CryoClim: A new system and service for climate monitoring of the cryosphere

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Abstract. 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. The service provides sea ice and snow products of global coverage and glacier products covering Norway (mainland and Svalbard). The sea ice sub-service is based on data from passive microwave radiometers (SMMR and SSM/I). The same period is covered by snow cover extent products based on passive microwave radiometers (SMMR and SSM/I) and optical (AVHRR from 1982). Glacier maps, including glacier area outline and glacier lakes have been generated from Landsat TM, ETM+ and historic topographic maps for all glaciers in mainland Norway starting the time series from 1952. For Svalbard, glacier products are based on optical data (SPOT and MODIS) for glacier area outline and glacier snow line, 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 and aerial images from earlier days.

1. Introduction

Air temperature measurements show a clear trend of global climate warming during the last decades. The Arctic temperature has increased at almost twice the rate compared to that of the rest of the world over the same period [1]. It has been generally agreed internationally that climate monitoring is urgently needed in order to quantify and better understand the climatic changes taking place [2]. Therefore, climate monitoring has been put at the top of the agenda by the UN and in the international Earth observation initiatives GEO and GMES.

The Global Climate Observing System (GCOS) has established a list of Essential Climate Variables (ECVs) that are both feasible and have a high impact on the UNFCCC requirements. In 2006, GCOS issued the document "Systematic Observation Requirements for Satellite-based Products for Climate" detailing the satellite-based component of the GCOS implementation plan [3].

Recognising the needs of climate monitoring as stated by UNFCCC and the implementation plan provided by GCOS, the project CryoClim was initiated in 2008. The CryoClim initiative was proposed by a group of Norwegian organisations and has been carried out as a European Space Agency PRODEX project supported by the Norwegian Space Centre (NSC).

The vision of the CryoClim initiative is to develop new operational services for long-term systematic climate monitoring of the cryosphere. The product production and the repositories are hosted by mandated organisations, and the service is delivered through a state-of-the-art web service and web portal. 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 database is 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 (GEOS).

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 (METNO), Norwegian Water Resources and Energy Directorate (NVE) and Norwegian Polar Institute (NPI). The project is now close to completion in 2013, and will then be fully operational.

2. Snow globally

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 time series starts in 1979 for PMR (SMMR followed by SSM/I), and in 1982 for optical (AVHRR). The processing chain is operated by METNO and was developed by METNO and NR in collaboration.

The approach for the PMR SCE retrieval algorithm has been 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 performance of the SMMR-based SCE estimator is comparable in performance with the SSM/I-based (87% versus 86%).

Two versions of optical retrieval algorithms have been developed, one by NR and another by METNO. NR's algorithm builds on advancement of the Norwegian Linear Reflectance-to-snow-cover (NLR) algorithm for retrieval of the Fractional Snow Cover (FSC) [4]. The NLR algorithm is based on a linear spectral mixture (LSM) model assuming that the spectra for snow and bare ground are combining linearly at the subpixel level weighted by the area fraction of each class. The optical snow cover algorithm developed at METNO builds on previous development in the EUMETSAT OSI SAF [6] 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 next step in the optical work is to make an intercomparison of the two algorithms and choosing one for further use in CryoClim.
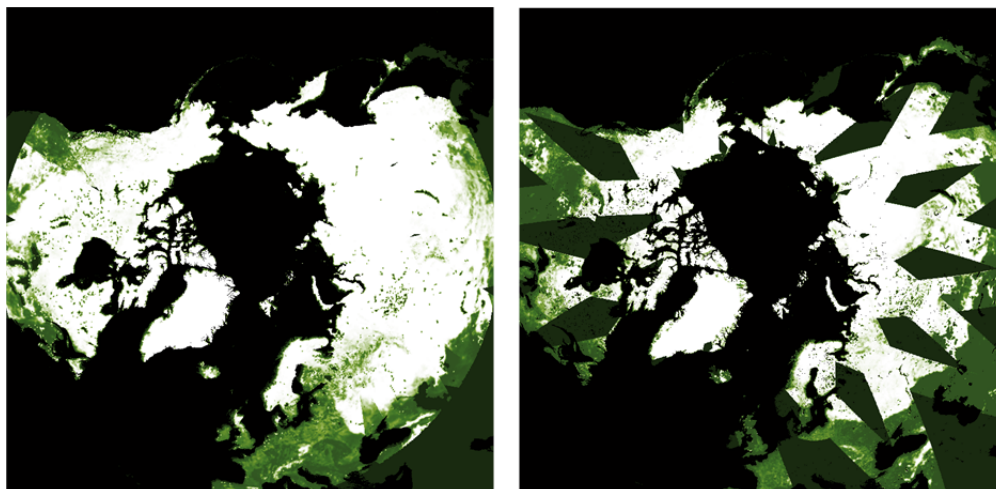
Figure 1. Comparison of an SSM/I-based SCE snow map from 1 March 2010 and a SMMR-based map from 12 March 1983.

Alternative multi-sensor algorithms are currently tested. METNO's principle algorithm combines probabilities for snow from the two single-sensor products to generate a fused result. NR's algorithm is based on a Hidden Markov Model (HMM) concept where the various seasonal snow states are modelled (based on ideas from [5]). Later in 2013 the algorithms' performance will be compared and a choice of algorithm done. Following this, the quality of the PMR, optical and multi-sensor products will be compared, and a final decision for which to be be provided and updated regularly in the CryoClim service will be taken.

3. Sea Ice globally

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 time series starts in 1979 and is based on SMMR and SSM/I data. The processing chain is operated by METNO and developed by METNO and Danish Meteorological Institute (DMI) in collaboration in EUMETSAT OSI SAF) [7]. The added value of the CryoClim service to the OSI SAF products is the combination of 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 re-analysis. 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 re-analysis.

The OSI SAF ice concentration algorithm development 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 [6] gave the best agreement. Consequently a hybrid algorithm [7] 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 products are in netCDF format with metadata elements implemented as global attributes. The monthly files contain averaged sea ice concentration and sea ice edge, as well as scalar values for sea ice extent and sea ice area. A range of auxiliary variables are also included. The climate indicator

values (sea ice extent and sea ice area) have been collected on separate indicator files, one for each month of the year.
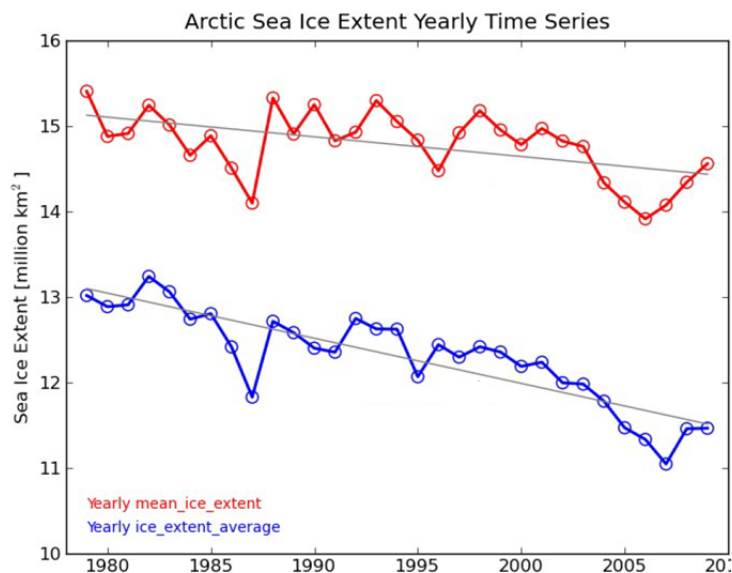
Figure 2. Yearly averaged sea ice extent time series for the Northern Hemisphere.

4. Glaciers for 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 [8]. For validation all glacier outlines were manually inspected using a Landsat image or orthophotos in the background [9]. 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 were used. 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.
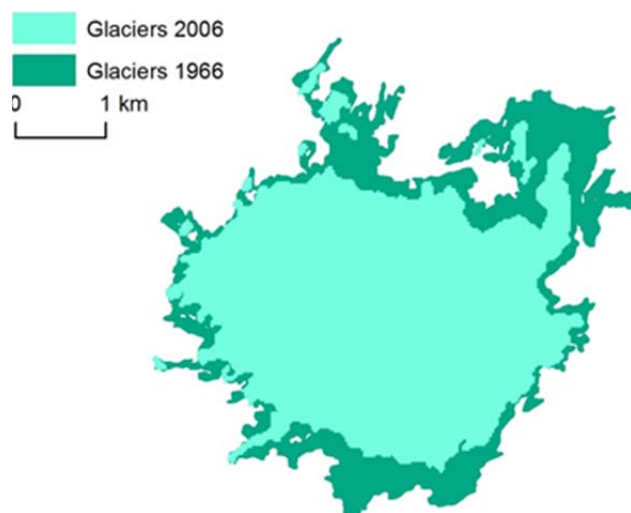
Figure 3. Area changes of the glacier Seilandsjøkelen in northern Norway derived from two GAO data sets.

5. Glaciers in Svalbard

The three glacier products are:

- Glacier Area Outline (GAO)
- Glacier Surface Type (GST)
- Glacier Snow Line (GSL)

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 file contains outline for the year 1990, while the third file contains the most recent glacier data from 2001–2010 [10, 11].

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 products are based on single-polarization SAR C-band data from ERS-1, ERS-2, Envisat and Radarsat [12] staring 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.

The GSL product displays the snow line for a given glacier, which is a proxy for glacier mass balance. Using MODIS albedo data, the algorithm distinguishes the brighter, snow covered upper glacier area from the darker glacier ice area and tracks the decrease in snow-covered area over the summer. The minimum extent of the snow cover at the end of the summer indicates the snow line. Snow line elevation correlates very nicely with glacier mass balance.
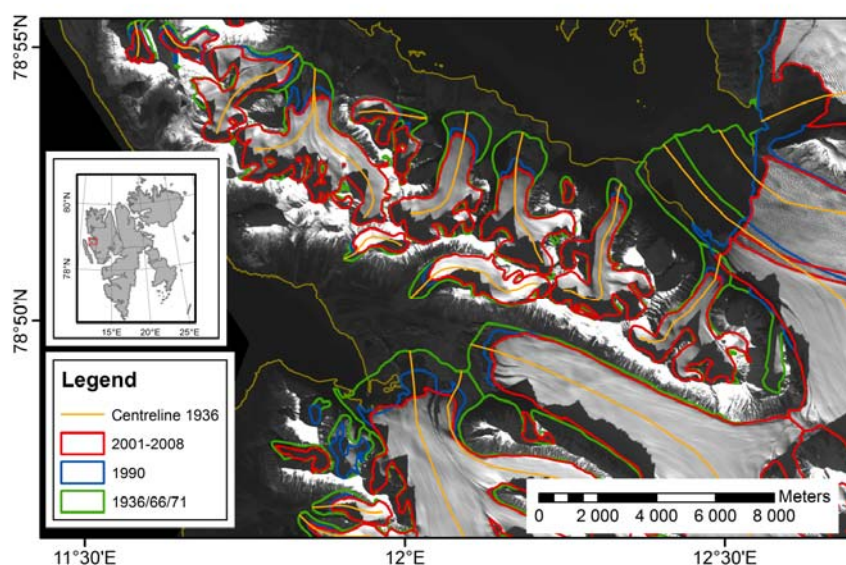
Figure 4. Example of the GAO product for the Ny-Ålesund region in Svalbard. Outlines from four periods are included, clearly showing the retreat of the glacier ice. A SPOT image from 2007 is shown as background.

6. The 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 will use a RESTful interface to facilitate a machine interface to the data and products.

7. 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 snow cover extent products. A multi-sensor product is currently being developed based on a fusion of retrieval data from optical and passive microwave radiometers. 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. A snow line product, providing a proxy for mass balance, is based on MODIS data. 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.

Our hope is that the CryoClim service with the new climate product time series represents a significant contribution to the crucial task of monitoring the development of the climate on our planet.

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