OBJECT BASED THERMOKARST LAKE CHANGE MAPPING AS PART OF THE ESA DATA USER ELEMENT (DUE) PERMAFROST

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ABSTRACT:

This study presents an approach to quantify thermokarst lake change and lake object structure change in spatial very high resolution remote sensing data as part of ESAs "Data User Element Permafrost". Lake Center points are used and multi temporal data is radiometrically normalized using a water mean rationing. A set of specific lake object characteristics (object shape, direction, lake object neighborhood structure and lake density) are parameterized in high resolution Rapideye data and in scanned pan-chromatic films from 1975 (Hexagon). Emphasis is on mapping of structural changes of thermokarst thaw lakes and changes of adjacent lake object properties. For this purpose specific relational neighborhood metrics are developed that quantify structural properties of the thermokarst lake areas and attributed changes. The classification is performed pan arctic on multiple test sites in Siberia, Alaska and Canada. The presented methodological approach provides a robust and transferrable concept for large scale change mapping and is important to quantify changes under potential permafrost degradation conditions. This work is part of the "Data User Element Permafrost" and is a contribution to an observation strategy for permafrost degradation.

1. INTRODUCTION

The proposed concepts in this work are linked towards a monitoring concept (Permafrost Information System) of larger regions as proposed for the ESA “Data User Element Permafrost” (DUE Permafrost) on the basis of 5-7 high resolution local scale monitoring sites situated in specific regions of the pan arctic zone. For this monitoring strategy a multi temporal data coverage is created using Key Hole data sets from Corona and Hexagon missions (1960s-70s), Rapideye data, Landsat MSS and ETM+ data. The final purpose of the water body/change mapping concept for the DUE Permafrost is 1. to provide snapshot based overall lake change information with a resolution that detects fine scale thermokarst lake changes, 2. to provide detailed information for upscaling analysis for regional and pan-arctic landcover levels and 3. to compliment process understanding and permafrost degradation modeling with information derived on sites with ground measurements and process understanding.

To create a comprehensive modeling framework for the permafrost state a list of other Earth observation (EO) based land surface products have been proposed (ESA User Requirement Document - URD). Water bodies have been defined as one of the key EO-based requirements beside land surface temperature, soil moisture, landcover, snow cover extend, snow water equivalent, elevation change/subsidence, and methane emissions.

Various remote sensing approaches have been used in the past for monitoring arctic regions and for permafrost-dominated landscapes in particular. Work has been done on mapping arctic vegetation and its change (e.g. Stow et al. 2004), the study of biophysical parameters (Laidler & Treitz, 2003; Ulrich et al. 2009), the quantification of methane fluxes based on land cover classifications (Schneider et al. 2009), and the indirect observation of permafrost properties (e.g. Peddle and Franklin 1993). The remote sensing of surface water bodies has a long tradition and various techniques were tested and applied in the past. Tarnocia & Kristof (1976) used early Landsat data to classify water bodies in the Mackenzie Delta, Canada. Grosse et al. (2005) used a thresholding approach to classify water bodies at the NE Siberian Coast in panchromatic Corona data and improved the results using visual interpretation to account for errors due to vegetation- and ice-cover and shadows. Frohn et al. (2005) mapped thaw lakes and drained thaw lake basins on the Northslope of Alaska using an object oriented concept. Duguay & Lafleur (2005) mapped lake depth and lake ice thickness using a combination of optical and SAR data.

A rather new and very promising technique not relying on reflectance values alone for water-land classification is additionally using object-based morphometric characteristics for identifying lakes and describing lake structure.

Despite the various existing approaches and the comprehensive datasets available today, the monitoring of long-term changes in lake area and distribution is still in its beginning. Water body change mapping for larger areas in the boreal zone is complicated by a high percentage of cloud coverage, strong inter-seasonal water level changes because of snowmelt, and the lack of historical high-resolution Earth observation data. For vast regions of the Eurasian Arctic the only readily available source for high-resolution data dating back into the 1960’s are declassified reconnaissance images from the US American Key Hole missions and sparse sets of air photos. Historical spatial

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high resolution remote sensing data for Siberia has only been becoming widely available with the declassified data from the photo-reconnaissance satellite systems of the "Key Hole"-series (Corona, Hexagon, Argon and Lanyard mission, the KH-Mission 1-9).
This study aims to develop a new robust object based approach to lake change mapping with robust feature sets that are transferrable to other datasets and regions. A robust approach is a prerequisite within the local multi plot analysis of the ESA DUE Permafrost Earth observation project. To achieve the listed goals: normalization of radiometric information is performed, relative geometric correction is based on a robust set of lake objects, feature-sets are utilized that compare robust lake object properties (e.g. object shape, object density, object neighborhood structure), and a multitemporal approach is created that is based on the spatial geometry of the highest spatial resolution dataset and uses all lower resolution datasets with upsized pixel footprint – utilizing the finest spatial scale for object formation (segmentation) and the lower spatially resolved datasets for spectral, shape and ratio-based descriptions.

2. STUDY AREA AND DATA

The Lena river delta is part of the Republic of Sakha and situated in North-east Siberia at the Laptev Sea coast. The delta has a size of appr. 30000 sqkm and is located in the continuous permafrost zone. The Lena river has a watershed area of approx. 2500000 sqkm. The delta is structured into three main terraces comprising a young active part (1st terrace, Holocene) in the east, an old passive part in the west (2nd terrace, Late Pleistocene-Holocene), and erosional remnants of an accumulation plain in the south (3rd terrace, Late Pleistocene) (Schwamborn et al. 2002). The studied area is part of the 2nd terrace. The cause of lake orientation is still debated but involvement of prevailing wind directions is likely (Morgenstern et al. 2008). For the Lena delta area, panchromatic data of the KH-9 mission "Hexagon" has been acquired from the USGS (Table 1) from 1975 with approx. 10 m spatial resolution (16.7.1975 - Entity ID: DS1009-2054DA103_103_a). Landsat MSS data was also acquired from USGS (Landsat MSS WRS1: 143/8).
The combination with multispectral data for this test area is unavoidable due to very shallow lake areas that were not distinguishable from vegetation in Hexagon datasets. The pan Kodak films that were used for this Key-Hole mission are not sensitive for the near infrared region.
For a recent status of the lakes Rapideye data from July 2009 was used (Table 2).

Hexagon	Source: USGS EROS data center, KH-9 Mission 1210-5 (KH-9-10)
Date	1975 07 16
Cloud Cover	0 %
Catalogue ID	(Entity Id) DZB1210-500150L003001
Spatial Resolution	07 micron scan from 9 x18 in B/W, appr. 20-30 feet (10 m)
Spectral Resolution	Pan
Digitization	8 bits (scanned)
Swath Width	24 mm optic, 10,6 x 144 miles
Orbit Altitude	Elliptical: 100 - 150 miles
Off-Nadir view	0 degrees

Table 1. Hexagon data (KH-9 „Big Bird", Mission 1210-5 – KH-9-10), declassified in 2002.

Rapideye	Source: Rapideye/RESA data project 275 (Rapideye Science Archive)
Date	2009 07 22
Cloud Cover	5 %
Data Set Identifier	2009-07-22T043052_RE5_1B-NAC_1467738_45429
Spatial Resolution	6.5 m
Spectral Resolution	MS blue, green, red, nir1, nir2
Digitization	16 bit
Off-Nadir view	0 degrees

Table 2. Rapideye data used for the medium scale lake change analysis from July 2009 (RESA – Rapideye Science Archive).

3. METHODS

3.1 Data Preprocessing

Landsat 1 MSS data was received in NDF format (National Land Archive Processing System (NLAPS) Data Format) in Level 1B processing status with systematic correction to UTM zone 52 WGS84.
Key Hole data is not provided with map coordinates therefore a georeferencing step using external image map coordinates was needed. For this study Hexagon data was spatially co-registered to Rapideye data using a lake center point correction procedure (LCPC) (Hese 2008) using centroid points from lake polygons.
In a first step the lake objects were derived from a preliminary water classification that creates an underestimated lake representation. For the calculation of centroid points all lake objects with more than 0.5 ha area were removed from the selection. To precisely register lakes from 1975 to lakes from 2009 (Rapideye data) ground control point (GCP) coordinate couples were generated using a "spatial attribute join" based on distance in a GIS. While other features might not be as precisely co-registered - using this method - the procedure has the advantage to create a multi temporal layer stack with precisely overlapping lake polygons. This is a crucial pre-requisite for lake object area, shape, direction and structural attribute analysis and comparison. LCPC will however also mask the relative shift of lake objects towards a specific direction (possibly induced by specific prevailing wind directions). This indicates that the method is not suitable for measuring lake object shifts in a region, as these "distortions" will be removed (corrected) using a polynom of higher order.
Rapideye data is acquired in the framework of the DLR RESA project (Rapideye Science Archive) within the project: "High Resolution Water Body and vegetation Mapping for Permafrost Degradation Modeling (as Part of ESAs DUE Permafrost Project)", Proposal IDs 275 and 344. Data was received for multiple coverages of 5 test areas (in Canada, Alaska and Russia). For this study a coverage at the 22nd of July 2009 was selected covering the western part of the Lena delta with low cloud coverage and ice free vegetation. Rapideye data was imported from the NIFT2.0 format into the PCIDSK format using Geomatica Orthoengine (with provided RPC coefficients). The data was projected to UTM zone 52 (WGS84) and interpolated bilinear to a spatial resolution of 6.5 m.
After the spatial co-registration the panchromatic grey values of Hexagon and Rapideye data were normalized using water mean statistics. The rationing with a mean value from water reflectance of the respective dataset creates a floating point

value raster layer that is scaled back into the 16 Bit space. The "Water Mean Normalization" (WMN) creates normalized grey values for all multi temporal or multi- sensor water objects and equalizes all kind of bit-formats originating from different sensors or preprocessing steps.

3.2 Lake Change Classification

Using Earth observation data in the 5-30 m spatial resolution domain (Rapideye to Landsat type of multispectral data) lake change mapping is restricted to larger water objects and does not provide enough spatial detail to detect fine scale polygon lake structures as can be found in the Lena delta. In Rapideye data most fine scale polygon lake structures (5x5 m polygon lakes) in the Lena delta study site showed mixed pixel values with increased reflectance due to a mixture with vegetation signals. These areas could only indirectly be detected using textural feature descriptions of larger image segments.
The Lena delta test area for the medium resolution lake change analysis is dominated by varying lake depths and water conditions. Very shallow lake areas are difficult to detect in historical Key-Hole data. The panchromatic Kodak films that were used for these Key-Hole missions („Kodak Eastman Panchromatic") are not sensitive for the near infrared region therefore the strong absorption over water areas is clearly missing in the panchromatic signal. The combination with multispectral data for this test area is therefore unavoidable to distinguish shallow water areas from vegetation classes. In consequence a combined analysis with Landsat 1 MSS data sets (available since 1973) is needed in order to integrate near infrared information into the image object classification system. As these datasets usually do not cover the exact time span and year for a given area a combined multitemporal data set in the 70s was created. The large pixel size of Landsat MSS data (80 meters) was uncritical for the object forming process as the objects were created with the Hexagon data sets. However the multitemporal nature of the data set in the 70s will have likely introduced an additional error (this error is difficult to quantify as the low spatial resolution of MSS data does not allow change mapping between 1973 and 1975).
Within the object based approach to image analysis the data fusion can be done prior to the lake mapping. The advantage of multisensor fusion concepts is limited when data segmentation is done in a spatially higher resolved object space and subsequent analysis is done on object basis and not on pixel basis. In order to implement this concept all data set have to be resampled to a common spatial resolution.
For this study the multispectral data from Landsat MSS was segmented together with Hexagon Key-Hole data within one bottom-up multiscale segmentation with weighting of 2 for Hexagon vers. 1 for MSS data. Within this dataset shallow water areas were differentiated from deep water areas based on the NIR information from Landsat MSS data (on a 15 meter cell resolution defined within the multitemporal data stack).
A Rapideye data set with 5 channels was used for this test area with an original spatial resolution of 6.5 m for 2009 – later reduced to 15 m. For the study area a multitemporal data set of July 1973/75 (combined for multispectral data) – and July 2009 (Rapideye) was created.
A hierarchical class description based on three hierarchical class levels and two different topologically connected image object segmentation scales were programmed as a processing routine within the Definiens eCognition image analysis environment. This segmentation creates 290093 image objects in the first level with a mean segment size of 3824,06 sqm for a region of 110933,3 hectares. A hierarchical classification and image object generation and fusion system was created based on the class hierarchy and an image object processing routine as conceptually summarized in Figure 2.

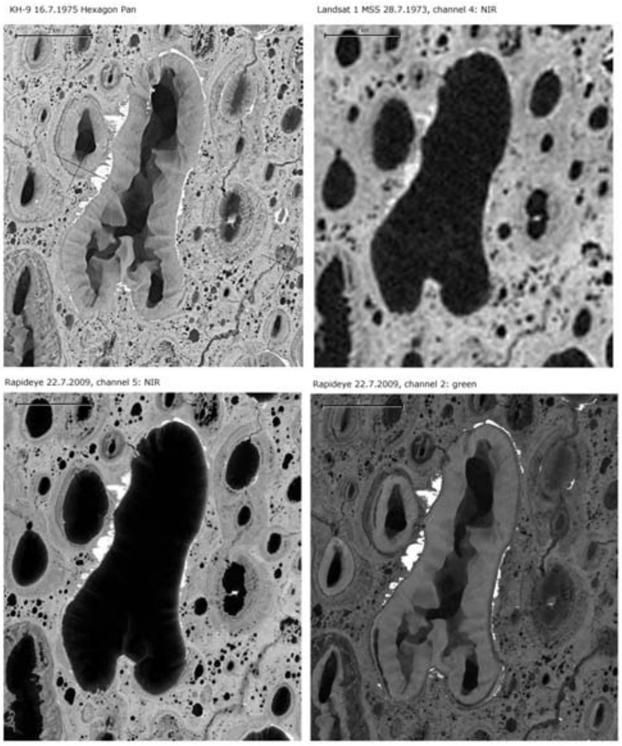

Figure 1. Examples of lake objects in Hexagon panchromatic data (1975), Landsat 1 MSS data (July 1973), and Rapideye data (July 2009)

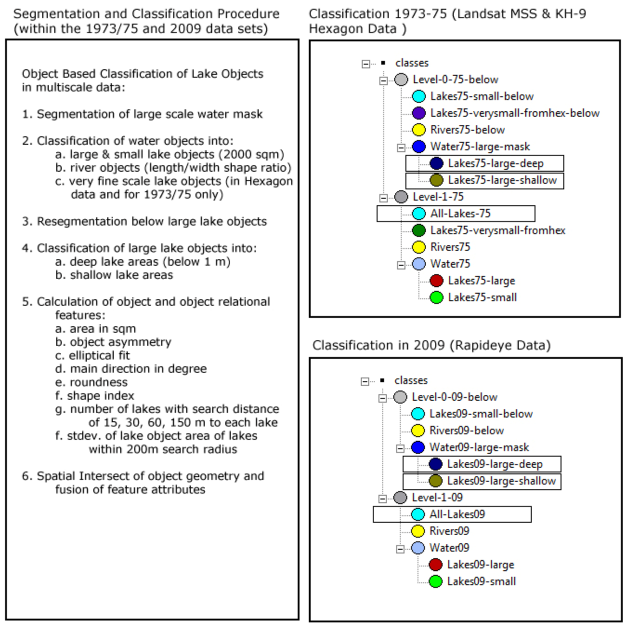

Figure 2. Image object forming and thematic classification concept for water object change mapping based on Hexagon and Rapideye data in two spatial scales

This concept iteratively merges image objects based on their thematic classification properties and generates a reduced number of objects (18896 objects in the first segmentation level).

Shallow and Deep lakes areas were sub differentiated using a second segmentation level in a finer subscale (below large lake objects only) with classification using Landsat MSS multispectral channels.

4. RESULTS

Results from the lake change analysis in the Lena delta test region indicated that only minor changes occurred in this region for the lake areas. The area statistics changed slightly but other lake object descriptions indicated that no major changes have occurred (compare with Table 3). There are changes detectable at large lake object boundaries (lakes larger than 2000 sqm, compare with Figure 3) but these changes can be a result of the limited spatial resolution of the Landsat MSS data that was used 1. to classify larger lake objects and 2. to differentiate between deep and shallow lake object areas.

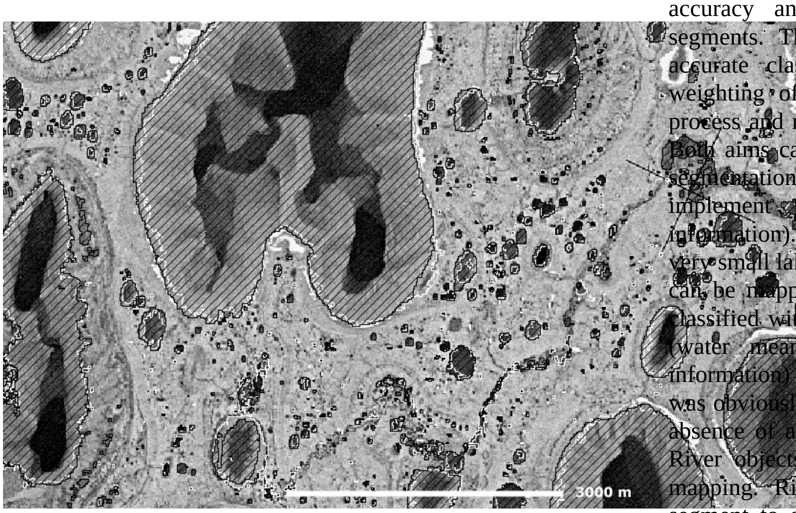

Figure 3. Subset of the lake change mapping results with black hatched polygons (lakes from 2009) and white outlined polygons (lakes from 1973/75)

Lake Object Feature	Statistics	1973/75	2009
Area (sqm)	Mean	54,381 439	66,49
	Sum	820344	840840
	Stdev	697,7	795,4
	Count /no.lakes	15085	12646
	Min	1	1
	Max	66915	68171
Shape Index	Mean	1,2	1
	Stdev	0,35	0,3
	Min	1	1
	Max	5	4,02
Number of Lakes in 150 m distance	Mean	225,1	180,91
	Stdev	77,9	62,62
	Min	1	1
	Max	158	589
Stdev of Area of lakes in 200m Distance	Mean	578	665,5
	Stdev	963	1064,5
	Min	0	0
	Max	7241	7150

Table 3. Lake object and lake object structure statistics for lake distributions in 1973/75 and 2009 (based on lake classification using Hexagon/Landsat 1 MSS data and Rapideye data)

5. DISCUSSION

The small changes classified in this study for the Lena delta test site likely are not linked to permafrost degradation processes or climate change induced processes of the water body structure. The direct linkage to degradation processes needs a combined analysis with local ground reference measurements and local long term monitoring results from the DUE Permafrost user group. These linkages are scheduled for a later stage of the DUE permafrost project with direct cooperation with various user groups that perform ground measurements on all local scale test sites.
The classification accuracy using Rapideye data is clearly superior compared with the classification of water with Hexagon/Landsat MSS in the Lena delta study area. The spectral information from Rapideye for shallow water areas delineates the water-to-land boundaries with higher spatial accuracy and therefore also creates more accurate lake segments. The underlying problem is the tradeoff between accurate classification of small lake objects with special weighting of Hexagon information within the segmentation process and retaining shallow water object boundary accuracy. Both aims cannot be fulfilled at the same time (although post segmentation object border improvement would be possible to implement with spatially higher resolved near infrared information). The region is dominated by a large number of very small lakes that are not detectable in Landsat MSS data but can be mapped in Hexagon data. Small lakes were therefore classified without Landsat MSS using the spectral information (water mean normalized grey values from panchromatic information) from Hexagon only. The classification accuracy was obviously reduced for the 1973/75 status mainly due to the absence of a spatially higher resolving near infrared channel. River objects were excluded from the water surface change mapping. River objects were merged to one river system segment to simplify neighborhood analysis within the object based image processing domain. More detailed analysis revealed however strong shifts of the river objects that indicate major changes for the position of river objects. The quantification is not a straight forward comparison of clearly delineated image objects. Mapping of river system shifts should quantify the relative changes with direction and value as a vector measure. The prerequisite for river change mapping is however a definition of reference points that are hardly detectable or visible if the river segments have changed considerably.

6. ACKNOWLEDGEMENTS

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