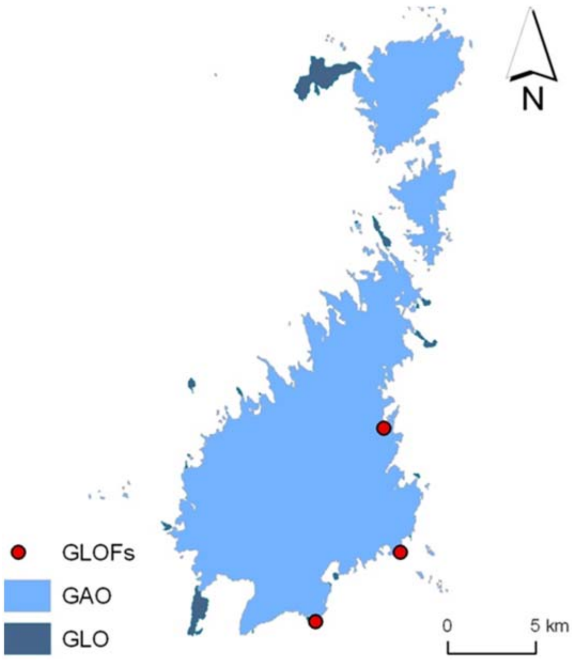
Algorithm Theoretical Basis Document (ATBD) for the GAO and GLO products

CryoClim sub-service for glaciers in mainland Norway



Authors Liss M. Andreassen and S.H. Winsvold

Date 14 October 2013

Project ref. ESA/NSC PRODEX/Norway, CryoClim

Revision history

Rev.no.	Author	Description	Date
0.9	L. M. Andreassen	First full version of document	7 Oct 2013
1.0	R. Solberg	Proofreading	14 Oct 2013

Contents

1 Introduction

CryoClim is an Internet service providing cryospheric climate products, primarily based on satellite observations. The service is delivered through a web service and web portal (www.cryoclim.net). The portal includes manual searching, viewing and downloading capabilities. CryoClim is an operational and permanent service for long-term systematic climate monitoring of the cryosphere. The product production and the product repositories are hosted by mandated organisations. The databases are connected over the Internet in a seamless and scalable network, open for inclusion of more databases/sub-services. CryoClim provides sea ice and snow products of global coverage and glacier products covering Norway (mainland and Svalbard). The service has been developed by CryoClim project (2008–2013) by the Norwegian Computing Center (NR; project coordinator), Norwegian Meteorological Institute (MET Norway), Norwegian Water Resources and Energy Directorate (NVE) and Norwegian Polar Institute (NPI). CryoClim was an ESA PRODEX project funded by the Norwegian Space Centre.

Glacier GIS products from mainland Norway in the CryoClim service consist of Glacier Area Outline (GAO), Glacier Lake Outlines (GLO) and Glacier Periodic Photo series (GPP) products. The GAO and GLO products are derived from Landsat TM/ETM+ imagery using image analysis and GIS techniques. In this report we document the GAO and GLO products derived from Landsat.

2 Selection of Landsat data

For generation of the Glacier Area Outline (GAO) and Glacier Lake Outlines (GLO) products, NVE chose to use Landsat imagery. For the 1999-2006 GAO and GLO products a total of 12 Landsat TM/ETM+ images were selected (Figure 2.1a and Table 2.2). The images are from the period 1999-2006 and cover all the glaciated regions in Norway.

For the period 1988-1997, 9 scenes were selected (Figure 2.1b, Table 2.2). The selected satellite images have been pre-processed, orthorectified and extraction of glacier products has been done using the same methods as for the 1999-2006 products. Limited orthophotos were available for this time period to validate the satellite scenes. Due to poor snow and cloud conditions a full coverage of mainland Norway was not possible for this product. All the images were either orthorectified or quality checked. The already processed product Level 1T (precision and terrain corrected) were used for four of the images and five were orthorectified through the software PCI Geomatics using a 25 × 25 m DTM and 1:50,000 map layer.

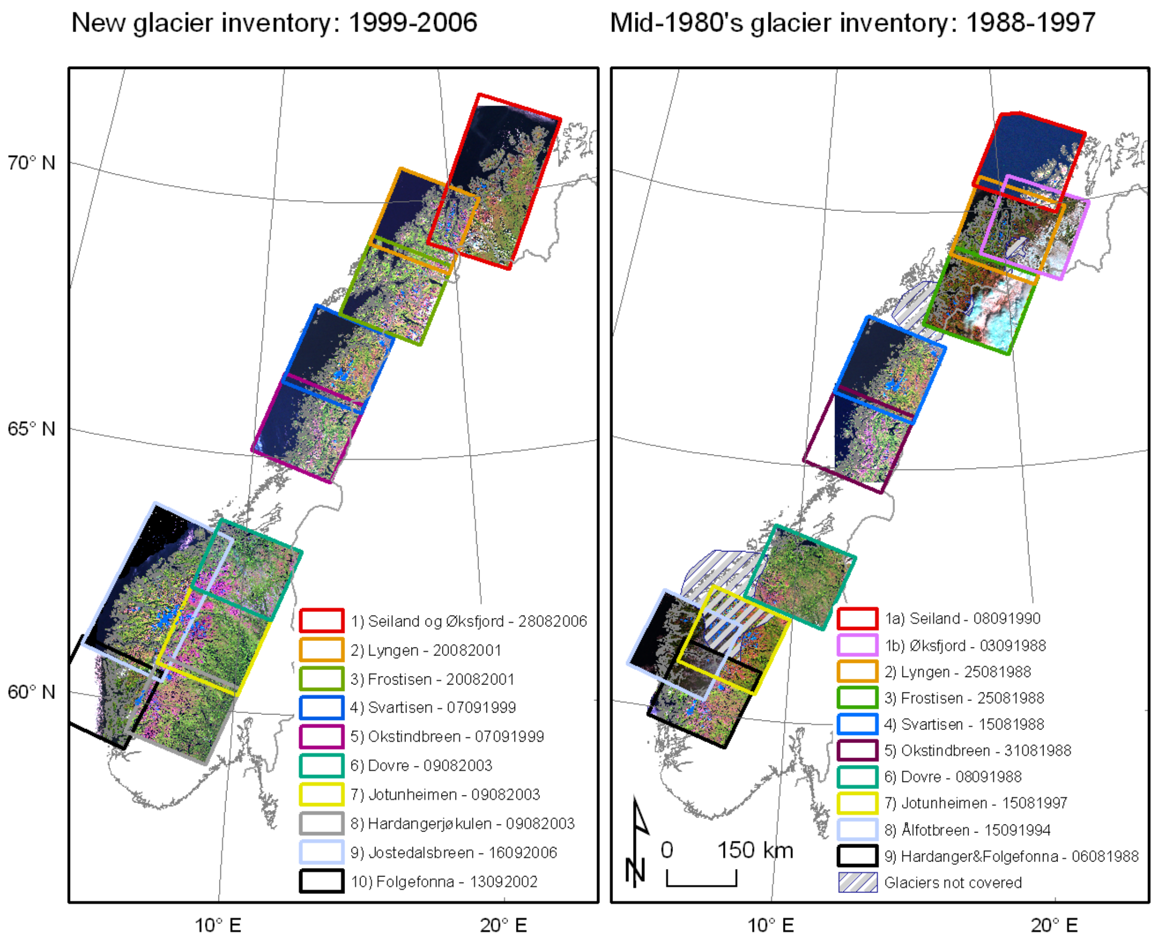


Figure 2.1: a) A total of 12 Landsat images were selected for deriving GAO and GLO from 1999-2006, b) A total of 9 Landsat scenes were selected for the mid-1980s GAO and GLO product from 1988-1997. Landsat scenes with preferable conditions are lacking for the grey areas.

Table 2.2: A list of Landsat satellite scenes used for deriving the GAO and GLO products of mainland Norway. The location of the scenes is shown in Figure 2.1.

New glacier inventory: 1999-2006				
Scene no.	Name region	Date	Landsat sensor	Path/Row
1	Seiland	20060828	L5 TM	196/10 & 11
2	Lyngen	20010820	L7 ETM+	198/11
3	Frostisen	20010820	L7 ETM+	198/12
4	Svartisen	19990907	L7 ETM+	199/13
5	Okstindbreen	19990907	L7 ETM+	199/14
6	Dovre	20030809	L5 TM	199/16
7	Jotunheimen	20030809	L5 TM	199/17
8	Hardangerjøkulen	20030809	L5 TM	199/18
9	Jostedalsbreen	20060916	L5 TM	201/16 & 17
10	Folgefonna	20020913	L7 ETM+	201/18
Mid-1980's glacier inventory: 1988-1997				
1a	Seiland	19900908	L5 TM	197/10
1b	Øksfjord	19880903	L4 TM	196/11
2	Lyngen	19880825	L4 TM	197/11
3	Frostisen	19880825	L4 TM	197/12
4	Svartisen	19880815	L5 TM	199/13
5	Okstindbreen	19880831	L5 TM	199/14
6	Dovre	19880908	L4 TM	199/16
7	Jotunheimen	19970815	L5 TM	200/17
8	Ålfotbreen	19940915	L5 TM	201/17
9	Hardanger & Folgefonna	19880806	L5 TM	200/18

3 Glacier area outline (GAO)

3.1 Algorithm idea and overview

Glacier outlines can be obtained from thresholded multispectral band ratios (Bayr et al., 1994; Jacobs et al., 1997; Sidjak and Wheate, 1999). The band ratio method is robust and accurate for GAO extraction for debris-free glaciers (Albert, 2002; Paul et al., 2003). An additional threshold in ETM band 1 can be used to improve the mapping of glacier tongues in cast shadow (Paul and Kääb, 2005). In a pilot study in a test region in Norway the applicability of standard glacier mapping methods were tested using segmentation of ratio images computed from the raw digital numbers for Landsat TM (Andreassen et al., 2008). The results confirmed that the applied method was robust and highly accurate for extracting glacier outlines in the test area. This method was therefore chosen in CryoClim for mapping GAO of all glaciers in mainland Norway (Andreassen et al., 2012). This choice is also in agreement with recent guidelines and recommendations (Paul et al., 2009; Racoviteanu, 2009).

3.2 Process description

Ratio images were computed from the raw digital numbers for bands TM3/TM5 for all scenes and made binary using different threshold values. The resulting glacier outlines for each scene were compared with a false colour-composite image (bands 5, 4, and 3 as RGB) to find the most suitable threshold value. To improve the GAO in cast shadow a threshold in the TM1 band was also applied where appropriate (e.g. Svartisen: Paul and Andreassen, 2009). An optimal threshold value was chosen and pixels were finally classified as ice or snow. As a next step, we applied a median filter (3 × 3 kernel) to the classified binary image to reduce noise in shadow regions and remove isolated pixels outside the glaciers (usually snow patches), although this filter is also known to close small voids in the glacier areas (e.g. due to rock outcrops) and to reduce the size of small glaciers to some extent. The median-filtered glacier map was raster-to-vector converted within ArcGIS and glacier polygons were obtained. Figure 3.1 illustrates how the spectral characteristics of snow and ice in Landsat bands TM3 and TM5 were used for automatic classification of the glaciers in Jotunheimen, Norway.

Polygons with a size of 9 pixels or smaller were excluded from the further editing and identification process. Then, all mapped snow and ice polygons were visually inspected using RGB composites of satellite image bands as background (typically combination 5-4-3 and 3-2-1). Validation of the glacier products was also done by comparison of the results with orthophotos from http://www.norgeibilder.no where available.

Manual corrections for debris cover, glacier-lake interfaces, clouds or cast shadow were done when necessary. Only very few glacier outlines had to be corrected for debris cover since the glaciers in mainland Norway show little debris cover. A much larger manual effort was required for excluding lakes that were wrongly classified as glaciers, a well-known problem when applying TM3/TM5 ratios for ice and snow mapping (Raup et al., 2007). Another challenge was the presence of snow in the satellite scenes. This was solved by manually classifying snow patches and excluding them from the GAO product. For some of the larger polygons snow ridges attached to the glacier had to be judged and possibly cut. As a general rule, we included all features with bare ice exposed. Some of the Landsat images included clouds that covered parts of the glacier. In these cases a combination of the glacier outline from 1:50,000 maps and available aerial photographs was used to replace the GAO. In some areas small glaciers located in shadow in the Landsat image were not included in the glacier classification. The glacier outlines were in these cases manually digitized based on orthophotos (where available) or Landsat image. For further method description see Andreassen et al. (2008; 2012).

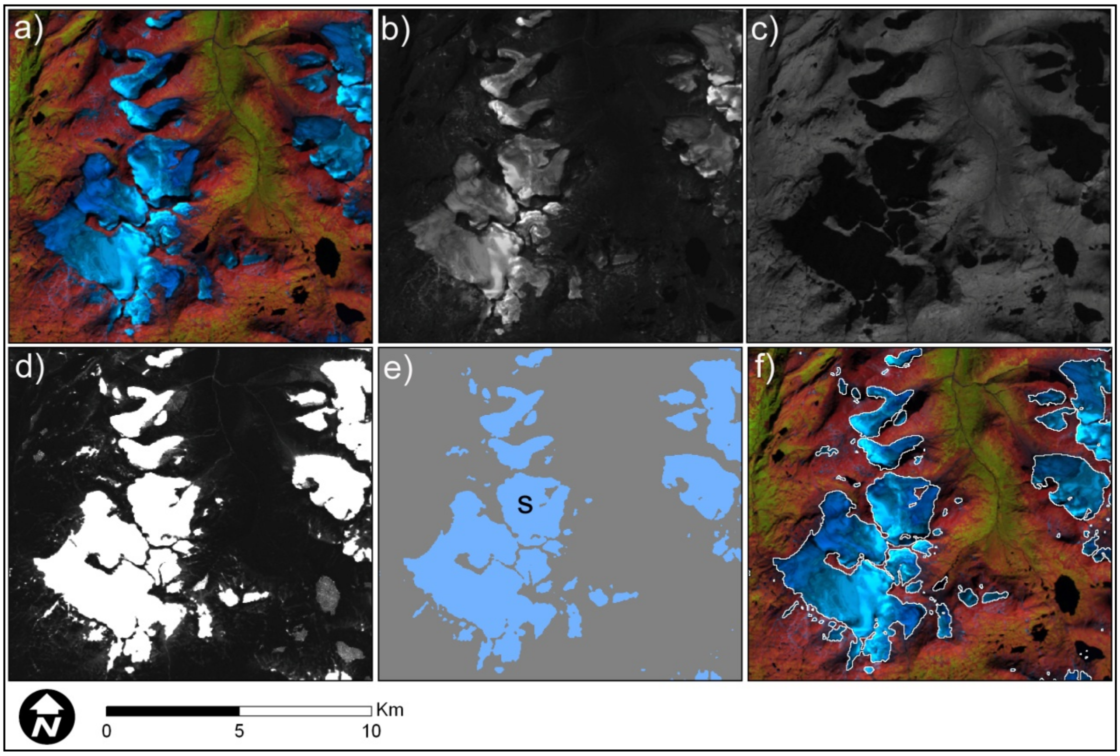


Figure 3.1: Automatic classification of snow and ice for a subset of glaciers in Jotunheimen containing Storbreen (S) using a Landsat TM scene from 9 August 2003. a) Red-green-blue (RGB) composite of TM bands 5, 4 and 3, b) Landsat band TM3 (0.63-0.69 µm), c) Landsat band TM5 (1.55-1.75 µm), d) ratio image of TM3/TM5, e) thresholded image of TM3/TM5 >2.0 and median filter (3 × 3 kernel), and f) as a) with outlines (in white) derived from raster-to-vector conversion of e).

3.3 Validation

When possible glacier outlines were manually inspected using Landsat image or orthophotos in the background and corrections were made where necessary as described (Figure 3.2). In addition, in the Jotunheimen/Breheimen region the GAO product have been compared with new digital glacier outlines from the 2004 aerial photographs for 16 glaciers (counting each composite glacier or ice cap as one) revealing a difference in total area of -1.5 km^2 or -2.4%. Thus, the 2004 map gave less area than Landsat 2003 for this selection of glaciers. Some of the area differences between the areas in 2003 and 2004 could be explained by actual glacier retreat, especially in calving zones and along the terminus. Compared with the 30 m resolution of Landsat the agreement was satisfactory.

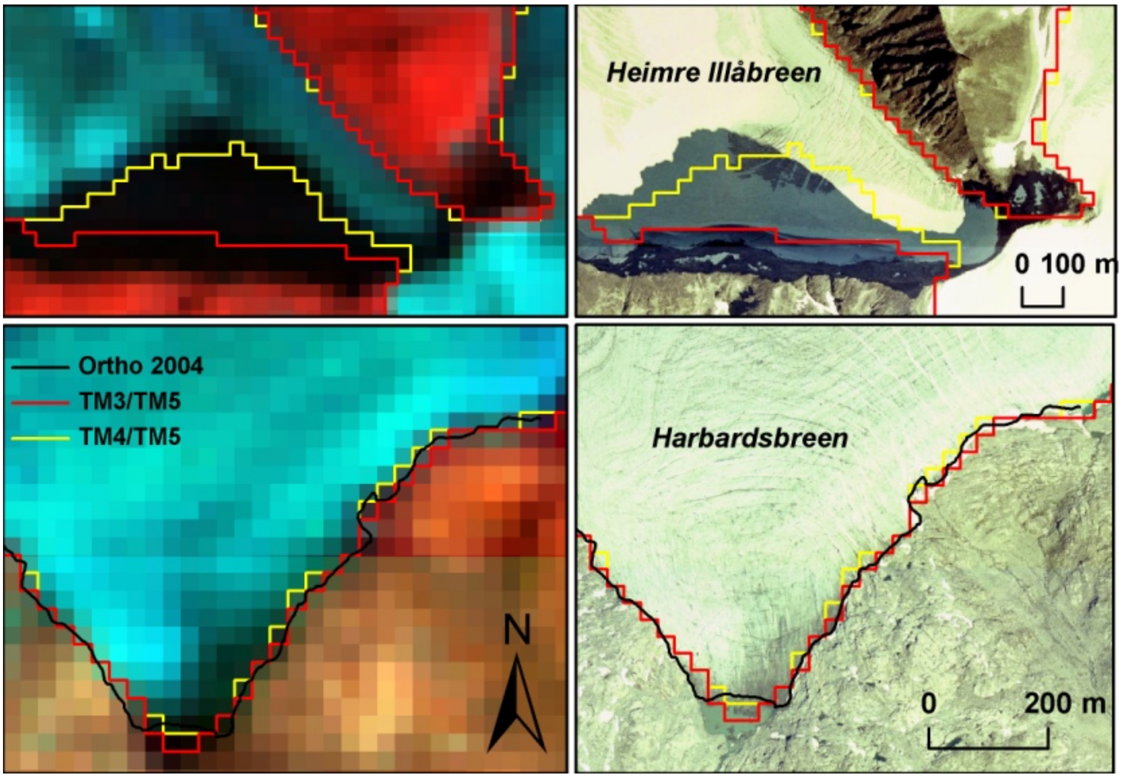


Figure 3.2: Validation of results from automatic mapping using thresholded band ratios TM3/TM5 and TM4/TM5 from Landsat (2003) and orthophotos (2004). Upper figure: performance of automatic mapping in an area with cast shadow. Lower figure: the terminus of Harbardsbreen, where also digital outlines from the Norwegian Mapping Authority have been constructed from the 2004 photos. To the left the outlines with the Landsat scene as background, to the right the orthophotos in the background. (Andreassen et al., 2008)

4 Glacier lake outline (GLO)

4.1 Algorithm idea and overview

Glacier-dammed lakes (also called ice-dammed lakes) can cause hazardous outburst floods. Such floods are also called jøkulhlaups or glacier lake outburst flood (GLOF). By using remote sensing based methods, glacier lakes that cause concern and represent hazard potential can be detected. Previous studies have shown the Normalized Difference Water Index (NDWI) can be used for semi-automatic glacier lake detection (Huggel, 1998; Huggel et al. 2002; Paul, 2007). The GLO product for the mid-1980s only includes the glacier lakes found in the 1999-2006 GLO product. In many occasions it is actually fastest to do a manual digitization of the lakes directly from the Landsat satellite image (Bolch et al, 2008), and this approach were mostly taken to derive the 1988-1997 product. In some occasions the GAO threshold classified glacier lakes as glacier ice. Outlines from the GAO product were then used for mapping the lakes. We defined GLO as water bodies that are either intersected by a glacier, or were within a distance of < 50 m of a glacier, or were completely within a glacier boundary. A total number of 475 glacier lakes were mapped in the 1999-2006 GLO product, and 217 glacier lakes were mapped at the same location in 1988-1997 GLO product.

4.2 Process description

The glacier lake outline can be found by using the spectral reflectance differences between lakes and other surface types (Huggel et al., 2002). Water has the characteristics to absorb near- and middle-infrared wavelengths (0.8-2.5 µm). Other surface types, like soil and vegetation, are strong reflectors of these wavelengths. In this way the water bodies are dark compared to the surroundings. The Normalized Difference Water Index (NDWI) uses two spectral reflectance bands which have a maximum spectral difference in water. The blue band (TM1) has high reflectance and the NIR band (TM4) has low reflectance (Figure 4.1).

$$\mathrm{NDWI}_{\mathrm{Landsat}} = \frac{\mathrm{TM}_4 - \mathrm{TM}_1}{\mathrm{TM}_4 + \mathrm{TM}_1}$$

This method depends on the conditions in the image used for mapping; therefore the mapping results from new images have to be validated using orthophotos and maps (1:50,000). Huggel et al. (2002) found that TM5 or TM7 could be used as alternatives to TM4, but the NDWI with TM4 was more capable of discriminating water from ice and snow, which is important in glacial environments. They suggest using NDWI threshold range values between -0.60 and -0.85. Figure 4.2 illustrate the sensitivity between small differences in threshold values.

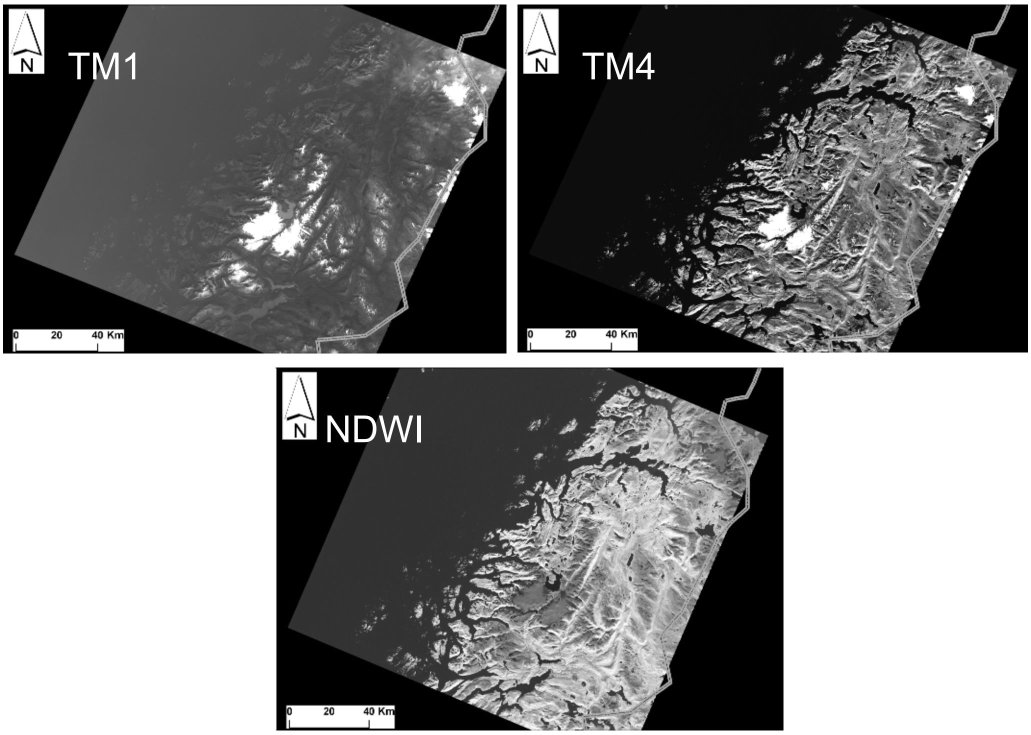


Figure 4.1. Calculated NDWI index at Svartisen (lower image) and the two bands (TM1 and TM4) used to calculate NDWI (upper images).

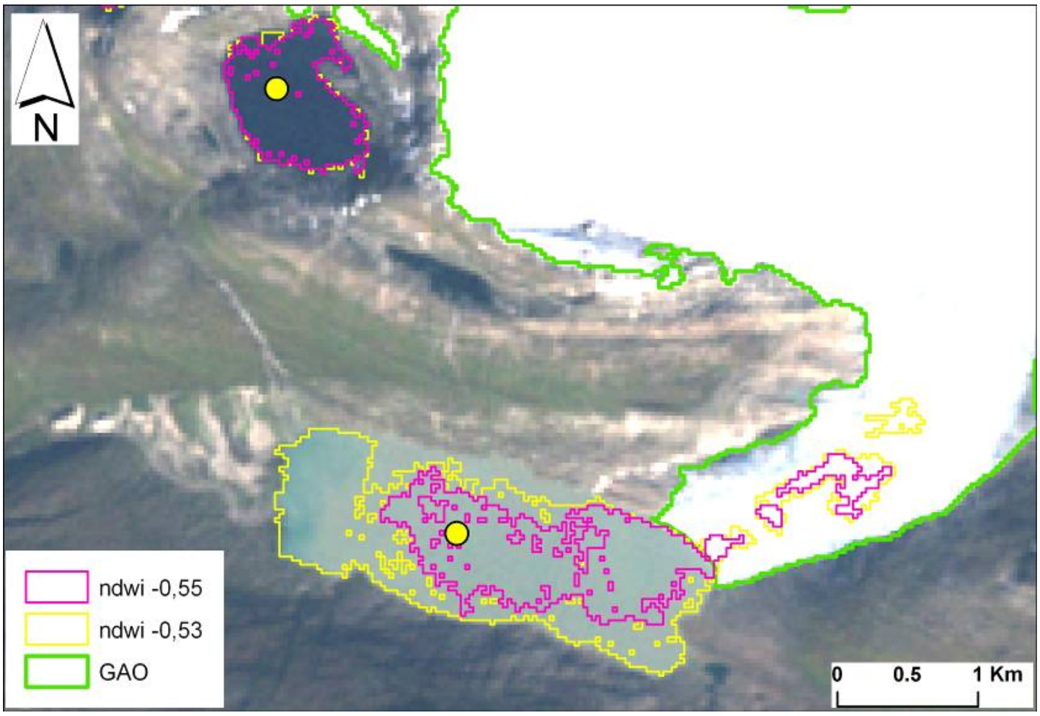


Figure 4.2 The figure illustrates the difference between two NDWI thresholds for a subset in the Svartisen scene from 1999. Lower values than -0.55 would detect less water body (especially turbid lakes), and higher values than -0.53 would classify other surface types as lake (e.g. glacier and shadow). Therefore the northern lake boarder of the southern lake had to be edited manually using the yellow threshold (-0.53) as reference. The image also illustrates the difference in turbidity between Kamplivatnet and Austerdalsvatnet (lower lake). Image background: Landsat displayed in natural colour band combination (RGB 3-2-1).

4.3 Validation

Applying TM3/TM5 ratios for mapping the 1988-1997 GAO product resulted in lakes being wrongly classified as glaciers. When the GAO product was edited, these edited outlines were given a certain edit code. In this way these lakes that intersected with GAO were already spectrally detected and could be used for validation of the 1988-1997 GLO product.

All mapped lake polygons were visually inspected using RGB composites of satellite image bands as background. Typically the combination TM 4-3-2 (used by Chen et al. 2007), 3-2-1 and 5-4-3 were used. Validation of the glacier products was also done by comparison of the results with available orthophotos (http://www.norgeibilder.no) and topographic maps. Corrections were made where it was necessary. Visual inspection of the result showed that areas in shadows were often misclassified as lakes. In such cases the 1:50,000 elevation layer was used to validate if it was shadow or lake that had been classified. The lakes in the 1:50,000 maps were used as an indication of glacier lakes were present or not. However, the lakes mapped in the 1988-1997 product might be older than the 1:50,000 maps and the two data layers do not necessarily correspond to each other.

5 Conclusions

Glacier area outline (GAO) and glacier lake outline (GLO) products have been processed for mainland Norway in the CryoClim project.

The 1999-2006 GAO product have been used to create a new updated inventory of all glaciers in Norway (Andreassen et al., 2012) and serve as an updated glacier mask of mainland Norway. The 1999-2006 GAO product have also been delivered to the GLIMS (Global Land Ice Measurements from Space) database (www.glims.org). The GAO products combined can be used for glacier-change assessments as been demonstrated in several studies already (e.g. Andreassen et al., 2008; Paul et al., 2011). The outlines also serve as baselines for future change assessments when new satellite data are available.

The GLO dataset can be used as source for mapping potential hazardous glacier-dammed lakes by using more detailed GIS analyses. The outlines also serve as baseline for new mappings of glacier lake outlines when new satellite data are available.

References

Albert, T. 2002. Evaluation of remote sensing techniques for ice-area classification applied to the tropical Quelccaya ice cap, Peru. *Polar Geography*, 26, 210-226.

Andreassen, L.M., Paul, F., Kääb, A., and Hausberg, J.E. 2008. Landsat-derived glacier inventory for Jotunheimen, Norway, and deduced glacier changes since the 1930s. *The Cryosphere*, 2, 131-145.

Andreassen, L.M., S.H. Winsvold (eds.), F. Paul and J.E. Hausberg. 2012. *Inventory of Norwegian glaciers*. NVE Rapport 38, Norges Vassdrags- og energidirektorat, 236 pp.

Bayr, K.J., Hall, D.K., and Kovalick W.M. 1994. Observations on glaciers in the Eastern Austrian Alps using satellite data. *International Journal of Remote Sensing* 15, 1733-1742.

Bolch, T., Buchroithner, M.F., Peters, J., Baessler, M., and Bajracharya, S. 2008. Identification of glacier motion and potentially dangerous glacial lakes in the Mt. Everest region/Nepal using spaceborne imagery. *Nat. Hazards Earth Syst. Sci.*, 8, 1329-1340.

Breien, H., De Blasio, F. V., Elverhøy, A., and Høeg, K. 2008. Erosion and morphology of a debris flow caused by a glacier lake outburst flood, Western Norway. *Landslides* vol. 5, 3, 271-280.

Chen, X., Cui, P., Li, Y., Yang, Z. and Qi, Y. 2007. Changes in glacial lakes and glaciers of post-1986 in the Poiqu River basin, Nyalam, Xizang (Tibet). *Geomorphology* 88, 298-311.

Huggel, C. 1998. *Periglaziale Seen im Luft- und Satellitenbild*. Diploma thesis, Department of Geography, University of Zurich.

Huggel, C., Kääb, A., Haeberli, W., Teysseire, P., and Paul, F. 2002. Remote sensing based assessment of hazards from glacier lake outbursts: a case study in the Swiss Alps. *Can. Geotech. J.*, 39, 316-330

Jacobs, J.D., Simms, E.L., and Simms, A. 1997. Recession of the southern part of Barnes Ice Cap, Baffin Island, Canada, between 1961 and 1993, determined from digital mapping of Landsat TM. *Journal of Glaciology*, 43, 98–102.

Paul, F. 2007. The New Swiss Glacier Inventory 2000 - Application of Remote Sensing and GIS. *Schriftenreihe Physische Geographie*, Universität Zürich, 52, 210 pp.

Paul, F., and Kääb, A. 2005. Perspectives on the production of a glacier inventory from multispectral satellite data in the Canadian Arctic: Cumberland Peninsula, Baffin Island. *Annals of Glaciology*, 42, 59-66.

Paul, F., Barry,R., Cogley, G., Frey, H., Haeberli, W, Ohmura, A., Ommanney, S., Raup, B., Rivera, A., and Zemp, M. 2009. Recommendations for the compilation of glacier inventory data from digital sources. *Annals of Glaciology*, 50, 119-126.

Paul, F., Huggel, C., Kääb, A., and Kellenberger, T. 2003. Comparison of TM-derived glacier areas with higher resolution data sets, EARSeL Workshop on Remote Sensing of Land Ice and Snow, Bern, 11.–13.3.2002, *EARSeL eProceedings*, 2, 15–21.

Paul, F., Kääb, A., Maisch, M., Kellenberger, T.W., and Haeberli, W. 2002. The new remote sensing-derived Swiss glacier inventory: I. Methods. *Annals of Glaciology*, 34, 355-361.

Paul, F., L.M. Andreassen and S.H. Winsvold. 2011. A new glacier inventory for the Jostedalsbreen region, Norway, from Landsat TM scenes of 2006 and changes since 1966. *Annals of Glaciology*, 52(59), 153-162.

Racoviteanu, A.E., Paul, F., Raup, B., Khalsa, S.J.S., and Armstrong, R. 2009. Challenges and recommendations in mapping of glacier parameters from space: results of the 2008 Global Land Ice Measurements from Space (GLIMS) workshop, Boulder, Colorado, USA. *Annals of Glaciology* 50, 53-69, 2009.

Raup, B.H., Kääb, A., Kargel, J.S., Bishop, M.P., Hamilton, G., Lee, E., Paul, F., Rau, F., Soltesz, D., Khalsa, S.J.S., Beedle, M., and Helm, C. 2007. Remote Sensing and GIS technology in the Global Land Ice Measurements from Space (GLIMS) Project. *Computers & Geosciences*, 33, 104-125.

Sidjak, R.W., and Wheate, R.D. 1999. Glacier mapping of the Illecillewaet icefield, British Columbia, Canada, using Landsat TM and digital elevation data. *International Journal of Remote Sensing*, 20, 273-284.

Acronyms and definitions

AMSR-E	Advanced Microwave Scanning Radiometer - Earth Observing System
ASAR	Advanced Synthetic Aperture Radar
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AVHRR	Advanced Very High Resolution Radiometer
CEOS	Committee of Earth Observation Satellites
CSW	Catalogue Services for the Web
DB	Data Base
DOKIPY	Data handling and coordination service for Norwegian IPY projects
DOS	Dark Object Subtraction
ECMWF	European Centre for Medium-Range Weather Forecasts
ECV	Essential Climate Variable
EEA	European Environment Agency
ERA-40	ECMWF 40 Year Re-analysis
ERS	European Remote-Sensing Satellite
ESA	European Space Agency
ETM+	Enhanced Thematic Mapper plus
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FCC	False Colour Composite
FCDR	Fundamental Climate Data Record
FMI	Finish Meteorological Institute
FSC	Fractional Snow Cover
FTP	File Transfer Protocol
GAO	Glacier Area Outline
GBA	Glacier Balance Area
GCOS	Global Climate Observing System
GEO	Group on Earth Observations
GEOSS	Global Earth Observation System of Systems
GFL	Glacier Firn Lines
GLO	Glacier-dammed Lake Outline
GLOF	Glacier Lake Outburst Flood
GMES	Global Monitoring for Environment and Security
GPP	Glacier Periodic Photo series
GSL	Glacier Snow Lines
GST	Glacier Surface Type
GSV	Glacier Surface Velocity
HTTP	Hypertext Transfer Protocol
ICT	Information and Communication Technology
IGOS	Integrated Global Observing Strategy
IHS	Intensity-hue-saturation
INSPIRE	Infrastructure for Spatial Information in the European Community
IPY	International Polar Year
ISO 19115	Defines schema required for describing geographic info. and services
ISO 23950	Information retrieval, application service def. and protocol specification
LSA SAF	Land Surface Analysis Satellite Application Facility (EUMETSAT)
N50	The most detailed of the national map data bases in Norway
NASA	National Astronautic and Space Administration
NDWI	Normalized Difference Water Index
NetCDF	Network Common Data Form
NOAA	National Oceanic and Atmospheric Administration
NPI	Norwegian Polar Institute
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NR	Norwegian Computing Center
NRT	Near Real-Time

NSC	Norwegian Space Centre
NTNU	Norwegian University of Science and Technology
NVE	Norwegian Water Resources and Energy Directorate
METNO	Norwegian Meteorological Institute
MODIS	Moderate Resolution Imaging Spectroradiometer
MPI	Max Planck Institute for Meteorology
OAI-PMH	Open Archives Initiative - Protocol for Metadata Harvesting
OGC	OpenGeoSpatial Consortium
OpeNDAP	Open-source Project for a Network Data Access Protocol
OSI SAF	Ocean and Sea Ice Satellite Application Facility (EUMETSAT)
PHP	Originally, scripting language for web pages, now extended functionality
PMR	Passive Microwave Radiometer
PLT	Project Leader Team
PMB	Project Management Board
REST	Representational state transfer
RESTful	Systems following REST principles
RGB	Red Green Blue
SAR	Synthetic Aperture Radar
SCA	Snow Cover Area
SCE	Snow Cover Extent
SCF	Snow Cover Fraction
SCE	Snow Cover Extent
SD	Snow Depth
SIC	Sea Ice Concentration
SIE	Sea Ice Edge
SMMR	Scanning Multichannel Microwave Radiometer
SOA	Service Oriented Architecture
SRU	Search/Retrieve via URL
SSM/I	Special Sensor Microwave/Imager
STAG	Scientific and Technical Advisory Group
SWE	Snow Water Equivalent
THREDDS	Thematic Realtime Environmental Distributed Data Services
TM	Thematic Mapper
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
UNIDATA	Diverse community vested in sharing data and tools to access and visualize
URL	Uniform Resource Locator
UTM	Universal Transverse Mercator
WCRP	World Climate Research Programme
WCS	Web Coverage Service
Web portal	Presents information from diverse sources in a unified way
Web service	Supports interoperable machine-to-machine interaction over a network
WFS	Web Feature Service
WGS	World geodetic system
WIS	WMO Information System
WMO	World Meteorological Organisation
WMS	Web Map Service
WPS	Web Processing Service
XML	Extensible Markup Language

Monitoring Climate Change in the Cryosphere

www.cryoclim.net • cryoclim@cryoclim.net

NR	Norwegian Computing Center (NR) P.O. Box 114 Blindern NO-0314 Oslo Contact person: Rune Solberg E-mail: rune.solberg@nr.no Role in project: Project coordinator, snow retrieval, system development
Norwegian Meteorological Institute	Norwegian Meteorological Institute (met.no) P.O. Box 43 Bindern NO-0313 Oslo Contact person: Mari Anne Killie E-mail: mari.a.killie@met.no Role in project: Global sea ice and snow services, system development
NVE	Norwegian Water Resources and Energy Directorate (NVE) P.O. Box 5091 Majorstua NO-0301 Oslo Contact person: Liss Marie Andreassen E-mail: lma@nve.no Role in project: Glacier service for mainland Norway
NORSK·POLARINSTITUTT	Norwegian Polar Institute Polar Environmental Centre NO-9296 Tromsø Contact person: Max König E-mail: max.koenig@npolar.no Role in project: Glacier service for Svalbard

CryoClim is funded and managed by

the European Space Agency and the Norwegian Space Centre

esa

Norsk Romsenter
NORWEGIAN SPACE CENTRE