokarst pond will increase drastically. Simultaneously, the degradation of ground ice masses at the bottom of the lake, increases the depth of the water body, facilitating the active and progressive development of thermokarst lakes. Hence, even in so-called continuous permafrost regions, discontinuity exists wherever there are lakes (Bosikov, 1989). It has been shown by Vasil'yev (1982) that thawing beneath water bodies can be up to twice as high as within dry polygonal formations.

Catastrophic lake drainage is a common phenomenon resulting from the change of the course of water through interconnected ice wedge systems (Murton, 2009).

Contrary to the polygon process, though, thermokarst creation is not a seasonal occurance but is triggered by climatic warming as well as by changes to the insulating surface properties, such as vegetational changes (Anderson, 2004). Climatic conditions such as an increase in the mean annual temperature of the soil and in the amplitude of temperature lead to the development of thermokarsts (French, 1996).

2.3 Ground ice conditions

Like with most periglacial features, thermokarst formation is highly dependent on ground ice conditions. The higher the ice content the greater the ablation possibility. The term ground ice is usually used for all types of ice that is formed within the ground. It can occur in cavities within soil and rock, as well as within pores. There are two quantities associated with ground ice: Ice content and excess ice. The former is defined as a percentage weight ratio of ice to dry soil, i.e.

$$\text{ice content } [\%] = 100 \text{ x } \frac{\text{moisture within soil [g]}}{\text{dry soil [g]}}. \tag{1}$$

Soils with low ice content are generally determined to be those with more than 50% dry soil. Those where moisture exceeds dry soil by 50 - 150% are said to be of high ice content.

Excess ice is the term ascribed to the volume of supernatant water that can be found from the thawing of a vertical column of frozen soil. This term is represented by a volume percentage.

$$\text{ice excess } [\%] = 100 \text{ x } \frac{\text{volume of supernatant water [cm]}}{\text{total volume of sediment and water [cm]}}. \tag{2}$$

This parameter allows for a potential identification of morphological changes and consequences due to volumetric ground ice loss. Soils that contain excess ice are usually referred to as 'ice-rich'. These may have ice excess values as high as 70-80% (French, 1996).

3 Technical Background

3.1 Microwave Remote Sensing

Remote sensing techniques are used to gather information on properties from distant objects and surface features without being in direct contact with these (Konecny, 2003). Most commonly, this is done using electromagnetic waves. Here it is important to distinguish between passive and active sensors. Instruments that incorporate an antenna to detect "natural" emissions from objects are called passive, whereas those that send out an electromagnetic wave and then measure the backscatter are termed to be active systems (Lillesand et al., 2008).

Microwave instruments play an important role in the cryo and hydrosphere of the northern latitudes. Apart from the fact that long wavelengths can penetrate cloud cover and can therefore be taken throughout the year, independent of weather situation, the dielectric properties of water allow for a categorical distinction of the transitions between its solid and liquid phases (Kimball et al., 2004).

Liquid water has a high dielectric constant. Therefore the penetration depth, δ_p, of a radar will decrease with increasing moisture levels (Woodhouse, 2006).

$$\delta_p \simeq \frac{\lambda\sqrt{\epsilon_1}}{2\pi\epsilon_2} \tag{3}$$

where λ is the wavelength of the active electromagnetic radiation and the complex relative permittivity is $\epsilon_r = \epsilon_1 - i\epsilon_2$.

Liquid water consists of highly polar molecules leading to a dielectric constant that preoccupies the microwave regime. Frozen water binds molecules into a crystalline lattice that has a highly decreased dielectric constant. Therefore, huge differences between frozen and thawed soil conditions can be made visible by microwave active sensors (Kimball et al., 2004). This property greatly alleviates monitoring periglacial environments, in particular with respect to seasonally frozen ground and snow cover. Changes from volume to surface scattering can result in a response change of up to 6 dB (Kimball et al., 2004). This backscatter difference can be associated with the rise in permittivity of surfaces that changed from frozen to liquid state and is a good indicator of ground thawing (Kidd et al., 2004).

With regard to thermokarst lakes, scattering off a smooth surface (for low wind conditions) has to be considered. In this case specular reflection, coherent scattering at a smooth boundary, occurs. The interaction of the wave with the surface follows the Huygens principle of secondary wavelets. According to the laws of reflection the incident angle of the radiation beam equals the reflected angle and a distinct peak in the direction of this specular reflection will occur (Woodhouse, 2006). Incident radar radiation on smooth water bodies will reflect away from the satellite, which makes these lakes clearly distinguishable from their surroundings due to the low grey level values of their associated pixels.

The active system that was used to gather data for this masters project is a radar instrument.

3.1.1 Radar

Radar was first developed by the military as a warning system that could pick up objects and determine their distances; hence the acronym radar stems from *radio detection and ranging* (Lillesand et al., 2008). Radar sensors are now widely used for environmental monitoring. It uses the microwave regime of the electromagnetic spectrum (from about 10^9 Hz up to 3×10^{11} Hz) which allows for one prominent feature: Atmospheric penetration. Long wavelength radiation is not affected by clouds or dust. Any radiation within the wavelength range of 1 cm to 30 m is capable of penetrating the atmosphere, allowing for effective monitoring (Hecht, 2002).

The fundamental principle of radar is that of echolation: The transmissal and the measurement of the returned signal (Woodhouse, 2006). There are various radar sensors which may produce images, but this function is not a necessity. For instance, speed cameras are non-imaging radar systems that measure the Doppler shifts in the transmitted and returned frequencies (Lillesand et al., 2008). However, the principle of echolation applies in either case and the measured power of the received signal will always be in accordance with the so-called radar equation. In particular,the *monostatic radar equation* is of interest here, as the same antenna is used to transmit and receive the radiation. It is stated below for completeness (see equation (4)). This equation allows the determination of whether an echo is detectable (and distinguishable from background noise) by the antenna (Woodhouse, 2006).

$$P_r = \Big(P_t G \frac{\sigma}{4\pi R^2}\Big)\Big(\frac{A_e}{4\pi R^2}\Big) \quad [W], \tag{4}$$

where P_r is the power of the signal received at the instrument, P_t is the power of the transmitted signal by the antenna, R is the range of the target from the antenna, G is the gain of the antenna and σ is the scattering cross-section.
The effective area A_e is equivalent to the cross-section of the antenna and is proportional to the gain and the square of the wavelength:

$$A_e = \frac{G\lambda^2}{4\pi\eta} \tag{5}$$

where η is the efficiency of the antenna (Rees, 2001). It therefore can be seen that the received power drops very fast with the range as it is inversely proportional to R^4, a severe limitation of radar sensors.

The radar equation can be rewritten as a *signal-to-noise ratio*, a convenient quantity for determining whether the signal from a target is larger than the noise of the instrument, N_0 (Woodhouse, 2006).

$$SNR = \Big(\frac{P_r}{N_0}\Big), \tag{6}$$

Only the backscattered component of the radiation is detected by most radar systems. Rewriting the above equation (4) gives the target radar cross-section:

$$\sigma = P_r \frac{(4\pi)^3 R^4}{P_t G^2 \lambda^2} \quad [m^2] \tag{7}$$

Generally, however, one refers to the normalised, dimensionless radar cross-section, σ^0, also known as the backscattering coefficient (Rees, 2001). This is due to the fact that in Earth Observations the target is usually a larger area, A, rather than an isolated object. We find that:

$$\sigma^0 = \frac{\sigma}{A} \tag{8}$$

Although, σ^0 is a dimensionless quantity it is usually represented in units of decibel (dB), the logarithm of the ratio of the quantity of interest over a reference quantity, chosen to be unity (Woodhouse, 2006).

The radar systems used for this project were imaging radar systems, in particular synthetic aperture radar (SAR).

3.1.2 SAR

Synthetic aperture radar systems use the principle of increasing the resolution by "creating" a larger aperture through the motion of the platform. By implementing a short physical antenna that follows a certain flight path a larger antenna is synthesised. This method allows for the improvement of the azimuthal resolution (the capacity to differentiate two target points at the same received power (as a function of time delay) but different azimuthal angles). This in turn enables an enhanced spatial resolution (Woodhouse, 2006).

The above mentioned equation (4) is for real-aperture radars. This equation needs to be altered slightly for SAR processing as this requires the addition of all n received echoes, rather than just from a single echo, therefore

$$SNR = n \left(\frac{S}{N}\right)_{single\ echo} , \tag{9}$$

where

$$n = \left(\frac{R\lambda}{2V_s\rho_a}\right) PRF , \tag{10}$$

ρ_a is the azimuth spatial resolution, V_s is the azimuthal velocity of the sensor and the PRF is the pulse repetition frequency.

In order to increase the number of received echoes it is therefore practical to maintain a small platform velocity as well as a high PRF (Woodhouse, 2006).

SAR imaging is a *coherent* technique that requires not only the intensity of the signal, but also its amplitude and phase to be stored. This is essential for the extraction of different frequency components from the multiple signals that are returned (Rees, 2001).

However, this ability also results in a characteristic noise, termed *speckle*. Speckle is due to interference among the coherent signals from individual scattered surface features. Strictly speaking, however, it should be noted that speckle does not classify as noise, as it is a definite and deterministic phenomenon (Woodhouse, 2006).

3.1.3 Range resolution and compression

Equation (7) shows that the accuracy of the target cross-section, and hence the backscatter values, are highly dependent on the accuracy of the measured range, R. The definition of the range resolution is: "The ability to distinguish (in time) the return pulses from two idealised point targets" (Woodhouse, 2006). If one decreases the range of two identical objects by moving them closer together these will become indistinguishable and will be picked up as a single broad object. The two objects will no longer be resolvable. The range resolution is limited by the duration of the transmitted pulse (the shorter the pulse the closer the targets can be situated to each other).

According to range resolution, it is therefore necessary to keep the pulse as short as possible. However, following (4) a high power transmission pulse is needed to overcome the R^{-4} drop-off. This is often by-passed by using a linear *frequency modulated* (FM) pulse. This allows for the pulse energy to be transmitted with a lower peak power. SAR data are hence collected by the transmissal of a long linear FM pulse, which is essentially an encoded signal that can be decoded by applying an appropriate filter. This process of matched filtering allows for the distinguishability of overlapping echoes. The entire procedure is known as range compression, an important step that is needed later on for geocoding the data (European Space Agency, 2009a).

3.2 Applications of SAR in periglacial environments

In section 3.1 it was shown that there is a strong dependency of radar signals on hydrological conditions. Therefore, active microwave sensors, such as SAR, are proven to be a useful method for providing observations and monitoring features of the hydrosphere.

In the past, SAR systems have mainly been used for mapping inundation (Bartsch et al., 2008b), although further potential applications have been explored in recent years and are discussed below.

In the context of Arctic monitoring, radar has an additional advantage over optical systems: Its wavelengths are long enough to avoid cloud obscuring and atmospheric attenuation. This is an important issue, as the number of cloud free days in the Arctic are low and radar allows for year round monitoring.

Here, three examples for the application of SAR data in high latitude regions are given: Wetland monitoring, inferring methane ebullition from thermokarst lakes and thaw lake bathymetry.

3.2.1 Monitoring wetlands

Wetlands can take many forms. They can be grasslands and shrublands, as well as bogs. They can contain permanent inundation (in the form of lakes), seasonal inundation or even just flooded areas. In every case, the interplay of vegetation with water has an important impact as these wetland ecosystems not only provide ideal nesting grounds for waterfowl and migratory birds but generally are areas with high biodiversity.

The importance of wetland monitoring is to be put into context with, on the one hand them being a sink and source of carbon emissions, and on the other hand with regard to the Ramsar Convention on Wetlands of International Importance.

Wetland monitoring primarily focuses on distinguishing various land cover classes from one another, i.e. classifying different vegetation and different inundation types. In particular, SAR allows for the mapping of inundation and areas that are protected wildlife habitat. Backscatter values of bogs and wetlands are different over the course of the year and hence these can be distinguished from one another (Bartsch et al., 2007).

The wetland characteristics that can be found from SAR observations are the extent and duration of inundation as well as the potential to map soil moisture (Bartsch et al., 2008b).

Mapping these changes in inundation are important in the context of monitoring protected wildlife habitat. Changes in inundation happen on a seasonal scale, in particular spring time flooding and inundation extent in the summer months is of interest in the boreal and tundra regions. Therefore it is important to have a temporal resolution high enough for some data within the summer months (since in the winter water in high latitudinal areas will be frozen). ENVISAT ASAR allows for this effective monitoring.

3.2.2 Inferring methane ebullition from thermokarst lakes

Another application of SAR systems is as a method for inferring CH_4 ebullition from thermokarst lakes. This procedure was first proposed by Walter et al. (2008) as a means to quantify the magnitude of carbon emissions from lakes on a regional scale, rather than by just doing a bottom-up estimation from random field work samples.

The development of this technique comes at a time when greenhouse gas accounting is becoming increasingly more important while at the same time it has been realised that carbon emissions from Arctic lakes have not yet been considered.

It has been shown by Zimov et al. (1997) that during winter methane is produced underneath the ice of these lakes, and is released to the atmosphere either in the winter by means of holes in the ice, or in the spring when the ice melt results in water column circulation.

Methane ebullition is the main process for carbon exchange with the atmosphere by thermokarst lakes. However, it is difficult to measure as it varies greatly temporally, as well as spatially. It is possible to undertake accurate mapping of, and to measure methane fluxes from ebullition bubbles that are frozen into the lake ice at the onset of colder temperatures in the autumn (Walter et al., 2006). However, this can only be done on a local scale and given the extensive number of water bodies in the Arctic, other means for estimating methane emissions are needed.

This is where SAR data comes into play. Lake ice phenology can be monitored by the discrepancies in backscatter values of floating and grounded ice. The ebullition bubbles can be detected through their high radar return signals, which are hence linked to the bubble abundance. For this method early winter SAR data are needed (Walter et al., 2008).

However, this technique is still in its experimental phase and further research into CH_4 flux estimations from SAR data needs to be carried out.

3.2.3 Thaw lake bathymetry mapping

The determination of the bathymetry of Arctic water bodies through the application of SAR measurements of lake depths, has been done by Jeffries et al. (1996) and Kozlenko and Jeffries (2000).

Jeffries et al. (1996) set out to establish the maximum water depth as well as water availability in two study areas in northwest Alaska using SAR imagery in combination with a numerical ice growth model. Their objective was to determine lake ice phenology with respect to complete freezing (i.e. top to bottom) as well as the establishment of the abundance of completely frozen versus solely ice covered lakes.

Differences in the backscatter values due to the previously explained dielectric properties of water, allow for the effective determination of whether liquid water can be found beneath the ice cover. Lakes that incorporate a liquid-solid water interface where the ice cover does not reach all the way to the bed, are denoted by high backscatter values. Whereas those that have low backscatter values represent completely frozen lakes due to the weak dielectric contrasts between the grounded lake ice and the frozen soil below of the bed. This method is not entirely new and has already been applied in the 1970s by Elachi et al. (1976).

Jeffries et al. (1996) established, by combining their SAR results with a computer model for determining ice growth, that lake depths distinctly vary according to ice phenology. Water bodies that are completely frozen before their ice thickness has reached a maximum are less than 2.2 m deep, whereas those that retain water below their ice cover at the time of maximum ice thickness have water depths that are greater than 2.2 m. In a consequitive study Kozlenko and Jeffries (2000) aimed at establishing bathymetry maps for lake topography using ERS-1 SAR imagery, again exploiting the physical differences in the signatures of floating lake ice and grounded ice as well as a simulated ice-growth curve to generate isobaths. The derived bathymetry maps exclude any lakes that are greater in depth than the maximum ice thickness. The SAR technique cannot provide any bathymetric data for these lakes. Depth assignment of isobaths greatly depends on accurate lake ice growth simulations and therefore it was found that more precise bathymetry maps could be established if the lake ice growth curves would also reflect regional climatic variability.

4 Study Area

4.1 Central Yakutia, Siberia

The area that has been analysed is the Siberian Central Yakutia region at a latitude of ∼62°N and longitude of ∼128°E. There are three main factors that characterise this region which make it an unique part of the world. Firstly, this area consists of terraces that are underlain by alluvial sand and silt that have a high ice content. Thick ice wedges are characteristic of this region. In some places their vertical size is thought to be greater than 50-60 m. Due to its ground ice properties this area favours thermokarst processes.

Secondly, the region was not glaciated throughout the Quaternary, leading to an uncommon geomorphic history. The climatic conditions are the reason for the aforementioned alluvial deposits.

Lastly, Yakutsk's present climatic conditions are among the most extreme in the world. It's continental climate allows for steep annual temperature gradients, with a possible temperature difference between summer and winter of ΔT as high as 62 ℃ (French, 1996). The annual mean temperature is -10.2 ℃ with a mean winter temperature of -38.3 ℃ and a mean summer temperature of +19.6 ℃ (Maximov et al., 2008).

In the past, little precipitation (the annual average being 240-320 mm), and the fact that evaporation itself exceeded precipitation, were major reasons for thermokarst development, which can hence be linked to fires and progressive salinisation of the soil. However, recent studies have showed an increase in the precipitation rate (Iwasaki et al., 2010; Iijima et al., 2010). A study by Iwasaki et al. (2010) showed that precipitation between the years 2005-2006 and 2006-2007 had gone up by 185 mm and 128 mm, respectively, compared to the mean precipitation value from the 26 year period 1982-2008 of 222±68 mm. This has implications on soil water storage in the active layer, as well as melt water runoff from thawing permafrost. Increased precipitation in the form of rain as well as snow changes the properties (in particular the thickness) of the active layer as well as soil temperatures, due to increased snow cover. This then is directly related to permafrost degradation and thermokarst development (Iijima et al., 2010).

Nevertheless, most of the thermokarst subsidence was established during the early Holocene and is no longer active (Brouchkov et al., 2004).

The exact coordinates of the study area in Siberia, as well as its areal extent that was considered for statistical analysis, are given in table 1

Table 1: Coordinates and size of the Siberian study area

Corner points	Latitude (N)	Longitude (E)
Upper left	62°26' 38.39"	129°00' 0.00"
Lower right	62°10' 16.79"	129°32' 2.41"
Areal extent	1 680.413 km^2	

4.2 Mackenzie Delta, Canada

The Mackenzie Delta in the Northwest Territories of Canada was the second region of interest.

The Mackenzie Basin itself extends from 52 to 70°N and 103 to 140°W.

The actual study region is the lowland area east of the Mackenzie River at a latitude of ∼68°N and a longitude of ∼134°W.

This area comprises various cold temperate environments, including mountain, lowland and coastal regions. It is a lake abundant environment. Mean annual air temperature in the delta region near Inuvik is -8.8 ℃ and mean annual precipitation at this cite is ∼250 mm of which about 50% is snow. Air temperatures in this region have been reported to follow an increasing trend, albeit the magnitude of warming is not uniform and differs throughout the basin (Goulding et al., 2009).

This is a lake rich area with predominantly Quaternary sediments consisting of coarse glaciofluvial and fine lacustrine deposits. The Mackenzie Delta lies within the continuous permafrost zone, however, taliks are found beneath most lakes. The permafrost is ice-rich, which can empirically be deduced from the land surface features that are present in this area. Pingos, ice-wedge polygons and retrogressive thaw slumps are all indicative of the above mentioned ground ice conditions. Collapsed pingo scars and high-centred polygons are very prominent in this region and suggest that thawing ground ice is common throughout the whole area (Kokelj et al., 2009).

The exact coordinates of the study area in Canada, as well as its areal extent, which was considered for statistical analysis are given in table 2.

Table 2: Coordinates and size of the Canadian study area 2007 and 2008

Corner points	Latitude (N)	Longitude (W)
Upper left	69°06’ 00.00”	134°00’ 00.00”
Lower right	68°50’ 14.40”	133°18’ 23.99”
Areal extent	878.25 km^2	

5 Data and Method

Microwave data from the European Space Agency's ENVISAT and the Japan Aerospace Exploration Agency's ALOS satellites were processed. Both these satellites are currently in a polar orbit around the Earth and as part of their payload both satellites contain synthetic aperture equipment. The instruments in question are ENVISAT's Advanced Synthetic Aperture Radar (ASAR) and ALOS's Phased Array type L-band Synthetic Aperture Radar (PALSAR). The latter, as its name suggests, operates in the L-band at $\lambda = 15$ to 30 cm (with a centre frequency of 1.27 GHz) (Japan Aerospace Exploration Agency, 2009), the former does so in the C-band at $\lambda = 3.8$ to 7.5 cm (with a centre frequency of 5.331 GHz).

ASAR can provide radar data in different modes of varying spatial and temporal resolution. For the study of thermokarst lakes ASAR's Wide Swath (WS) mode is available. WS mode uses a pixel spacing of 75 m, which corresponds to a spatial resolution of 150 m (European Space Agency, 2009a).

PALSAR has a spatial resolution of 12.5 m (European Space Agency, 2009b), which allows for a more detailed analysis.

Like-polarisation is required for the effective classification of surface water bodies. For both ASAR and PALSAR horizontally transmitted and horizontally received (HH) polarisation were acquired. In the case of ALOS, horizontally transmitted and vertically received (HV) polarisation were also initially processed, although these data are usually more useful for monitoring vegetation.

Data of the Mackenzie Delta for the years 2007 and 2008 and for Yakutsk for the year 2009 were acquired from both space agencies. In the case of PALSAR each year consists of one summer scene. ASAR, however, allows for more frequent imaging and therefore multiple images within the summer months were processed and merged by the IDL extracting algorithm.

The exact dates for the acquired data are given in table 3. It is important to realise here that the dates do not overlap exactly for the two sensors, but differ by a few days/weeks. Indeed, although all of the ASAR Mackenzie 2007 dates are within July, there is about a 2 week difference to the PALSAR date. On the other hand, ASAR Mackenzie 2008 is only separated by PALSAR through a few days, but only one scene within August was acquired and additional dates from July were used. This was necessary since the August scene was over a very small region. With respect to Yakutsk 2009, no ASAR data were accessible for August, and September scenes were processed.

These temporal differences in data can impact the classification, as seasonal changes in backscatter values will result in over/underestimating the threshold values (especially for ASAR for which, as explained in section 6.1 an automated procedure was utilised).

The raw data were first processed in an ENVI™ software environment, using algorithms

Table 3: Exact dates of the scenes acquired by the two satellites

	Mackenzie 2007	**Mackenzie 2008**	**Yakutsk 2009**
PALSAR	18. July	18. August	26.August
ASAR	02. July	09. July	01. September
	05. July	21. July	20. September
	08. July	25. August	
	09. July		

that have been developed by the Institute of Photogrammetry and Remote Sensing of the TU Vienna that call ENVI™'s SARscape software.

The Shuttle Radar Topography Mission - Geological Survey Global 30 Arc-Second Elevation Data Set (SRTM-GTOPO30) was used as a digital elevation model to correct for topography.

The processing steps were then followed up by a spatial analysis with the aid of Geographical Information Systems (GIS).

The data were extracted in raster format (i.e. a digital image consisting of a 2-dimensional rectangular array of numerical values representing the radiance of electromagnetic radiation received at the sensor from a particular direction (Rees, 2006)) and were then manipulated within the ENVI™ software environment.

The three steps of image processing that need to be considered are: preprocessing, image enhancement and image classification (Rees, 2001). Once these were carried out the classified data were investigated with the aid of the ArcGIS™ software.

5.1 Preprocessing

The first few stages within the processing chain are usually referred to as preprocessing steps. These can vaguely be divided into calibration and georeferencing, where the former encompasses the conversion of the raw digital numbers, which are measured by the sensors, into their representative physical quantities (Rees, 2006).

The Preprocessing steps are as follows:

1. Radiometric calibration
2. Geometric correction
3. Normalisation - Local incident angle correction
4. Speckle removal - Adaptive filter correction (only done for ALOS data)

A flow chart of the preprocessing steps for the ENVISAT ASAR data is given in figure 1. Due to the different nature of the ALOS PALSAR data, these needed to be processed manually in the ENVI™ software environment, but the underlying principles of preprocessing remain the same.

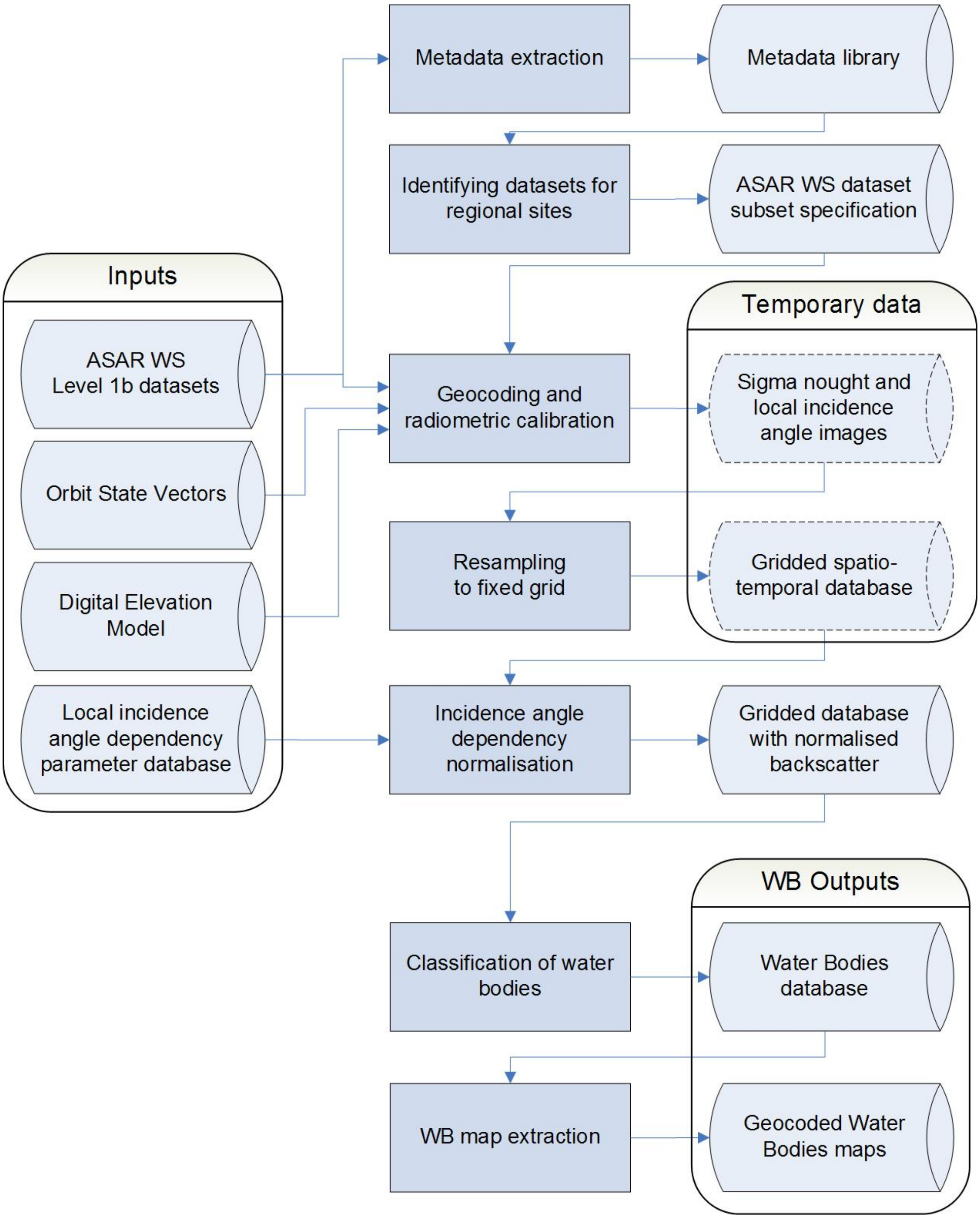


Figure 1: Overview of processing steps for ASAR data (Sabel, 2007)

5.1.1 Radiometric calibration

The ENVISAT ASAR raw data are level 1b data. These have been prepared and calibrated for antenna gain offsets by the European Space Agency. Sigma nought is calculated according to the equation:

$$\sigma^0_{i,j} = \frac{DN^2_{i,j}}{K} \; sin(\alpha_{i,j}) \tag{11}$$

where DN^2 is the pixel intensity value, K is the absolute calibration constant that is found from measurements over precision transponders and α is the incidence angle (Rosich and Meadows, 2004).

5.1.2 Geometric correction

Geometric correction refers to the determination of the relationship between image pixel coordinates and the spatial coordinates on the surface of the Earth. This is done by establishing mathematical relationships between pixel coordinates and so-called ground control points, while at the same time taking topographic features of the Earth into consideration with the aid of a digital elevation model (Richards and Jia, 2006).

In general, the step of geometric correction can be divided into two parts: georeferencing and resampling.

Georeferencing is the determination between the relationship of the spatial coordinates of the image to its respective geographic coordinates on the Earth. This involves attributing the column and row coordinates (i,j) of a pixel to its corresponding latitude and longitude on the Earth's surface (Rees, 2001).

The data are geocoded using the SARscape module of the ENVI™ software. This software uses the range-Doppler method which solves each pixel for range and azimuth distance. The azimuth distance is found from the Doppler shift frequencies that are caused by the motion of the platform and the rotation of the Earth. Input parameters for the satellite's position are established through Doppler Orbit determination and Radiopositioning Integrated on Satellite (DORIS) orbit files. This navigation system is based on a dual-frequency Doppler effect method where the receivers are on board the satellite and the transmitters are incorporated in a terrestrial beaconing network (Federal Agency for Cartography and Geodesy, 2010).

As explained above, the ALOS PALSAR data were geocoded manually in the ENVI™ software environment, while procedures that have been developed by the IPF and which call the SARscape routines were used for automatic geocoding of the ENVISAT ASAR data (Sabel, 2007).

The ASAR data are then resampled to a fixed grid, i.e. transferring the pixel coordinates in the original image to the new coordinates in the transformed image. As the new pixel grid will not be exactly consistent with the locations of the pixel centres in the original image, interpolation techniques are necessary.

Most commonly this is done by nearest-neighbour resampling. This procedure simply chooses the pixel that is nearest to the position in the image and transfers it to the new grid location (Richards and Jia, 2006). The PALSAR data were resampled using this method.

The ASAR WS data were resampled using the optimal resolution technique. The grid was divided into 0.1°by 0.1°gridboxes which results in 3600 columns and 1800 rows. The origin of the grid is set to -180°W -90°S and the projection datum is chosen to be WGS-84 (Sabel, 2007).

5.1.3 Normalisation

Normalisation of the data is an important step as radar backscatter is highly dependent on the local incidence angle. Normalisation decouples the angular dependence of the backscatter intensity from the local incidence angle. The ASAR data are adjusted to a reference incidence angle of $\theta = 30°$(Sabel, 2007).

The backscatter data are on a power scale, these therefore needed to be converted to the log-scale of decibels (dB) according to dB $= 10 \log_{10}$ (power scale).

5.1.4 Speckle removal

Speckle can corrupt an image if it is not appropriately dealt with. One method of overcoming speckle is multilooking. This step is done before geocoding the data, it is however mentioned here as it is relevant for speckle statistics. Multilooking is done by splitting the azimuthal beam into sub-beams. These then synthesise “sub-apertures” that correspond to multiple measurements of exactly the same resolution cell (Woodhouse, 2006).

In addition, a spatial filter can be applied after the image has been created (Rees, 2001). The intention of a speckle filter is to average across relatively homogeneous areas. The difference to the above mentioned multilooking procedure is that spatial averaging is done over different resolution cells, whereas multilooking averages over the same resolution cell (Woodhouse, 2006). Speckle filtering is done with so-called adaptive filters. In the case of the PALSAR data, a gamma filter was applied to the image. No filter was used with the ASAR data as there is only little interference from the surface at this resolution.

5.2 Water body classification

Preprocessing is followed by image classification. This step essentially consists of turning the measured intensities into a thematic map, which can either be done through automated procedures within the software, or manually. The aim is to gain quantative results by identifying certain features. In effect the intent is to classify all pixels of the image into land cover classes (Lillesand et al., 2008).

When considering the water body classification we are only interested in one land cover class: The thermokarst lakes themselves. The approach that is taken is known as density-slicing. A threshold for the backscatter values of the lakes is set. Those pixels that lie below the threshold are classified as water, those above are classified as *NoData*. It is a simple procedure that can be applied to single-band images. The determination of the threshold value itself was done empirically within ENVI™, and as a second step, this was checked by inspecting the entire distribution of backscatter values for the raster images as well as in addition by fitting a Gaussian function to the backscatter value distribution of the lakes.

5.3 Pixel count differences between PALSAR and ASAR

The amount of information that is gained or lost by using a different sensor is examined by comparing the pixel count of the lakes in each region. Both the ALOS and ENVISAT data were resized to have exactly overlapping coordinates for each sensor for the respective years. The images were then inspected in ArcGIS™ and the differences were visually compared.

5.4 Lake classification according to ground ice conditions

The final step, is to classify each lake according to its ground ice conditions. Thermokarst formation is highly dependent on ground ice content. The ability to attribute each lake to specific ground ice conditions gives further insight into lake dynamics.

As ground ice is a subsurface phenomenon it cannot directly be measured using radar but *in situ* measurements need to be done for this identification to take place. Therefore, the classification of the lakes according to their ground ice conditions has to be inferred with the aid of geographic permafrost maps, in particular those of the National Snow and Ice Data Centre (NSIDC) in the United States.

The approach that is taken is to first classify the lakes according to their water density and then to compare this classification to the ground ice conditions acquired from the permafrost maps. Therefore, the lake density needs to be established. This was done in ArcGIS™ by the initial step of converting the raster image into vector data. The area within each polygon (representing the lake boundaries) was then calculated and used to determine the amount of water per m^2. In order to be able to do this the geographical projection needed to be changed to UTM (52°N for Yakutsk and 8°N for the Mackenzie Delta).

The classification of each lake according to the lake density was likewise done in ArcGIS™ by applying a zonal statistics function. The chosen input features were the lake boundary vector files as well as the water density raster files. The statistics of the density raster within the lake boundaries were calculated, such that each lake was allocated a specific zone. The statistics were calculated according to the mean of all cells in the input raster (i.e. of the density raster) that belong to the same zone as the output cell.

The classified lakes were then compared to the permafrost maps, to analyse whether ground ice conditions play a role according to the classification of the lakes.

6 Analysis and Results

6.1 Density-slicing of water bodies

In order to create a thematic map of the water bodies a certain backscatter threshold needed to be applied for the differentiation of the lake surfaces from their surrounding environment. The threshold was first determined by inspecting the backscatter values in the images themselves.

Table 4: Backscatter threshold values for PALSAR

	Mackenzie 2007	**Mackenzie 2008**	**Yakutsk 2009**
		Backscatter values [dB]	
Polarisation (HH)	-19.75	-20	-18.5
Polarisation (HV)	-26.8	-27.5	-26.8

This procedure was more straightforward for the PALSAR data. Since only one scene per year was available, each scene was inspected separately. For each scene the appropriate backscatter threshold was set accordingly.

As the ASAR data were processed in an automated manner the inspection of each scene individually did not make sense. Therefore it was important to set the threshold value by analysing the entire distribution of backscatter values for a given region and to in addition take a statistical approach and fit a Gaussian distribution to these data allowing the threshold to be set at the level of quantification of 3σ within the mean.

Table 5: Gaussian fit of Mackenzie ASAR backscatter distribution

	Mackenzie 2007	**Mackenzie 2008**
Mean (μ) [100dB]	-1587.29	-1712.36
Stdv (σ)	52.1681	81.53

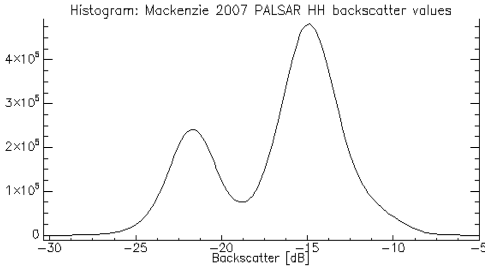
According to this approach it was decided that a threshold of -14 dB would be sufficient for adequate classification. This value was included in the IDL code that extracted the processed data.

The statistics were computed for the Mackenzie Delta for both years. No statistics were done on the Central Yakutian region, as it was decided to test the automated classification and therefore no normalised data sets were created (this was done separately in a first instance investigation for Mackenzie). Rather the threshold was set in the IDL extraction algorithm according to the established statistics for the Mackenzie Delta. Figure 2 shows a histogram of the backscatter values, while figure 3 depicts the classified lakes for the Mackenzie Delta 2007.

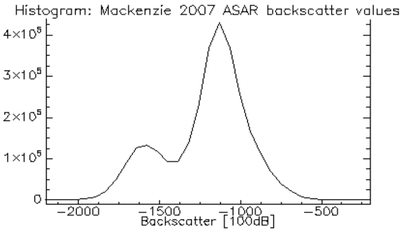
6.2 Pixel count comparison

As a means for determining how much information is lost by using two different sensors, the pixel counts of ASAR and PALSAR for each region were compared to each other.

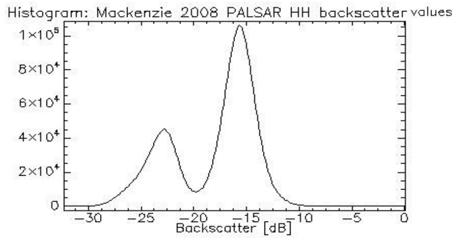
Since it is important that the pixel counts of two exactly overlapping regions are considered, the ASAR data were resized in ENVI™ so that they were completely within



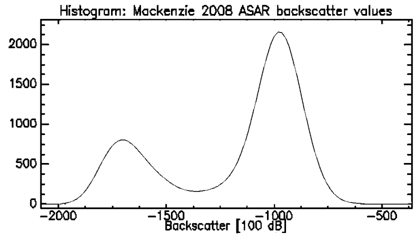
(a) Histogram of PALSAR backscatter values for Mackenzie 2007



(b) Histogram of ASAR backscatter values for Mackenzie 2007



(c) Histogram of PALSAR backscatter values for Mackenzie 2008



(d) Histogram of ASAR backscatter values for Mackenzie 2008

Figure 2: Example of threshold determination for the Mackenzie Delta 2007 and 2008

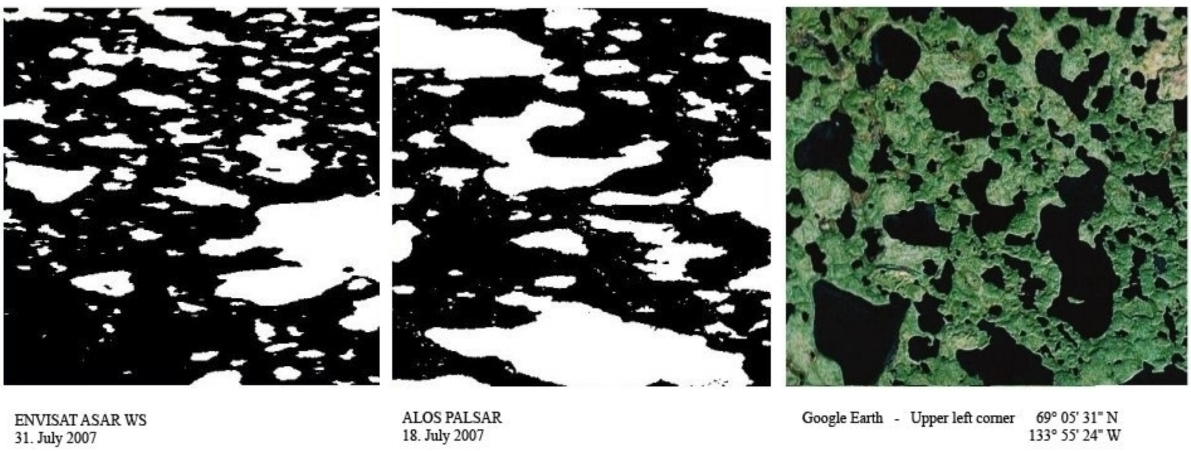


Figure 3: Classified Lakes for the Mackenzie Delta 2007

the area of the PALSAR data.

Figure 4 depicts a subset of the 2007 Mackenzie data for PALSAR, overlain by the ASAR data for comparison. Here it has to be noted that a certain trend, i.e. a small shift of the ASAR data to the West, is visible. This indicates a certain geolocation error, that must have occurred during the georeferencing step. Nonetheless, this has no implications for the pixel counts, as their abundance will not vary due to such an error. The amount of lake pixels was found to be approximately 3 to 10 % higher for the PALSAR data, depending on the region (lake pixel percentages for both regions and sensors are given in table 6). This is unsurprising as PALSAR has a greater spatial resolution and therefore is able to pick up more information than ASAR.

The difference in pixel counts for both years of the Mackenzie Delta amounts to 1 to 3 %. This is within reason and supports the method of threshold determination.

Table 6: Percentage of thaw lake pixel counts

	Mackenzie 2007	Mackenzie 2008	Yakutsk 2009
ASAR [%]	23	26	0.92
PALSAR [%]	32	31	3.5

It is interesting that in Central Yakutia both sensors experience a drop in pixel counts. This is mainly due to the different geomorphological conditions compared to the Mackenzie Delta, which result in fewer thermokarst lakes, however, another component must also be considered: Vegetation. Yakutsk lies at a lower latitude than the Mackenzie Delta and vegetation is more abundant than further North due to slightly milder climes. Therefore, backscatter values are decisively different and less pixels can be associated with lake surfaces.

6.3 Water density determination

The calculation of the amount of water per m^2 was done in ArcGIS™. Vector files of the lake boundaries were established and used to calculate the size of each lake in m^2. With the aid of the spatial analyst tool box and its density function, the density of the lakes was calculated for a search radius of 5000 m^2. It was decided to created three water density classes (high, medium, low). The density classification was adjusted so that the PALSAR data had the same classification range as ASAR.

The output raster for Central Yakutia and for the Mackenzie Delta are depicted in figures 7 as well as 8 and 9 respectively.

When comparing the Yakutsk data a clear trend is visible, nevertheless, the density maps differ from one another greatly in particular in the North of the study area.

In the Mackenzie area it is possible to not only compare the data of the two different sensors to each other but also the data for two consecutive years. Naturally, it is found that the water density for PALSAR is higher than that of ASAR, however, the discrepancies in the two sensors are not as great in this area as can be found in Siberia.

The differences in the water density in the Mackenzie Delta are due to the high

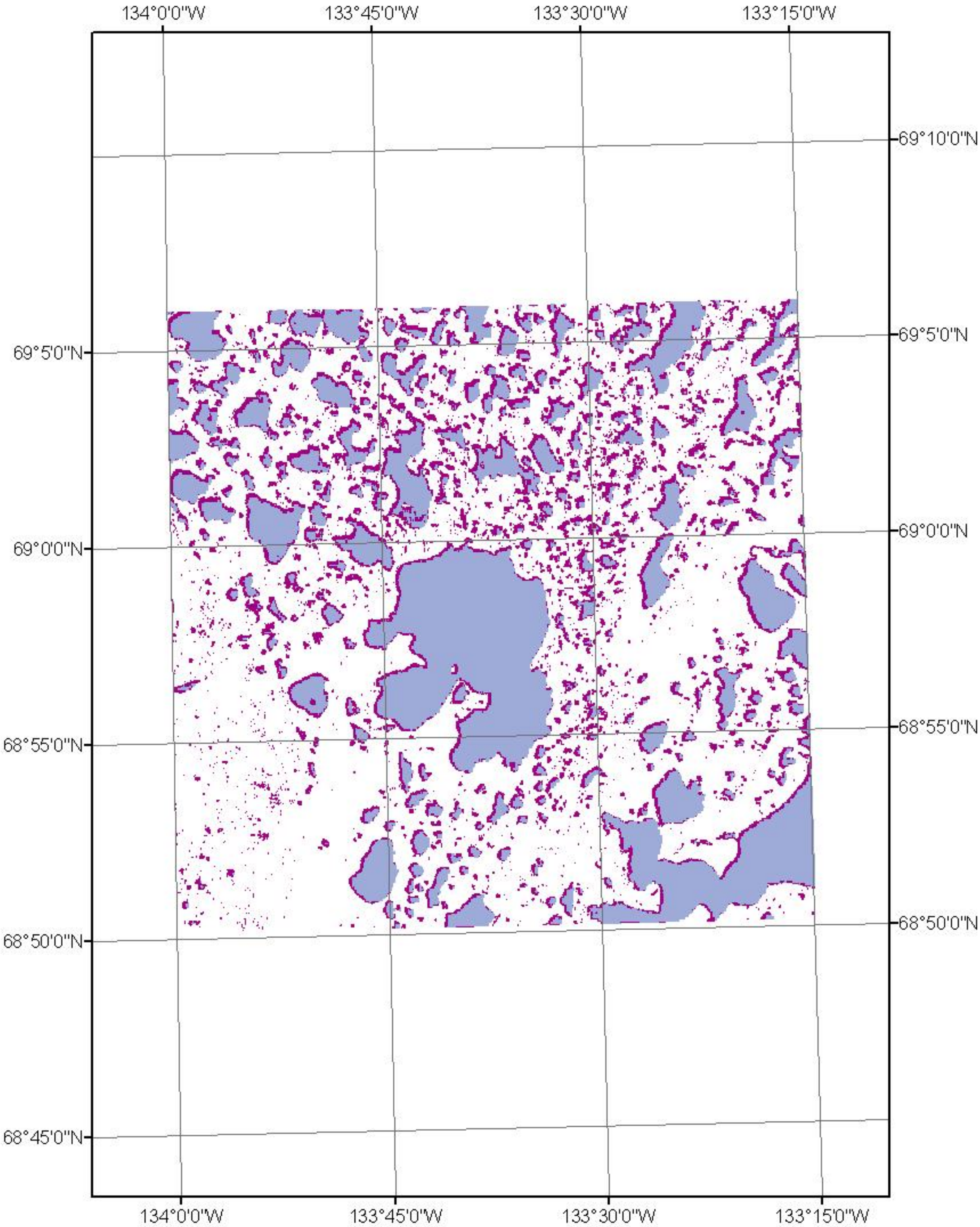


Figure 4: Pixel count comparison between ASAR (violet) and PALSAR (pink) for the Mackenzie Delta study area (2007).

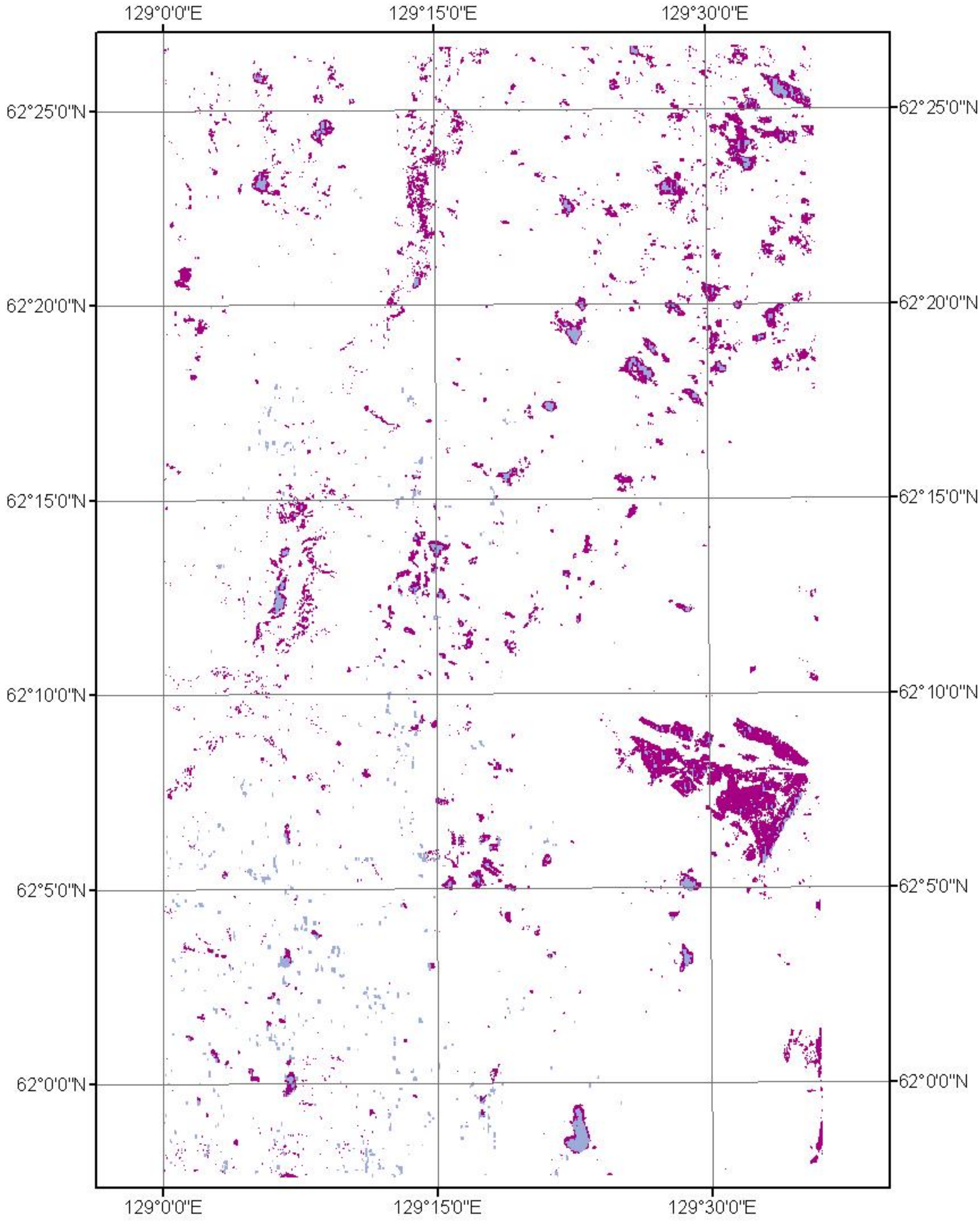
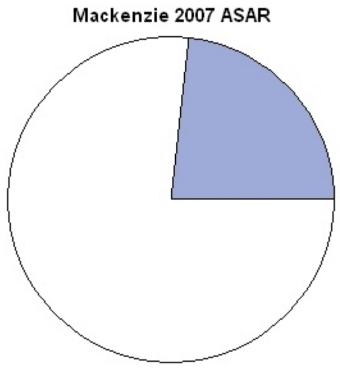
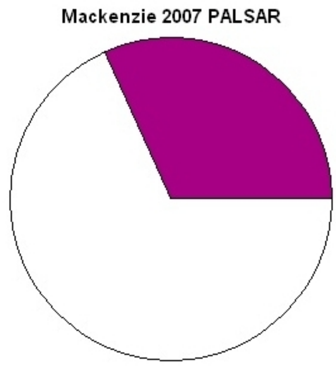


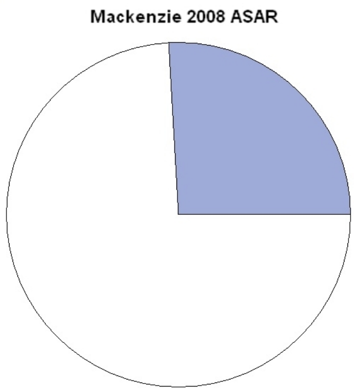
Figure 5: Pixel count comparison between ASAR (violet) and PALSAR (pink) for the Central Yakutian study area (2009).



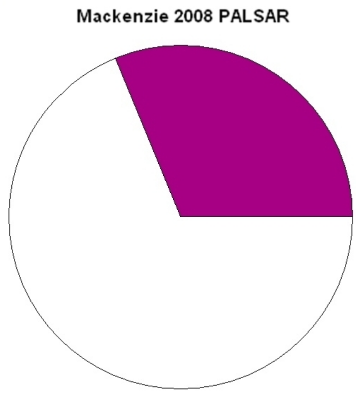
(a) ASAR pixel counts (∼23% lakes)



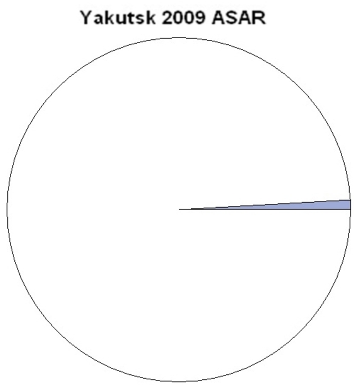
(b) PALSAR pixel counts (∼32% lakes)



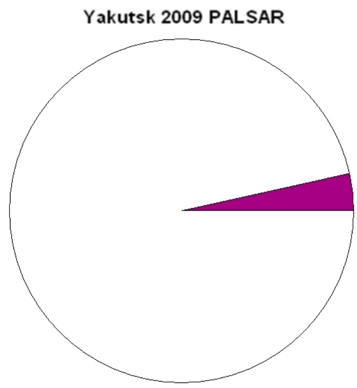
(c) ASAR pixel counts (∼26% lakes)



(d) PALSAR pixel counts (∼31% lakes)



(e) ASAR pixel counts (∼0.92% lakes)



(f) PALSAR pixel counts (∼3.5% lakes)

Figure 6: Percentages of lake pixel counts for the Mackenzie Delta 2007 for (a) ASAR and (b) PALSAR, the Mackenzie Delta 2008 for (c) ASAR and (d) PALSAR and Central Yakutia 2009 for (e) ASAR and (f) PALSAR.

abundance of lakes, in particular small lakes which cannot be detected by ASAR with its spatial resolution of 150 m.

The differences in water density that have arisen in Central Yakutia are related to the fact that there are fewer lakes in this region and vegetational growth in the summer is high. Therefore, the L-band frequencies are small enough for radar penetration. The C-band's wavelength is not long enough to be able to detect these vegetated lake areas.

In both cases, water density is not just related to surface water abundance but also to lake abundance itself, e.g. both areas containing many small lakes as well as areas containing few large lakes can be classified as high water density regions.

6.4 Zonal statistics of water bodies

The final stage was to classify the lakes according to their ground ice conditions. This was done in two steps:

1. Calculate zonal statistics according to the water density profiles.
2. Compare the results to circumpolar maps that are available from the National Snow and Ice Data Centre (NSIDC), as well as the International Institute for Applied Systems Analysis (IIASA).

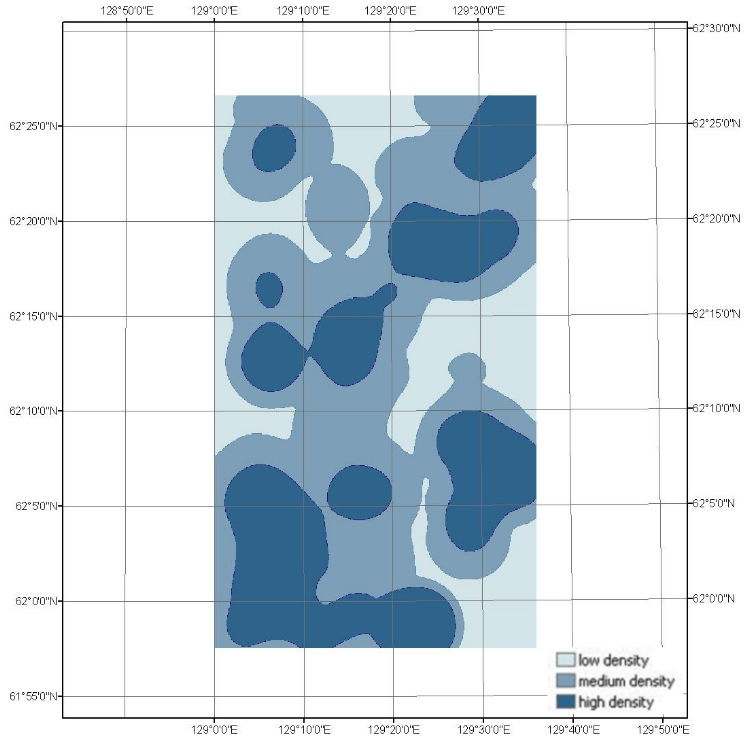
The zonal statistics tool within ArcGIS™ provides the appropriate means for the former step. The lake area statistics according to the three above established water density zones were calculated for each data set. The results are given in table 7 below.

Table 7: Lake area statistics in m^2 within each water density zone.

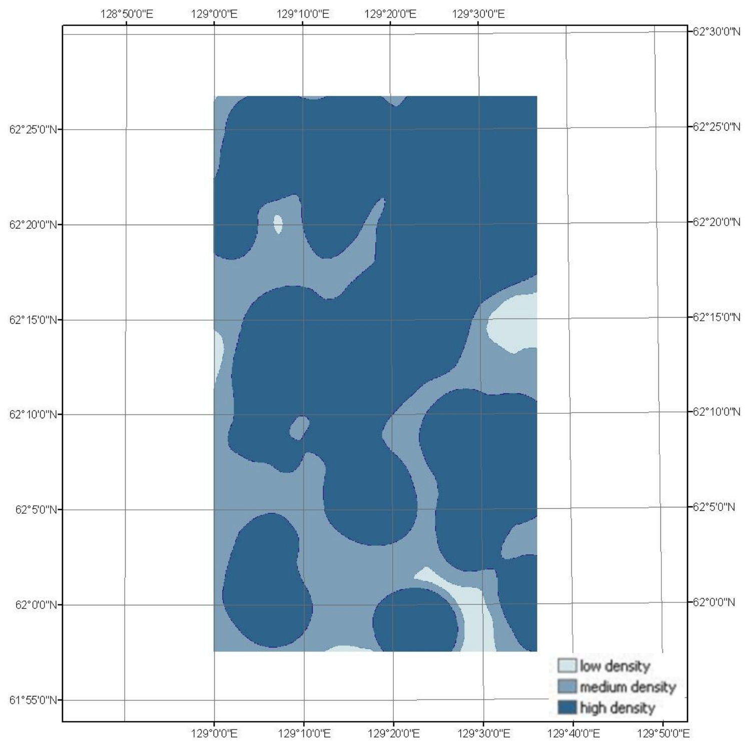
		Mackenzie 2007		**Mackenzie 2008**		**Yakutsk 2009**	
		ASAR	PALSAR	ASAR	PALSAR	ASAR	PALSAR
water density	lake area [m^2]						
low	minimum	2815	1524	2665	-	2017	-
	maximum	1.5*10^5	3.6*10^7	3.1*10^7	-	1.8*10^4	-
	mean	1.1*10^5	2.5*10^7	1.1*10^7	-	7.4*10^3	-
medium	minimum	1412	137	1337	130	2017	196
	maximum	5.9*10^7	6.3*10^7	6.1*10^7	6.2*10^7	1.6*10^5	1.5*10^5
	mean	1.6*10^7	2.8*10^7	1.7*10^7	2.1*10^7	3.2*10^4	3.5*10^4
high	minimum	1412	137	1337	130	1887	196
	maximum	5.9*10^7	6.2*10^7	6.1*10^7	6.2*10^7	1.2*10^5	8.8*10^6
	mean	2.5*10^7	1.9*10^7	2.3*10^7	1.9*10^7	2.1*10^5	1.7*10^6

By inspection of figure 7(b) it is visible that the low densely populated water areas in Yakutsk are hardly existent for PALSAR and it so happens that no lakes can be found within this zone.

Within the medium and high water density zones, the minimum PALSAR lakes are up to one magnitude smaller than the ASAR lakes. However, the mean lake sizes within these two regions do not differ greatly from one another for PALSAR and ASAR.

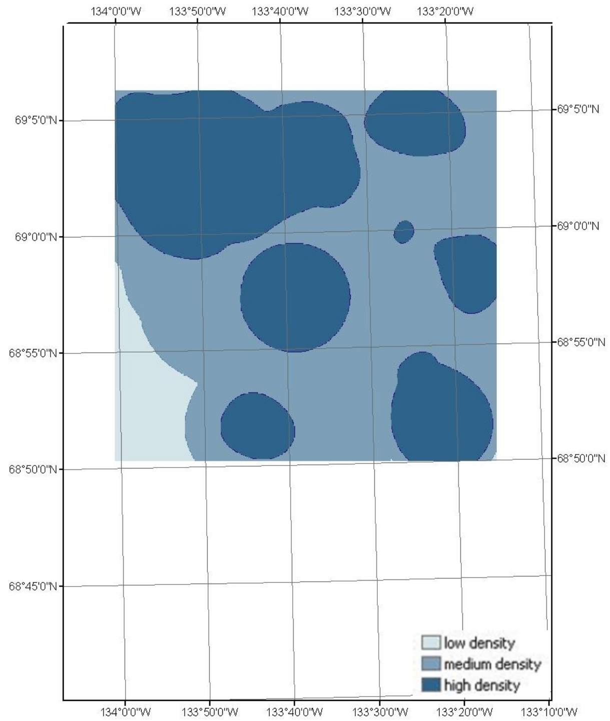


(a) Lake density in water/m^2 for ASAR

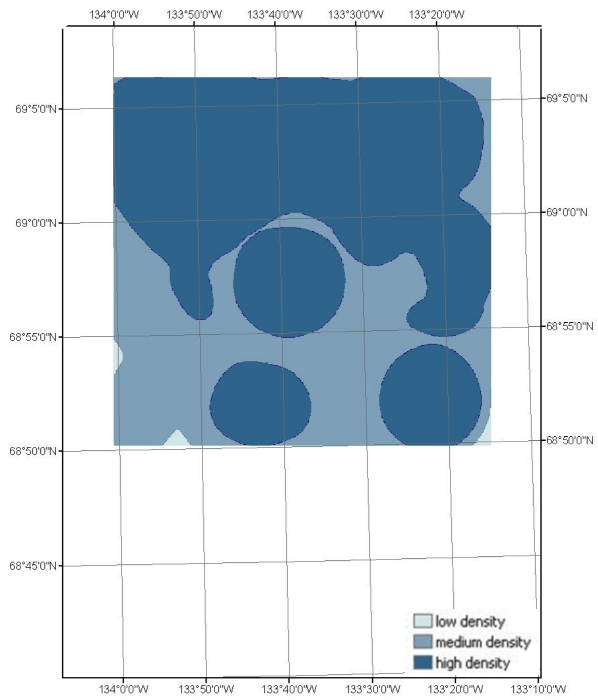


(b) Lakes density in water/m^2 for PALSAR

Figure 7: Lake density for Central Yakutia 2009 for (a) ASAR and (b) PALSAR data. Increasing water density with increasing opacity according to the zonal classification of table 7.

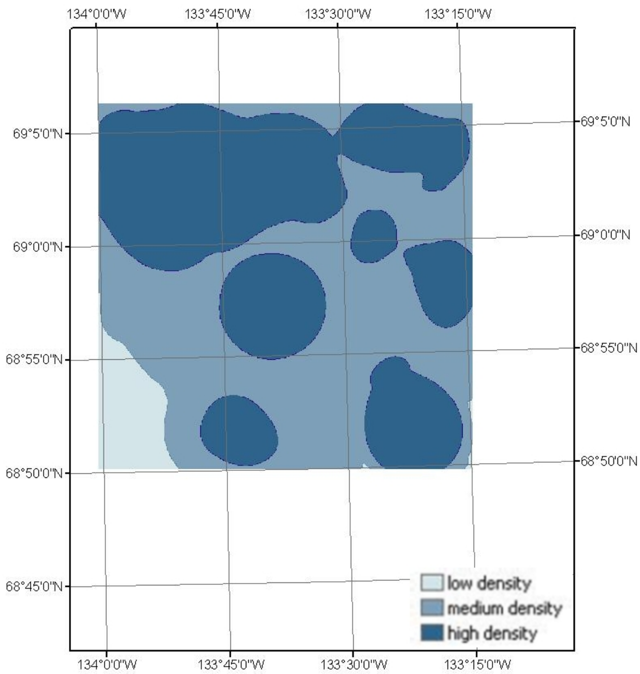


(a) Lake density in water/m^2 for ASAR

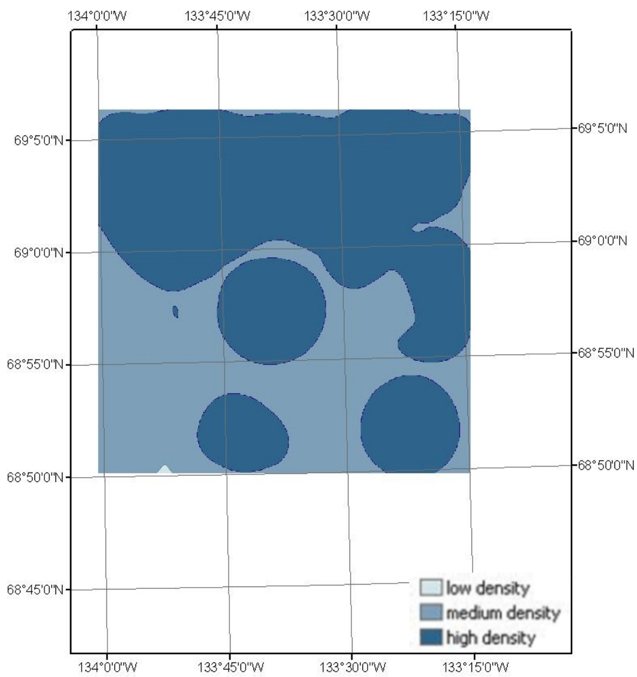


(b) Lake density in water/m^2 for PALSAR

Figure 8: Lake density for the Mackenzie Delta 2007 for (a) ASAR and (b) PALSAR data. Increasing water density with increasing opacity according to the zonal classification of table 7.



(a) Lake density in water/m^2 for ASAR



(b) Lake density in water/m^2 for PALSAR

Figure 9: Lake density for the Mackenzie Delta 2008 for (a) ASAR and (b) PALSAR data. Increasing water density with increasing opacity according to the zonal classification of table 7.

As a second step, the results were compared to circum-arctic permafrost maps that were provided by the NSIDC and IIASA with the aim of determining a possible trend between ground-ice conditions and water density.

According to the NSIDC map the Yakutsk study area lies within a region whose ground ice content is on average within the range of 10 - 20% v/v, but at its greatest can be up to 40% v/v. The IIASA permafrost map for Siberia gave a similar result.

Most of the Mackenzie Delta study area lies within a region of continuous permafrost with high ground ice content (ranging from $\sim$ 20% v/v). However, the most southwesterly corner of the Canadian study area is identified as lying within a discontinuous permafrost zone (where permafrost extent is 50-90% of the area) with medium ground ice conditions. Identifying this discontinuous area on the water density maps shows that only a low abundance of water surface area of the 2007 ASAR data can be found within this region whereas a medium abundance of lakes are found in this area according to PALSAR. This is not surprising, since PALSAR has the ability to resolve smaller lakes (and according to the zonal statistics these lakes are of the order $1.5 \cdot 10^3$ m^2). However, interesting is that according to the 2008 datasets, this region is classified as being of medium water density for PALSAR and ASAR alike. Indeed if we investigate the two ASAR datasets further, we can clearly see that in 2007 ASAR did not see the lakes within this small area of discontinuous permafrost (see figure 11). A first thought was that there might have been a lake increase from 2007 to 2008, however, comparing the 2008 ASAR dataset to the 2007 PALSAR dataset clearly shows that the lakes that have been made visible for ASAR in 2008 already existed in 2007 according to PALSAR (see figure 10). Therefore, an increase in lake abundance due to an annual difference in ground ice conditions in this area of discontinuous permafrost can be ruled out. Indeed, the discrepancy in the 2007 and 2008 ASAR data might have arisen due to the unified threshold value that was set for the automated classification procedure, especially given the different observation dates. Only one of the ASAR images in 2008 was taken at the start of July, meaning that there is up to nearly a 2 month difference between the 2007 and 2008 data (see table 3).

Furthermore, it was unfortunately found that the permafrost maps were a little too coarse given the small study areas in Siberia and Canada. Indeed, more detailed, local permafrost maps would be required for the task of comparing these to the evaluated zonal statistics. This therefore remains an open task that is suggested to be investigated in further studies.

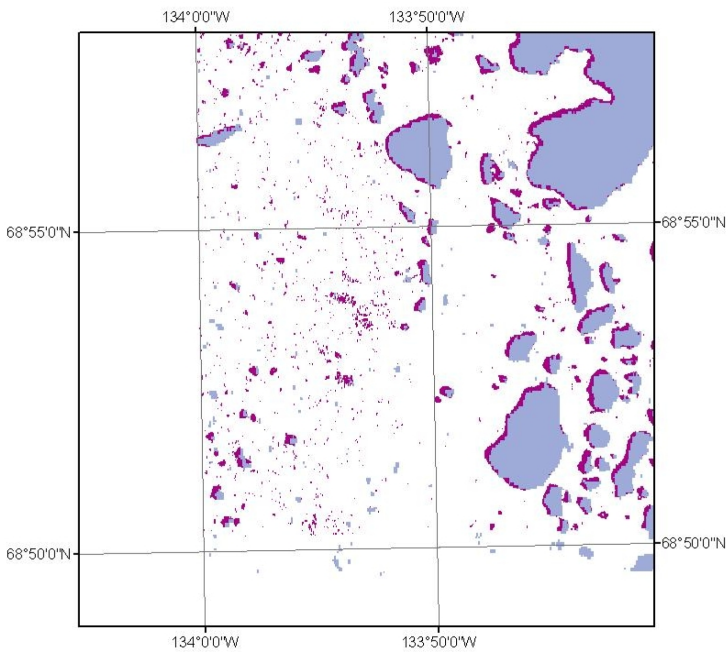


Figure 10: Comparison of the ASAR dataset for the Mackenzie Delta 2008 (violet) with the PALSAR dataset for 2007 (pink).

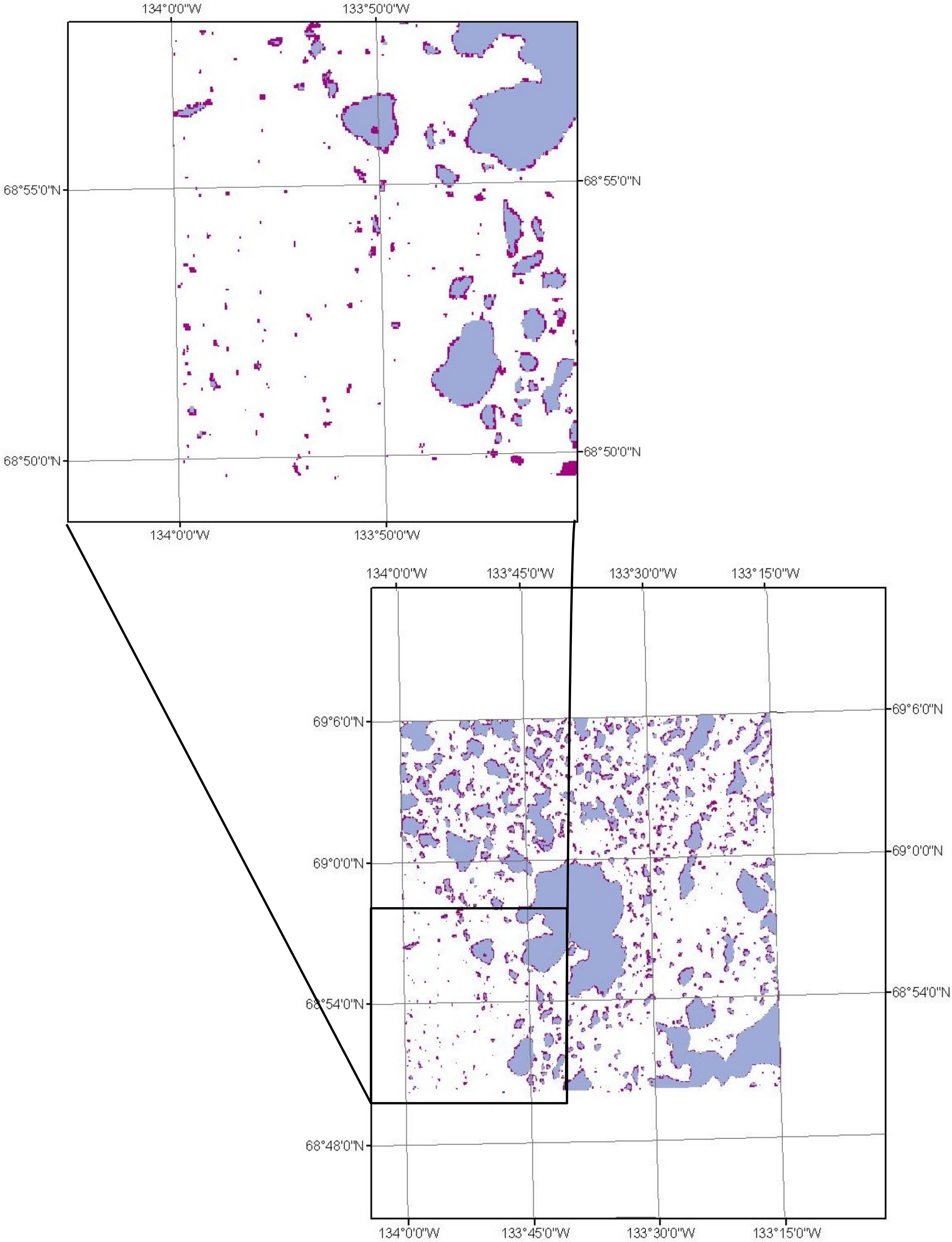


Figure 11: Comparison of the ASAR datasets for the Mackenzie Delta in 2007 (violet) and 2008 (pink).

6.5 Errors

The accuracy of the results has important implications for further analysis. In order to connect a degree of confidence to the results error handling needs to be undertaken. Classification accuracy is usually done empirically by comparing sample pixels from the classified thematic map and checking their classes against reference data. Usually these reference data are in-situ measurements. This step is also known as validation or ground truthing. It is hence possible to estimate the percentage of pixels that have been classified wrongly and of those that have been classified correctly. The accuracy of the classification is determined by creating a so-called *confusion matrix*. The matrix represents the amount of validation pixels that have been correctly and incorrectly associated with a specific class within the thematic map classification. One distinguishes between errors of omission and errors of commission. The former are related to those pixels that were not recognised to belong to its specific class, whereas the latter correspond to those pixels that have falsely been identified as belonging to a certain class. In the confusion matrix errors of omission are represented by columns and errors of commission are represented by rows. The accuracy of the classification is then determined by the ratio of the number of pixels that have been correctly labelled within a specific class and the total number of validation pixels of this class (Richards and Jia, 2006).

Unfortunately, no validation data have been made available for this study and therefore all classification attempts need to be handled carefully. It is fortunate that for the first classification procedure the sole interest lies within distinguishing surface water bodies from surrounding areas, i.e. we are only interested in one land cover class: Lakes. As explained earlier, the classification procedure has been greatly simplified due to the characteristic specular reflection of microwaves off smooth water surfaces. However, erroneous pixel allocation is especially difficult to handle at lake shorelines. Here, it is most likely that both errors of omission and commission have occurred. This issue is termed the mixed pixel problem.

In addition to mixed pixels, there are also errors of commission, which are due to low backscatter values within the surrounding soil, possibly due to standing water and non-permanent inundation. These errors have occurred due to vegetational interference. The longer wavelengths of PALSAR (L-band) can penetrate vegetation more than ASAR (C-band). Therefore PALSAR can pick up water surfaces below vegetational cover. Inundation does not automatically have to be associated with lakes. Indeed, standing water below vegetational cover can easily be falsely classified as lakes, especially for PALSAR.

A particularly problematic area for classification was found to be in Central Yakutia. Here, it was quite visible that a great amount of the pixels (more so for ALOS but also for ENVISAT) were classified as lakes, despite the associated land cover feature clearly being unnatural (see figure 12). It was decided that this area had to be of anthropogenic origin due to its distinct geometric properties that do not resemble those of a natural

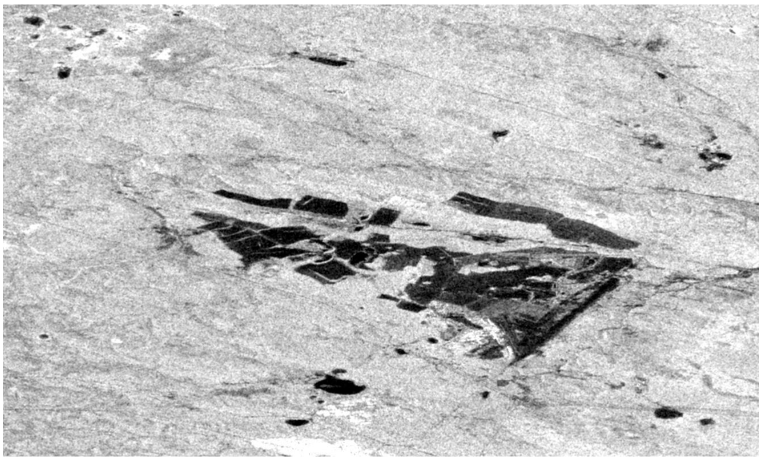


Figure 12: Scene from PALSAR in Yakutsk. Region of low backscatter that can clearly be identified to be of anthropogenic origin.

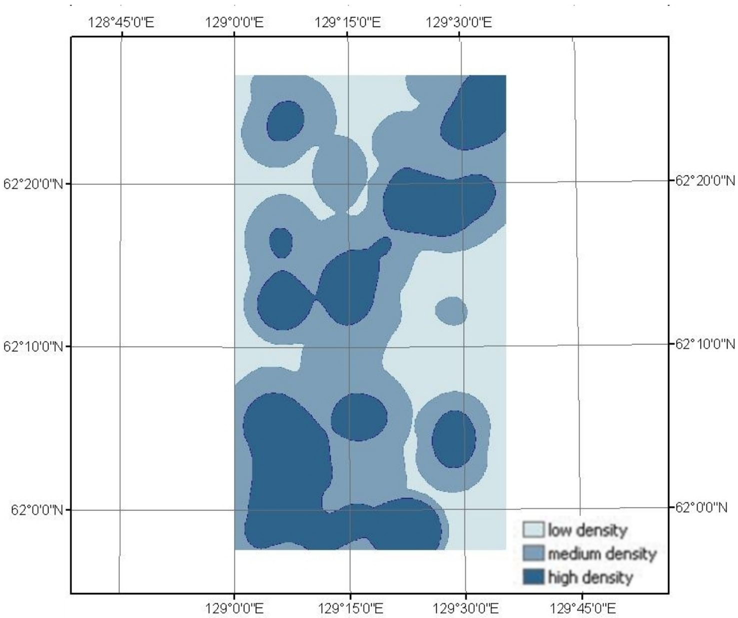
lake. Indeed, if the confusion matrix approach was applied to ALOS PALSAR for the Yakutsk data, then approximately 202427 out of 205005 pixel counts would have been errors of commission, resulting in a very low accuracy of the thematic map of barely 1.26%. This is clearly insufficient. Therefore, it was decided to exclude a polygonal area around this feature. The four coordinate points of this area are given in table 8.

Table 8: Coordinates of the polygonal Siberian area identified as being of human origin

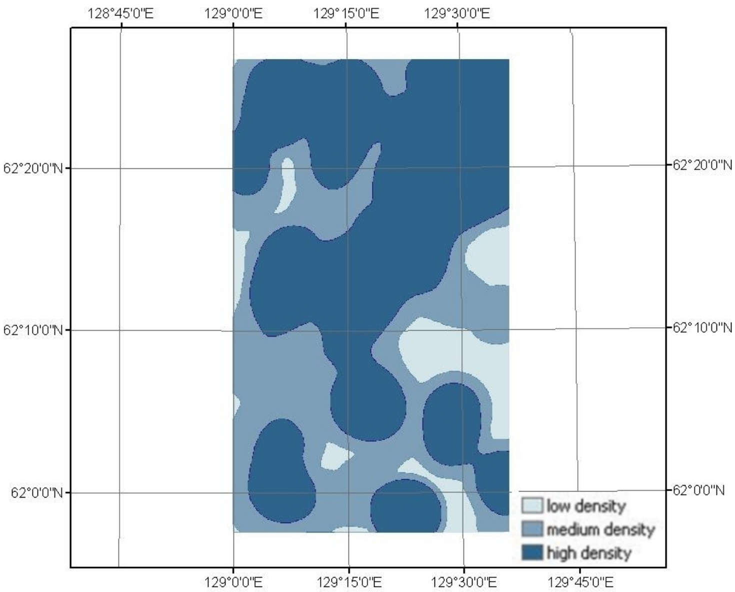
Corner points	Latitude (N)	Longitude (E)
Upper left	62°10' 56.518"	129°24' 48.278"
Upper right	62°08' 37.024"	129°35' 45.586"
Lower left	62°08' 29.005"	129°23' 05.562"
Lower right	62°03' 45.629"	129°35' 45.586"

The exclusion of this area, also means that the pixel counts have changed and the low return in lake pixels for Yakutsk has increased further.

Subsequently, the same approach as earlier for the water density determination was applied. As expected the density regions slightly change when we remove this area (compare figure 13 to figure 7). According to this improved lake classification new zonal statistics for Yakutsk were established (see table 9).



(a) Lake density in water/m^2 for ASAR



(b) Lakes density in water/m^2 for PALSAR

Figure 13: Lake density for Central Yakutia 2009 for (a) ASAR and (b) PALSAR data, where the area of anthropogenic origin has been removed. Increasing water density with increasing opacity according to the zonal classification of table 7.

Table 9: Lake area statistics for Yakutsk with improved water density classification

		Yakutsk 2009	
		ASAR	PALSAR
water density	lake area [m^2]		
low	minimum	2017	$1.1*10^4$
	maximum	$1.8*10^4$	$1.1*10^4$
	mean	$1.03*10^4$	$1.1*10^4$
medium	minimum	2017	$1.1*10^4$
	maximum	$1.6*10^5$	$1.3*10^5$
	mean	$3.4*10^5$	$3.7*10^4$
high	minimum	1886	$1.01*10^4$
	maximum	$1.2*10^6$	$1.6*10^6$
	mean	$2.3*10^5$	$4.1*10^5$

7 Discussion

7.1 Previous studies on thermokarst lakes

In the past few years there has been increasing research on thermokarst lakes. This can be associated with their importance in the context of climatic studies and their relevance for modelling greenhouse gases. Therefore, many of these studies are related to methane exchange and emission upscaling.

For instance Schneider et al. (2009) set out to classify land cover types on a wetland in the Lena Delta in Northeastern Siberia using Landsat-7 Enhanced Thematic Mapper (ETM+) data, and to attribute measurements of methane emissions to the various land cover classes. Thermokarst lakes played an important, but tricky role in the upscaling of methane emissions. In particular, the assignment of emission rates to water bodies in general turned out to be a challenging task, as these differ greatly in hydrological and cryolithological properties as well as size and depth. Thermokarst lakes are located in a region of ice-rich permafrost and organic-rich soils and were therefore found to be large methane sources by decomposition of Pleistocene carbon which is subsequently exchanged with the atmosphere through methane ebullition. In total, seven land cover classes were determined of which two were related to water bodies (one of which was labelled thermokarst lakes). It was found that in the Lena Delta region only 3% of the lakes could be classified as thermokarst, but these accounted for methane emissions that were 3 times higher than those of all other water bodies.

Landsat-7 ETM+ data in combination with digital elevation data were also used by Grosse et al. (2006) for establishing a method to quantify permafrost degradation in relation to thermokarst features and for the reconstruction of the regional palaeogeography. Mapping and classifying periglacial, circum-Arctic lowland terrain enables the quantification of thermokarst activity during the Holocene and an assessment of coastal dynamics and sediment and soil organic matter fluxes to the Arctic Ocean. The study showed a self-reinforcing reaction of thermokarst development in ground ice-rich areas and subsequent drainage changes. The classification approach of using both Landsat data as well as a DEM, that was calculated from manually digitised elevation data, allowed for a good classification result with an overall accuracy of 79%.

Hinkel et al. (2005) likewise used Landsat-7 ETM+ image scenes to undertake a statistical spatial analysis of thaw lakes and drained thaw lake basins (DTLBs) in the Western Arctic coastal plain of Alaska.

When thaw lakes drain, they leave behind DTLBs. It has been established that these are good sites for the aggregation of soil organic matter (SOM), which exists in the form of peat. Field samples from this area showed that on average 48 kg C m^{-3} where found in the near-surface soil profiles of DTLBs. This is a considerable amount of carbon that at the moment is sequestered in the permafrost but with increasing temperatures could be mobilised by the thawing ground and result in carbon exchange with the atmosphere.

Hinkel et al. (2005) were interested in establishing a relationship between thaw lakes and DTLBs, in particular their size, shape and orientation were analysed to allow for a better understanding of their physical properties that in turn are inevitably related to their geochemical characteristics. This area of Alaska is associated with elliptical thaw lakes that have fairly high eccentricities and a major axis orientation that is 10-20° to the West of North, a characteristic that is claimed to be due to thermo-mechanical erosion of ground ice rich permafrost controlled by wind dynamics.

In a follow-up study, Frohn et al. (2005) mapped these thaw lakes and DTLBs with an overall classification accuracy of 97.7%. Their aim was to establish a method for extrapolating field measurements of organic layer thickness, thaw depth and SOC across large areas, so that one can arrive at good estimations of spatial distribution of SOC.

However, there have also been studies on lake dynamics themselves, most importantly those of Smith et al. (2005, 2007). In 2005, their paper entitled *Disappearing Arctic Lakes*, in which they analysed changes in lake abundances in continuous and discontinuous permafrost regions in Siberia, was published. Their investigation was based on a comparison of recent satellite data (from 1997 to 2004) with imagery from the early 1970s. Multispectral satellite data were used for inundation mapping. Many drained thermokarst basins were identified to be overgrown with vegetation. This can be determined from its high reflectance in the near-infrared regime of the electromagnetic spectrum.

It was found that there was a net lake area increase in the continuous region, while there was a net lake area decrease in the discontinuous zone. Therefore, it was argued that the initial surface warming leads to the well-known thermokarst development, which in turn is associated with thaw lake formation and further expansion as the permafrost continues to degrade. However, they then hypothesise that further degradation results in lake drainage and lake disappearance.

Another study on thermokarst lakes was conducted by Smith et al. (2007), evaluating their spatial distribution and examining the influencing factors using a statistical approach. The abundance of lakes and inundated areas were established and compared to lake density populations in different environments. This resembles to some extent the method that was used for the above described investigation of Central Yakutia and the Mackenzie Delta. However, in this case Smith et al. examined lake distributions according to different terrain classes that were provided by the Global Lakes and Wetlands Database (GLWD), while lake area distributions according to a lake density classification were investigated in this study. Unfortunately, it was shown by Bartsch et al. (2008a) that the GLWD is too coarse for a more detailed analysis as it varies a considerable amount in accuracy which is location dependent. Otherwise, this could have been considered as a source for further work on lake classification within Yakutsk and the Mackenzie Delta.

7.2 Current study's findings and their relevance

The prime objective of this study was to establish any discrepancies that arise between the two sensors ALOS PALSAR and ENVISAT ASAR (WS) with respect to monitoring thermokarst lakes. Indeed, this investigation set out to verify that any detailed information that is lost due to ASAR's lower spatial resolution is negligible for operative monitoring of these lakes.

Spatio-temporal changes in thaw lake abundances have, important implications for climatic studies. It is a well-known fact that spatial resolution has an inverse relationship to temporal resolution. The higher the resolution, the less frequent will the data return be and vice versa. This trade-off has to be compensated for by carefully deciding on how coarse or fine the spatial resolution needs to be. Pixel size plays an important role, as it is impossible to see anything below the spatial resolution. Therefore, choosing the necessary spatial resolution is essential.

The study showed that despite having a far coarser resolution to ALOS PALSAR, ENVISAT ASAR WS does provide adequate information for the effective monitoring of thermokarst lakes.

A comparison of the pixel counts resulted in an approximately 5-9% difference for the Mackenzie Delta and less than 2.5% difference for Yakutsk. However, the result for Yakutsk is slightly skewed and might not be an ideal comparison to Mackenzie, as the ground ice conditions are very different and the lake abundance in Siberia is far less than that in Canada. Furthermore, the difference in sensor wavelengths need to be taken into account as well. The Siberian site lies further South than the Canadian Mackenzie Delta and therefore in the summer months more vegetation flourishes in this region, which can be penetrated by PALSAR's L-band, but not by ASAR's C-band.

Further to the pixel count investigation it was hoped to establish a relationship between water density zones and ground ice conditions with the aid of permafrost maps. Here it has to be said that this was not possible in an effective manner, as the permafrost maps were too coarse for any detailed classification to be made. The spatially averaged statistics that were presented above for the zonal abundance of lake sizes provide little value for understanding physical properties of lake formation with respect to ground ice conditions. However, further investigation might be an option if more precise permafrost maps or even in-situ validation measurements of ground ice conditions were to be made available.

Nonetheless, metrics of lake size within each water density zone were established and it was found that apart from the low water density zone, the mean lake size for both ASAR and PALSAR within the medium and high density zones were within the same magnitude. This result shows that ASAR can indeed be a useful tool in monitoring thermokarst lakes within water abundant permafrost regions.

Following the objective of establishing a comprehensive analysis of the ASAR versus the PALSAR sensors for the operational monitoring of thermokarst lakes, it can be said that ASAR WS does indeed provide enough information for continued monitoring, especially in combination with its high temporal resolution.

It is interesting to note that most of the previous studies on thermokarst thaw lakes were undertaken using Landsat-7 ETM+ data. This sensor has a spatial resolution of 30 m and a temporal resolution of 16 days (National Aeronautics and Space Administration, 2010). PALSAR, with its 12.5 m resolution, could provide more detailed analysis than the previous studies. However, PALSAR has a repeat cycle of 46 days (European Space Agency, 2009b). The low temporal resolution of the ALOS satellite's instrument has implications on continuous and effective monitoring of thaw lakes. As explained previously, changes in thermokarst dynamics can occur rapidly. Data availability is a crucial, limiting factor for operational monitoring. PALSAR's strength lies within its high spatial resolution and is therefore a useful tool for a 2^{nd} tier investigation once regions of interest (where spatio-temporal lake changes have been identified) have been established using higher temporal frequency data. PALSAR's strength should therefore be exploited in combination with other data for a more complete picture.

In addition, it has be noted that Landsat-7 ETM+ has in the past not only been used for inundation mapping but mainly for land cover classification studies (including the classification of thermokarst lakes). The potential of the ETM+ instrument lies in its multispectral sensors, and the possibility to identify different spectral signatures. The physics behind this method is very different to that of radar. Both rely on the interaction of radiation and matter, however, ETM+ is not only a passive sensor, but it measures the spectral reflectance of land cover types. Microwaves, in turn, take advantage of the dielectric properties of matter and the coherent distortion of radiation that arises from the scattering of incident electromagnetic waves off discrete objects (Woodhouse, 2006). It is hence not surprising that different a kind of information reaches the sensors. Due to characteristic spectral reflectances of soil, vegetation and water, ETM+ is particularly useful for examining land cover classes.

Radar data can also be used for measuring above-ground biomass changes, due to volume scattering and surface roughness. Vegetation shows up as changes in the degree of image brightness when using cross-polarisation (HV or VH), an effect that arises from the scattering off multiple branches and leaves (Short, 2010). However, radar's main advantage lies within the realm of hydrology.

It is therefore apparent that the decision whether to use PALSAR or ETM+ data depends on the anticipated aims of the investigation. Thaw lake mapping with the aid of ETM+ data has the highly negative, and unavoidable issue of cloud cover. This is not the case for radar. Once again, the holistic approach would be to make use of both kinds of data.

8 International Outreach

The international community is interested in Arctic issues on different levels: Socio-economic and environmental, with regional and global impacts. A warming climate has a key role to play when it comes down to both regional and global problems. International organisations are interested in ensuring that the Arctic's unique characteristics are preserved and adequate mitigation measures are being taken. However, there are also those organisations and initiatives that aim to monitor essential climate variables (ECVs). One such ECV is permafrost.

It has recently been established that most climate models do not take enough observational data into consideration. The need for the generation of Fundamental Climate Data Records (FCDRs) has been realised, which includes the monitoring of permafrost, since it is one of the established ECVs.

Therefore, this section on International Outreach discusses on the one hand the international community's interest in Arctic protection itself and on the other hand the need for spaceborne climate monitoring.

8.1 The Arctic Council

Cooperation among the eight Arctic nations (Canada, Denmark, Iceland, Norway, Sweden, Russia and the United States) takes its highest form in the Arctic Council. Originally established as a "high level forum" (Bloom, 1999) to address any issues that might arise in the Arctic regions and promote mutual assistance, the Arctic Council has in the past few years become an influential entity with increasing importance.

The realisation that the Arctic is a delicate region, susceptible to many human disturbances, lead to the adoption of the Arctic Environmental Protection Strategy (AEPS) in 1991. A particular turning point was the devastating *Exxon Valdez* oil tanker accident that happened in 1989. It was realised then that the Arctic belongs to one of the areas with the highest ecological sensitivity whilst at the same time it has a low ability to recover from any environmental impacts (Howard, 2009).

The AEPS was envisaged as a coordinated environmental programme that was to deal with environmentally precarious situations. However, it was not a legal regime and as such, AEPS did not issue any legally binding decisions but relied upon the good will of the Arctic States to listen to the recommendations of the established working groups (Rothwell, 1995). In 1987, before the collapse of the Soviet Union, President Gorbachev made a speech in which he urged for more political collaboration (Keskitalo, 2007). However, it was the end of the Cold War that would provide the basis for the possibility of cooperation to emerge. As a result, one of the main goals of AEPS was dedicated to the improvement of the air conditions in the Russian Arctic caused by industrial pollution (Bloom, 1999).

From the very beginning the Canadian government had pressed for cooperation not just on an environmental but also on an economic level. The incentive for such a development was political in nature and induced by the unauthorised transit of US ships through Canadian waters (Keskitalo, 2007). The Canadian government was of the opinion that a more influential organisation could strengthen its own position. Canada, therefore, was the driving force and initiator of the Arctic Council which was established in the Ottawa Declaration of 1996. Its significance was a change from a purely environmental protection programme to the more encompassing notion of sustainable development. The Council took on all existing programmes under AEPS and broadened its functions to incorporate economic development as well as environmental protection (Bloom, 1999).

The Council was created as an intergovernmental forum and is not an international organisation. The establishment of a forum with no legal personality was very much in the interest of the United States, who were in favour of creating an informal but common framework in the Arctic without having to confer too much power on the institution. This structure does, however, have the benefit that each state can determine for itself which activities should be funded and how much money they are willing to spend on each. On the other hand, it also means that financial burdens are not necessarily equally partitioned and funding can be ceased without any legal repercussions (Bloom, 1999).

Nonetheless, there are other advantages in an informal institution. All decisions in the Arctic Council are taken by consensus of each Arctic State and therefore no agreements can be made that are conflicting or contrary to national policies (Bloom, 1999). This is an important incentive for collaboration, as the Arctic Council can only work in unity with all its member states.

The Arctic Council has allowed for observers to participate and contribute to its work. NGOs such as WWF and IFRC (International Federation of Red Cross and Red Crescent Societies), as well as non-Arctic states that have had historical interest and are familiar with Arctic issues have been admitted to the status of an observer (Bloom, 1999). France, Germany, Poland, Spain, the Netherlands and the UK all hold permanent observer status (Arctic Council, 2007)

8.2 The IPA and the IPY

In 1983 the International Permafrost Association (IPA) was founded as a non-governmental association of national organisations interested in permafrost research. The IPA's goals are to facilitate the dissemination of knowledge concerning permafrost and to encourage cooperation among its members (IPA, 2010).

The endeavour to integrate permafrost data in other realms of science, with the goal of creating a broader scientific picture, calls for cooperation among the scientific community and is promoted by the IPA. As an institution promoting research, the IPA has nine working groups and two task forces. These range from working groups on *isotopes and geochemistry of permafrost*, though *periglacial landforms, processes and climate* to *planetary permafrost and astrobiology.* The two task forces are on remote sensing and subglacial permafrost.

The main aim of the working group on periglacial landforms, processes and climate is to investigate the climatic significance of periglacial environments cumulating in a report that is to review previous research into this field.

The task force on remote sensing's goals are to create a database containing information on study sites that are being or have been investigated in the past using remote sensing techniques. The task force promotes the use of air and spaceborne sensors for mapping and determining specific properties intrinsic to permfrost as well as periglacial features and their relation to climate change. In addition, the task force tries to further the links between space agencies as well as other institutions that have remote sensing bodies within them, with the aim of facilitating the acquisitions of satellite and airborne imagery of permafrost study sites.

The remote sensing task force beseeches the permafrost community to advance any information on previous and ongoing research data on changes in permafrost conditions. This would provide a more holistic overview of changes observed through remote sensing techniques in relation to ground based data. All the input that is given to the task force is used for educational outreach activities of the IPA and all datasets are forwarded to the National Snow and Ice Data Centre (NSIDC) in Boulder, Colorado, USA (IPA, 2009)

Understanding the climatic system of the Earth is one of the greatest challenges of our time. As discussed earlier, both polar regions play a crucial role with regard to the Earth's climatic system. With this information in mind, the forth International Polar Year[1] 2007-08 (IPY) took place from March 2007 - March 2009. The IPY is a collaborative programme addressing polar research. The urgency for such an initiative comes from the findings of abundant changes in snow and ice. Therefore this international framework was in particular a coordinated international campaign promoting the investigation of climate change studies and the analysis of impacts on high-latitude regions (Drinkwater et al., 2008).

Research in the harsh environment of the polar regions can only be done with great logistical efforts. The IPY allowed for the coordination of these efforts of scientists from over 60 nations. The goals are not only the better understanding of the global climate system but also educational outreach. The IPY hopes to be able to encourage young students and pupils in polar research and engage the public in easily accessible information (IPY, 2010).

With respect to satellite observations, the IPY initiated a working group, the Space Task Group (STG), that worked towards achieving coordinated acquisition of data across different space agencies focusing in particular on SAR and InSAR (Interferometric SAR) data, as the analysis of these data would achieve the highest number of

[1]The other IPYs took place in 1882-83, 1932-33 and 1957-58

IPY scientific objectives (Canadian Space Agency, 2008). However, the acquisition of high-resolution optical data has also been considered. The STG's purpose is to allow for the development of a coordinated acquisition strategy of high data rate sensors (Drinkwater et al., 2008).

The IPY is convened by the International Council for Science (ICSU) and the World Metereology Organisation (WMO).

8.3 The European Union and Arctic affairs

At first glance the links between the European Union and the Arctic do not seem extensive. However, these links do exist through a complex combination of history, geography and economy. Three out of the current 27 Member States of the European Union have territories within the Arctic circle (north of the latitudinal boundary of 66°33' N). These are Denmark (Greenland), Finland and Sweden. In addition, two other Arctic countries (Iceland and Norway) are members of the European Economic Area.

The European Union has realised that its policies within the fields of environment and climate change as well as energy, research, transport and fisheries have a direct impact on the Arctic, which could result in changes to geo-strategic dynamics and international stability with potential repercussions for European citizens (Commission of the European Communities, 2008).

It is in accordance with this realisation that the three main EU policy objectives in relation to Arctic affairs, as proposed by the Commission (Council of the European Union, 2009), are:

- *Protecting and preserving the Arctic in unison with its population;*
- *Promoting sustainable use of natural resources;*
- *Contributing to enhanced governance in the Arctic through implementation of relevant agreements, frameworks and arrangements, and their further development.*

One of the main issues that the Council of the European Union addresses is the crucial importance that the Arctic region has on the world's climate system and the need for action in conformity with the United Nations Framework Convention on Climate Change (UNFCCC). The mitigation of negative consequences as well as adaption to unavoidable changes that will occur due to global warming are of chief concern (Commission of the European Communities, 2008).

The Arctic Council runs many research programmes that it publishes. The information the Arcitc Council provides is of essential value to the European Union. Therefore, the EU is an active supporter of the Arctic Council and other international bodies, such as the United Nations Environment Programme (UNEP). Furthermore, the EU has established that long-term monitoring and data availability is still insufficient and hence it encourages the enhancement of observations of the Arctic regions and the implementation of a monitoring system, so that adequate input parameters for future climate models can be determined (Council of the European Union, 2009). As Wilson et al. (2010) nicely put it: *"The biggest contribution to uncertainty in climate scenarios is the uncertainty in initial conditions."* Limiting uncertainty in climate models is related to increasing our knowledge of these initial parameters through space-based observations. Therefore, Earth Observation data play a key role for future climate predictions and have lead to the European Union's initiative on the Global Monitoring for Environment and Security (GMES). This programme aims at ensuring European capabilities in the area of environmental monitoring (Commission of the European Communities, 2008).

8.4 European and international potential for space based climate change observations

In 2008, at the 5^{th} Space Council meeting on "Space and Climate Change", a resolution between the EU and the European Space Agency was adopted which amongst other statements

> *EMPHASISES the objective to improve the qualitative and quantitative understanding of the extent of climate change and of its consequences and the need to continue and expand the European contributions to this understanding and related modelling, in order to provide the evidence base for key decisions to be taken in environment policy;*

and further

> *CALLS for the scientific community, in conjunction with the EC, ESA, EUMETSAT, to define how the range of GMES services and European space observation archives can contribute most effectively to the provision of data including Essential Climate Variables for scientific research* (Council of the European Union, 2008).

Climate science is becoming a dominant part of politics. A coherent understanding that greenhouse gases are driving the climate has lead to the realisation that adequate climate monitoring is required. It has also been noted that standardised observational data are a necessity for determining rates of change of essential climate variables.

According to the European Commission the focus is meant to be on three main climate services: *Climate monitoring, climate prediction* and *climate research* (Wilson et al., 2010).

Since key policy decisions are usually made on the basis of scientific information, such as climate predictions, it is essential that any climate information does not only hold in the models but in the real world as well.

8.4.1 GCOS and ECVs

One of the main responsibilities outlined in the UNFCCC is related to the above climate services. In particular the establishment of long-term climate data archives is a key commitment of the convention. Following this concern the Global Climate Observing System (GCOS) was established in 1992. GCOS is the internationally approved mechanism for promoting the UNFCCC's commitment.

It is according to the GCOS 2003 report that a list of ECVs were found. All ECVs are both suitable to measure from space and have a high impact on climate following the requirements and principles set out in the UNFCCC for effective monitoring. GCOS determined 44 ECVs that are stated in table 10 below. Nevertheless, GCOS recognises

Table 10: ECVs that were established by GCOS following the requirements of the UNFCCC (GCOS, 2010)

Domain		Essential Climate Variable
Atmospheric (over land, seaand ice)	**Surface:**	Air temperature, Precipitation, Air pressure, Surface radiation budget, Wind speed and direction, Water vapour
	Upper-air:	Earth radiation budget (including solar irradiance), Upper-air temperature (including MSU radiances), Wind speed and direction, Water vapour, Cloud properties.
	Composition:	Carbon dioxide, Methane, Ozone, Other long-lived greenhouse gases and Aerosol properties.
Oceanic	**Surface**	Sea-surface temperature, Sea-surface salinity, Sea level, Sea state, Sea ice, Current, Ocean colour (for biological activity), Carbon dioxide partial pressure.
	Sub-surface	Temperature, Salinity, Current, Nutrients, Carbon, Ocean tracers, Phytoplankton.
Terrestrial		River discharge, Water use, Ground water, Lake levels, Snow cover, Glaciers and ice caps, *Permafrost and seasonally-frozen ground*, Albedo, Land cover (including vegetation type), Fraction of absorbed photosynthetically active radiation (FAPAR), Leaf area index (LAI), Biomass, Fire disturbance.

that these are the absolute minimum of ECVs that need to be monitored and that other types of climate observations do exist (Wilson et al., 2010). However, the focus of international climate observations is to remain on the above list of ECVs as these have been internationally accepted to be the prerequisite parameters for any climate models.

When Wilson et al. (2010) was published it was determined that adequate platforms existed in space for monitoring only 29 out of the 44 ECVs, permafrost not being part of these 29. However, science progresses rapidly and meanwhile methods have been developed for indirect measurements of permafrost parameters from radar observations in combination with ground measurements and models.

In particular with respect to the freeze/thaw cycle, new developments through the implementation of microwave scatterometer sensors have been made. These instruments are highly sensitive to changes in dielectric properties and can hence determine the phase of surface waters (Kimball et al., 2004). However, the inspection of permafrost should always be done in conjunction with field data, as seasonally frozen ground does not automatically imply this being the active layer of permafrost. The existence of permafrost can only be found through borehole probing.

8.4.2 CEOS and IGOS

Although it is a recent development within the European Union to promote spaceborne Earth Observations, the international community realised the need for satellite data more than two decades ago. In 1984 the Committee for Earth Observation Satellites was founded by the spacefaring nations. The organisation's aim is to coordinate all civilian space-based observations of Earth (CEOS, 2010). In particular, a coordination system with respect to data acquisition, calibration and validation standards and data policy was established (Brachet, 2004).

Indeed, these issues have been outlined in a Space Council resolution and are thought to be essential for addressing the effective implementation of any spaceborne climate monitoring scheme (Wilson et al., 2010).

- What standardised data are needed?
- Which data are currently available and which will become available?
- How much additional computing power is needed?
- How can any new infrastructure be established?
- How can coordination be improved?

CEOS plays a vital role within this framework. Since each sensor is built differently, a standardised calibration of each instrument is a necessity in order for inter-comparison of data to be possible. This is in particular relevant to this thesis, as SAR data from two different sensors (and different space agencies) were acquired and comparison can only take place if the calibration of each sensor is compatible with the other. CEOS has taken on the responsibility, together with the World Metereology Organisation (WMO), to develop a Global Space-based Inter-Calibration System (GSICS). In addition, CEOS encourages data exchange among its Members and helps with the coordination of mission planning for optimal and effective Earth monitoring. Space agencies are urged to maintain archives of FCDRs and metadata from all missions, current and past (Wilson et al., 2010).

The increased influx of information needs to be managed and coordinated globally and it is CEOS task to achieve this in an efficient manner.

However, coordination of Earth observations has to be seen as a first stage, but in succession environmental data collection should be considered in combination with in-situ data for the joint application and assimilation in computer models. A method long utilised by the meteorological community, at its forefront the World Meteorological Organisation, but with regard to environmental observations this approach is barely 15 years old. In 1995/96 the concept of an Integrated Global Observation Strategy (IGOS) was presented. This was followed up 2 years later by the establishment of the IGOS Partnership that encouraged CEOS members to undergo serious discourse with scientific research and user communities. The aim was to create space-based and in-situ observation networks, with an emphasis on the recognition of each technique of data collection to be an essential contribution in their own right to an observational system and a holistic scientific picture.

IGOS furthers the interaction between the EO scientists and other scientific communities. As such it has allowed for constructive interactions and has aided in converging environmental research from space with that of traditional scientists on Earth (Brachet, 2004).

8.4.3 The Baveno Manifesto and GMES

European efforts in establishing policies are usually purely politically driven, rather than scientifically. Historically, the European Union has always struggled to find enough common ground among its member states. It should therefore be no surprise that discrepancies have arisen in the context of a common space policy. The European Commission realised these difficulties and former director of its Joint Research Centre, Herbert Allgeier, invited concerning parties, primarily from the space sector, to join together in a series of talks on the development of a European strategy in Earth Observations, held in Baveno along the shores of Lago Maggiore in northern Italy in 1998. Representatives from ESA, Eumetsat, as well as national space agencies, such as Britain, France, Germany and Italy met with participants from the industrial sector who were represented by the European Association of Remote Sensing Companies (Brachet, 2004). The outcome of these meetings was the production of the 'Baveno Manifesto'. This document states that all organisations and agencies that are involved in space activities aim to devote themselves to a *"common European vision and strategy towards global environment monitoring"* (Commission of the European Communities, 1998).

The Baveno Manifesto embodies the awakening of the European Union with regard to the implementation of a common European strategy for global environmental monitoring.

In 2000 a joint EC-ESA document on an European space strategy was produced, a chapter of which was entirely dedicated to *Global monitoring for environment and security* (GMES). In October 2001 the first Communication of the Commission on GMES was presented.

In the wake of the Baveno manifesto ESA member states started to debate the future of its EO programme. In 2001 ESA's Ministerial Council met in Edinburgh, Scotland, were it developed the Earth Observation Envelope Programme (EOEP), which closely follows the well-established executive structure of the science programme assigned to planetary and astrophysical exploration. This mechanism strongly relies on active participation of the scientific community in establishing mission priorities. Although, this was a big step in the correct direction, one great deficiency remained: The opportunity to move forward in accordance with the Baveno manifesto was not taken. No measures to include consultation with the European Commission, despite the existing joint EC-ESA document, were decided upon (Brachet, 2004).

The shortcomings of 2001 were amended when in 2002 GMES entered into its first implementation stage. The aim of GMES is to coordinate and consolidate European undertakings in EO in space as well as with in-situ projects, by including participants from the international scientific community.

The European Community hopes this initiative will allow the establishment of the appropriate infrastructure for long term operational services on climate data sets that have been derived from EO and in-situ observations, including the ECVs that were determined by GCOS.

Under the EOEP the ESA Data User Element (DUE) programme was created with the aim to bridge the gap between user communities and the space agency (European Space Agency, 2010).

The ESA DUE Permafrost project is one of the ongoing activities funded by the DUE; its main contractor being the IPF of the TU Vienna and is also supported by the IPA's remote sensing task force.

The objective of this project is to develop EO permafrost products with close participation of the scientific user communities. This will enable the establishment of integrated EO services based on user requirements with the aim to facilitate the accessibility of remotely sensed permafrost data to these user communities for their own scientific research in the field of climate change detection and modelling, as well as hydrological modelling (European Space Agency, 2008).

The work for this thesis was done in conjunction with the ESA DUE Permafrost project. Its contribution to this project is related to the development of a high latitudinal water body product.

9 Conclusion

The Arctic has in the past gone through much environmental stress. Environmental problems have had troubling implications on the livelihood of plant, animal and human life. It was for this reason that the Arctic Council was estalished, whose work remains at the forefront of Arctic environmental protection. Although, still a pressing issue, however, the focus has shifted from environmental disturbances to climatic concerns. At the centre of this concern lies the recognition that vast amounts of carbon that are stored within the Arctic permafrost are mobilised through rising air temperatures. The need for monitoring permafrost and related periglacial features has lead to the the establishment of programmes and initiatives and furthered international scientific cooperation.

The necessity for adequate monitoring of periglacial features such as thermokarst lakes have become apparent in the past few years. In the wake of the climate change debate, the relationship between thaw lakes and atmospheric methane exchange underlines the importance of an operating monitoring system that would provide sufficient information on changes in landscape dynamics in high latitudinal permafrost regions that will also allow for paeleo reconstruction. Understanding the changes in lake dynamics that have occurred in the past will allow for the adequate adjustment of model input parameters for future predictions.

Exact analysis of ground ice ablation and permafrost degradation needs to be done by field measurements, however, with the use of remote sensing techniques localised measurements can be used for regional upscaling.

A scientist's goal is to establish a big picture, to put his/her research into perspective and give it a broader relevance. The relevance of thermokarst lakes lies within climate research. The combination of field work, remote sensing and modelling is the means of arriving at this big picture. Indeed, this is possibly the ultimate goal of the ESA DUE Permafrost project. The establishment of EO permafrost products for user communities with the input from these scientific users shows the willingness and need for scientific interdisciplinary cooperation.

The realisation of the need for such cooperation, as well as data standardisation and the establishment of appropriate infrastructural networks, has been taken on by the international community. Various programmes have been initiated to tackle these issues.

The establishment of the ECVs by GCOS should be recognised as a milestone, in creating a holistic view of global warming. Encouraging the scientific world to continuously record these ECVs through spaceborne remotely sensed data will benefit our understanding of the climatic changes that are thought to be occurring as well as our possibilities to adapt accordingly.

Thaw lakes in the Arctic tundra fall within the ECV category of *permafrost and seasonally frozen soil*. As such, the operational monitoring of these water bodies is required under the GCOS initiative. Providing the appropriate infrastructure for the management and coordination of data as well as its standardisation is essential to an operational satellite monitoring system. However, the establishment of such a monitoring system does also depend on utilising the adequate sensors. Remote sensing methods incorporate a trade-off between temporal and spatial resolution that need to be taken into consideration. In addition, the decision on wavelength regime of the satellite and in relation to this on whether to use an active or passive instrument, are further factors that come into play. Active microwave as well as optical data are possibilities for thermokarst lake monitoring. Radar's asset lies within the specific dielectric properties of water as well as its ability to penetrate cloud cover (a powerful attribute when dealing with high latitude regions).

The study of thermokarst lakes in the Mackenzie Delta and Central Yakutia was undertaken to analyse discrepancies in the two different radar sensors, ALOS PALSAR and ENVISAT ASAR. Determining which of the two sensors is more adequate for thaw lake monitoring is in coherence with GCOS and accordingly is of great value to the European Commission's GMES initiative.

The discrepancies of pixel counts between the two sensors are up to 10% (including a regional dependency); PALSAR being able to resolve small, abundant lakes. However, the zonal classification of water density shows that lake sizes within these zones are of the same order of magnitude for both ASAR and PALSAR. It was therefore established that although, PALSAR provides a more detailed analysis of lake attributes, such as size, ASAR's data gives sufficient information on these and, more importantly, does this at a higher temporal resolution. The acquisition frequency of lake datasets is a factor that is not to be underestimated, since lake dynamics can change rapidly and need to, therefore, be recorded accordingly.

Other studies on thermokarst lakes mostly took advantage of Landsat-7s ETM+ instrument. With a spatial resolution lying in between PALSAR and ASAR, ETM+ could provide additional information on lake dynamics, especially as it allows for the possibility of identifying surrounding vegetation classes, which influence ground ice conditions and are therefore associated with permafrost changes.

For an all encompassing investigation into lake dynamics it is recommended that the microwave data is to be combined with other data sources, such as optical imagery as well as in-situ measurements.

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