CRYOCLIM: A NEW OPERATIONAL SYSTEM AND SERVICE FOR CLIMATE MONITORING OF THE CRYOSPHERE

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Abstract

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).

INTRODUCTION

The CryoClim project has developed a new 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, and the service is delivered through a state-of-the-art web service and web portal (www.cryoclim.net). The portal includes manual searching, viewing and downloading capabilities. The machine interface makes the CryoClim service accessible from other web services and applications. The service is free of charge. The databases are connected over the Internet in a seamless and scalable network, open for inclusion of more databases/sub-services. The system and service is a contribution to the Global Earth Observation System of Systems (GEOSS) and the Global Cryosphere Watch (GCW) according to the climate monitoring principles recommended by the Global Climate Observing System (GCOS).

The service provides sea ice and snow products of global coverage and glacier products covering Norway (mainland and Svalbard). The service has been developed by the Norwegian Computing Center (NR; project coordinator), Norwegian Meteorological Institute (MET), Norwegian Water Resources and Energy Directorate (NVE) and Norwegian Polar Institute (NPI). The project, which develops the CryoClim service, is under the ESA PRODEX programme and funded by the Norwegian Space Centre. The final development of the service is now close to the end.

The sea ice sub-service is based on data from passive microwave radiometers (SMMR and SSM/I). Sea ice concentration and sea ice edge have been retrieved for a time series covering the period 1979-2009. For snow the period 1979-2010 is covered by snow cover extent products. The snow products are based on optical (AVHRR starting from 1982) and passive microwave radiometers (SMMR and SSM/I). The time series will be extended with regular updating starting operation soon. Glacier maps, including glacier area outline and glacier lakes, have been generated from Landsat TM, ETM+ and aerial photos for all glaciers in mainland Norway covering three periods [1952-1985 (aerial); 1982-1999 and 1999-2006 (satellite)]. Additionally, in situ photos and information on glacier-lake outburst floods are provided. For Svalbard, SAR data (ERS-1, ERS-2, Envisat ASAR and Radarsat) has been used for glacier surface type (1990-2012) mapping. The glacier area outline time series covers three epochs, using optical data (ASTER, SPOT and Landsat) for the most recent with

complete coverage (2001-2010), and using cartographic data for partial coverage of 1990 and the period 1936-1971.

GLOBAL SNOW PRODUCT

Three spatial snow products have been developed:

- Snow Cover Extent (SCE) based on passive microwave radiometers (PMR),
- Snow Cover Extent based on optical radiometers,
- Snow Cover Extent based on a multi-sensor approach of PMR and optical.

The first product has grid resolution of 10 km, while the two others have grid resolution of 5 km. Products are provided at three aggregation levels: as daily, monthly and yearly products. In addition there is a selection of climate-change indicator products. The processing chain is operated by MET and was developed by MET and NR in collaboration.

The approach for the PMR SCE retrieval algorithm is based on a Bayesian estimation rule. For SSM/I four snow classes are defined in order to model the SCE: (i) wet snow, (ii) dry snow, (iii) no snow, and (iv) no snow with a large fraction of nearby water, and for SMMR the two snow classes snow and no-snow are considered. The algorithm estimates the probability for each snow class given the PMR measurements. The PMR algorithms were trained using meteorological station data on snow depth and temperature.

The optical snow cover algorithm builds on previous development in the EUMETSAT OSI SAF (Breivik et al. 2003) and CryoRisk projects). The method consists of two steps: 1) Each swath is processed individually. Bayes approach is used to combine information from optical and infrared AVHRR channels. Probabilities for the three independent classes snow, cloud and snow-free land are estimated for all land pixels of the swath. The cloud masking and the identification of snow cover are thus done in the same operation. 2) The classified swaths are gridded and averaged, and we get a daily snow/no snow product. All processed swaths falling within the time interval of interest are collected.

The multi-sensor/multi-temporal algorithm is based on a Hidden Markov Model (HMM) concept where the various seasonal snow states are modelled (based on ideas from Solberg et al. 2008). Optical and PMR data are fused in the algorithm, trying to utilise the best properties of the respective sensors for SCE mapping under varying conditions. For validation we applied SYNOP snow depth data records from the Global Historical Climatology Network Daily (GHCN-D) database for the snow-season 2004-2005. A total accuracy of 92.4% was obtained with full mapping-coverage spatially as well as temporally.

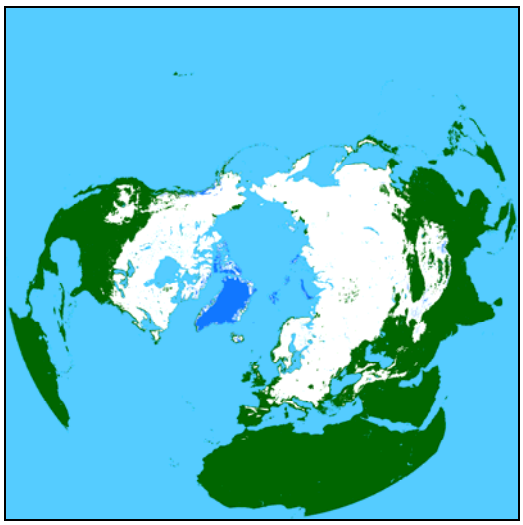

Figure 1: **Multi-sensor/multi-temporal fusion of optical (AVHRR) and passive microwave radiometer (SSM/I) data showing the snow cover extent (SCE) on 1 March 2005 for the Northern Hemisphere.**

GLOBAL SEA ICE PRODUCT

Two spatial sea ice products have been developed:

- Sea Ice Concentration (SIC)
- Sea Ice Edge (SIE)

Both products are global of 10 km grid resolution and aggregated into monthly and yearly climate products. In addition there is a selection of climate-change indicator products. The processing chain is operated by MET and developed by MET and Danish Meteorological Institute (DMI) in collaboration in EUMETSAT OSI SAF) (Andersen et al. 2007). The added value of the CryoClim service to the OSI SAF products is the combination of daily products into aggregated climate products, adding standardised quality information to each product and providing sea ice products that are consistent with the other products delivered by CryoClim.

The sea ice products are based upon EUMETSAT OSI SAF reanalysis. The SSM/I brightness temperatures are corrected for contamination arising from atmospheric water vapour content and wind roughening of the open water. The correction is computed using a radiative transfer model and atmospheric input data from ECMWF reanalysis.

The OSI SAF ice concentration algorithm is based on testing and evaluation of established algorithms. Analysis of atmospheric sensitivity showed that the Bootstrap frequency mode algorithm had the lowest sensitivity to atmospheric noise over open water. Conversely, comparison to high-resolution SAR imagery revealed that of the algorithms using the low-frequency channels (i.e. below 85 GHz), the Bristol algorithm (Breivik et al. 2001) gave the best agreement. Consequently, a hybrid algorithm (Andersen et al. 2007) has been established as a smooth combination of the two. To ensure an optimum performance over both marginal and consolidated ice, the Bristol algorithm is given little weight at low concentrations, while the opposite is the case over high ice concentrations.

The monthly products contain averaged sea ice concentration and sea ice edge, as well as scalar values for total sea ice extent and sea ice area.

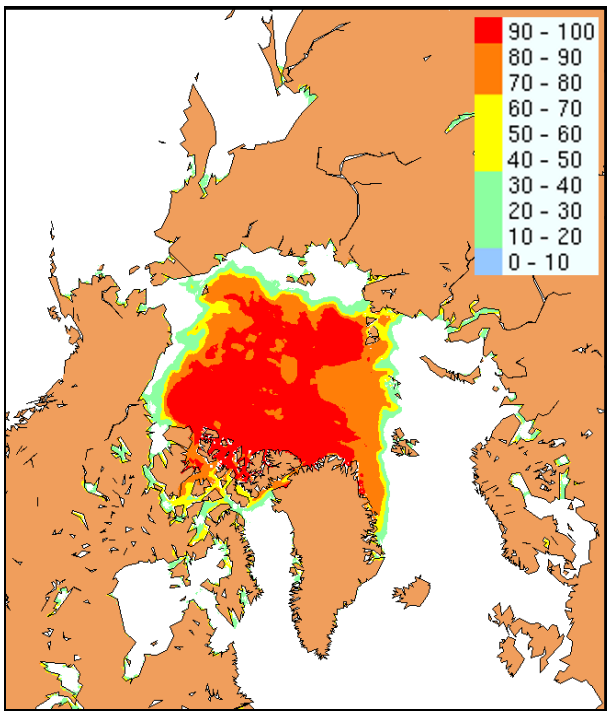

Figure 2: **Minimum sea ice concentration (SIC) in October 2000 based on the monthly aggregated product.**

GLACIERS MAINLAND NORWAY

The four glacier products are:
- Glacier Area Outline (GAO)
- Glacier Lake Outline (GLO)
- Glacier Lake Outburst Floods (GLOFs)
- Glacier Periodic Photo series (GPP)

The products are based on Landsat (or possibly also other optical satellites as the upcoming Sentinel-3), air-borne sensors, topographic maps and terrestrial photography. The processing chain is hosted by NVE and consists of several steps, going from finding satellite imagery to product delivery. After ortho-rectification glacier products are derived from the imagery using standard glacier mapping algorithms and normalized difference water index (Andreassen et al. 2008). For validation all glacier outlines were manually inspected using a Landsat image or orthophotos in the background (Andreassen et al. 2009). Some manual editing of the products were needed in areas with debris cover, interference between glaciers and lakes, cast shadow and for glacier lakes with different spectral characteristics due to varying turbidity. The final glacier products are stored at NVE.
A time series of GAO and GLO are based on Landsat TM and ETM+ images ranging back to 1984. The spatial resolution of GLO and GAO derived from Landsat are ~30 m. The products can be used for glacier change detection and are used to derive climate indicator products.

Topographic maps have been used for a pre-satellite era extension of the GAO product. NVE has digitized glacier outlines from totally 166 topographic maps from the Norwegian mapping authority to cover all glaciers in Norway. The glacier outlines are from 1952 to 1985. NVE has also tested the potential of extending GAO further back in time using older maps. Results from one test region showed that older maps' topographic information and the glacier outlines were not of sufficient quality for accurate results.

Knowledge on previous glacier lake outburst floods is useful to identify potential new events and can be used to inform the public where hazards potentially can occur. Glacier-dammed lakes with previous known glacier lake outburst floods (GLOFs) have been compiled and presented as a separate point layer in the CryoClim portal. Spread over 16 glacier localities, totally 87 GLOFs have been registered so far.

The GPP product (time series of glacier photographs: terrestrial and airborne imagery without geo-referencing) is be used to illustrate glacier changes for selected glaciers where photo series are available for use. A number of GPPs have been selected for more than 30 glaciers in mainland Norway. The number of photos and photo quality vary from glacier to glacier. The oldest photos are from 1869, the newest from 2012. The climate change indicator products include glacier mass balance, length and area changes for selected glaciers and glacier regions in mainland Norway.

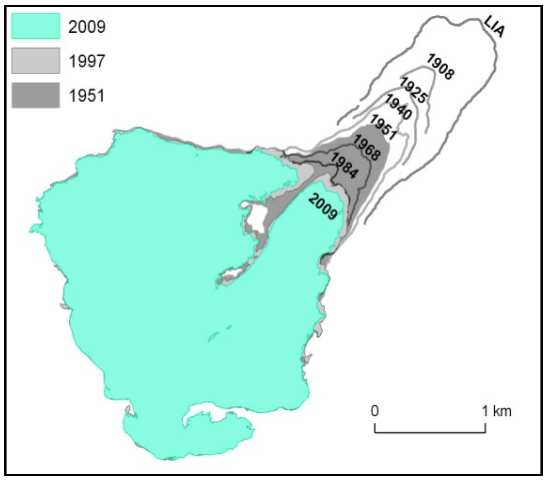

Figure 3: **Glacier area outline (GAO) change from the Little Ice Edge (LIA, determined from the moraine), until present (green from Landsat data) for Storbreen in mainland Norway.**

GLACIERS SVALBARD

The two glacier products are:
- Glacier Area Outline (GAO)
- Glacier Surface Type (GST)

The GAO product provides digital polygons delineating the area of Svalbard glaciers, including various attributes for each glacier. The dataset consists of three individual Shapefiles corresponding to three epochs. The first file contains the earliest data between 1936 and 1971, the second contains outlines for the year 1990, while the third contains the most recent data covering 2001–2010 (König et al. 2013; Nuth et al. 2013).

The historic glacier outlines from before 2001 were created using cartographic data from the original Norwegian Polar Institute topographic map series of Svalbard by delineating individual glaciers and ice streams, assigning unique identification codes relating to the hydrological watersheds, digitizing centre lines, and providing a number of attributes for each glacier mask. The 2001–2010 glacier outlines are derived from orthorectified satellite images from the SPOT-5 and ASTER data. The dataset thus contains outlines for up to three dates in time for each glacier and allows analysis of changes on Svalbard. However, only the 2001–2010 dataset has a full coverage of Svalbard glacier outlines, since historic data is not available for all glaciers at a given point in time.

The GST product is based on single-polarization SAR C-band data from ERS-1, ERS-2, Envisat and Radarsat (König et al 2004) starting in 1992. The retrieval method is based on the fact that a histogram of SAR backscatter of the glacier surface typically shows three peaks corresponding to the three glacier surface types (glacier ice, superimposed ice and firn). These areas can be displayed by thresholding the SAR image at the minima in the histogram separating the surface types. The firn area size is, similar to a glacier front, less sensitive to annual, short-term changes but displays long-term trends. A retreating glacier will show a decrease in firn-area size over the years, as seen for example on Kongsvegen glacier on Svalbard.

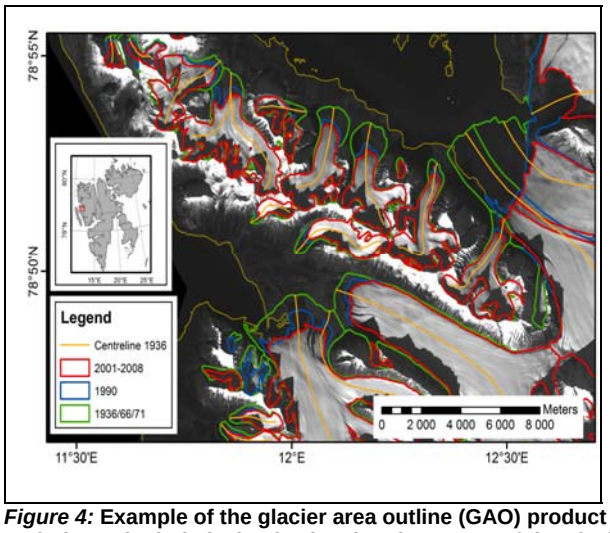

Figure 4: **Example of the glacier area outline (GAO) product for the Ny-Ålesund region in Svalbard. Outlines from four periods are included, clearly showing the retreat of the glacier ice. The most recent outline is derived from SPOT satellite data, the other from aerial imagery. A SPOT image from 2007 is shown as background.**

CRYOCLIM SYSTEM

CryoClim is a distributed system involving production chains hosted by several organisations. As such CryoClim is a system of systems, and the focal point of the system architecture has been to set up interoperability principles that support the distributed idea of CryoClim as well as the interoperability of the CryoClim system within a global environment as defined by e.g. GEOSS, WIS and INSPIRE

principles. The architecture of the system is fully decentralised and relies on Service Oriented Architecture (SOA) concepts and utilises web services to achieve the service orientation.

To ensure compatibility with upcoming systems/ requirements (e.g. GEOSS, WIS and INSPIRE) standard interfaces are utilised. This implies that each production chain within the system publish data and products using OGC interfaces. Metadata is published using OGC CSW (with ISO 23950 binding through SRU to achieve WIS and GEOSS compatibility). Data should be available through OGC WMS and WCS/WFS when technology is mature enough. OAI-PMH and OpeNDAP is used to achieve a jump start concerning interoperability. By using THREDDS Data Server, both OpeNDAP, HTTP and WCS access is achieved at least when using some standard file formats. This increases the interoperability of the system on a global basis as well as link to important communities concerning interoperability development (e.g. UNIDATA, NOAA, NASA, etc). The CryoClim service is publicly available, and use a RESTful interface to facilitate a machine interface to the data and products.

SUMMARY AND CONCLUSIONS

The CryoClim project has developed a new operational service for long-term, systematic climate monitoring of the cryosphere (www.cryoclim.net). The sea ice sub-service is based on data from passive microwave radiometers (SMMR and SSM/I). Sea ice concentration and sea ice edge have been retrieved for a time series covering the period 1979 until present. The same period is covered by the snow cover extent product, which is based on multi-sensor/multi-temporal fusion of passive microwave radiometer and optical data.

Glacier maps, including glacier area outline and glacier lakes, have been generated from Landsat TM and ETM+ for all glaciers in mainland Norway covering two periods (1982-1999 and 1999-2006). Additionally, historic data has been digitized to extend the time series back to 1952. For Svalbard, glacier products are based on optical data (SPOT and ASTER) for glacier area outline and SAR data (ERS-1, ERS-2, Envisat ASAR and Radarsat) for glacier surface type. The period covered with satellite data starts in the early 1990s. The glacier area outline time series has in Svalbard also been extended with map data from earlier days. The web portal and web service are developed with an operational backend system.

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