FIRST RESULTS FROM THE CRYOCLIM SYSTEM FOR CRYOSPHERIC CLIMATE MONITORING

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ABSTRACT

The vision of the CryoClim initiative is to develop new operational services for long-term systematic climate monitoring of the cryosphere. The project develops services for sea ice and snow products of global coverage and glacier products covering Norway (mainland and Svalbard). The envisioned system will be provided as a web service based on state-of-the-art principles for spatial data. The system and services is designed to be integrated with the international system of systems for global monitoring (GEOSS) – the part of the system aimed for climate monitoring. At this stage the project has developed the first (incomplete) version of the web service, completed the sub-service for sea ice, developed the passive microwave component of the snow sub-service, made the first full glacier product coverage for mainland Norway based on optical data and validate SAR-based algorithms for glacier monitoring in Svalbard. The upcoming two project phases will complete the sub-services, produce the full time series of cryospheric products and establish fully operational production to regularly update the product sets. The web service will be completed with an operational backend system and a web service with a portal and machine-readable interfaces.

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. This is further emphasised in article 4.1(g) of United Nations Framework Convention on Climate Change (UNFCCC) where all parties agree, to "Promote and cooperate in scientific, technological, technical, socio-economic and other research, systematic observation and development of data archives related to the climate system and intended to further the understanding and to reduce or eliminate the remaining uncertainties regarding the causes, effects, magnitude and timing of climate change and the economic and social consequences of various response strategies".

The Global Climate Observing System (GCOS) – established in 1992 to ensure that the observations needed to address climate-related issues are obtained and made available to all potential users – is now the recognized mechanism to facilitate the implementation of UNFCCC commitments. 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: Norwegian Computing Center (NR), Norwegian Meteorological Institute (METNO), Norwegian Water Resources and Energy Directorate (NVE) and Norwegian Polar Institute (NPI). Phase 1 and 2 of the project has been carried out as an ESA 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 system and services is designed to be integrated into the planned international system of systems for global monitoring (GEOSS) – the part of the system aimed for climate monitoring. Based on scientific and technological results from several past and current projects, it develops a network-based system building on standards and communication languages identified by GMES and

GEO for the global system of systems. The network of processing chains and databases (the nodes) are hosted by mandated organisations in order to ensure long-term and stable operation.

2. SYSTEM FUNCTIONALLITY

The CryoClim data repository component is responsible for storing spatial data, metadata and indicators on stable storage. It is also responsible for accepting data from and providing data to components in the system that are authorized for these operations. One data repository component may be used by any number of production components.

The data management component is responsible for transparently coordinating and managing access to data repository components and for providing spatial data in standard formats through standard interfaces. It is also responsible for providing the capability to search for spatial data by metadata. All these functions are available to both the web portal component and downstream service providers.

Furthermore, the data management component performs searches by searching through a cache of metadata collected from each data repository component. As a consequence it needs to ensure that the cache is up-to-date and consistent.

The web portal component is responsible for all interaction with end users through web browsers and for generating the graphical user interface and handling user input. This includes the generation of and navigation in an interactive map. The web portal performs its tasks by using the distribution component to perform search queries and data accesses.

The system also offer machine interface for search and product download functionality. This is provided through an application programming interface that allows downstream service providers to search in spatial data and download products. This will be CryoClim's link to, e.g., the Global Earth Observation Systems of Systems (GEOSS).

3. SYSTEM ARCHITECTURE AND INTEROPERABILITY

The CryoClim system is a distributed system involving production chains hosted by several organisations. As such the CryoClim system will be a system of systems, and the focal point of the system architecture is 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 to be developed (Fig. 1) is fully decentralised and relies on Service Oriented Architecture (SOA) concepts and utilises web services to achieve the service orientation.

A basic design based upon SOA is in line with INSPIRE, WIS and GEOSS requirements and will ensure a potential for future development and addition of web-service interfaces as they become mature enough. Basically, SOA implies that the communication between the data user and the data provider is handled through services that may be used both interactively and as machine-readable interfaces.

To ensure compatibility with upcoming systems/ requirements (e.g. GEOSS, WIS and INSPIRE) standard interfaces will be 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 will be publicly available, and it is planned to use a straightforward RESTful interface to facilitate a machine interface to the data and products.

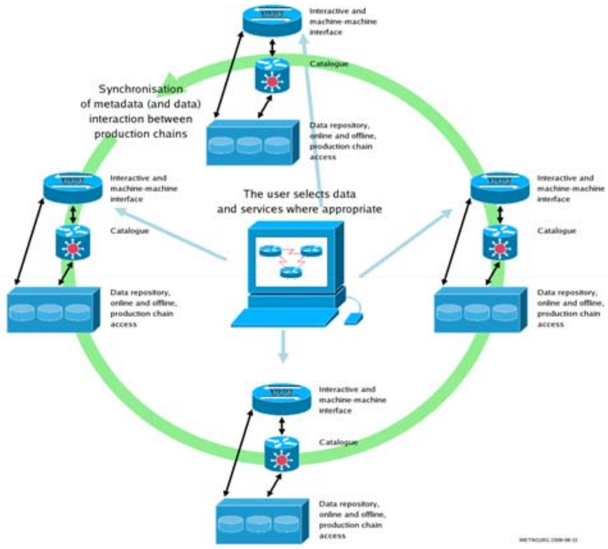

Figure 1. CryoClim system concept, which is based upon a fully decentralised system. Data are not synchronised unless specifically required by some internal or external requirement

4. SUB-SERVICE FOR SEA ICE

There are currently two spatial sea ice products:

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

Both products are global of 10 km grid resolution and currently aggregated into monthly climate products. In addition there will be a selection of climate-change indicator products. The time series starts in 1979 and is based on passive microwave radiometer (PMR) data. The processing chain is operated by METNO and developed by METNO and Danish Meteorological Institute (DMI) in collaboration in EUMETSAT OSI SAF. 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 [4] 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 [5] gave the best agreement. Consequently a hybrid algorithm [6] has been established as a smooth combination of two of the tested algorithms, the Bristol algorithm and the Bootstrap frequency mode algorithm. 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.

In order to achieve unambiguous estimates it is necessary to provide typical emissivities, commonly referred to as tie-points, of the pure type surfaces i.e. first-year ice, multi-year ice and open water. To ensure stable performance and time/climate consistent results, a new method to estimate dynamic tie points has been developed and implemented. In this method new tie points are calculated based on the last two days of data.

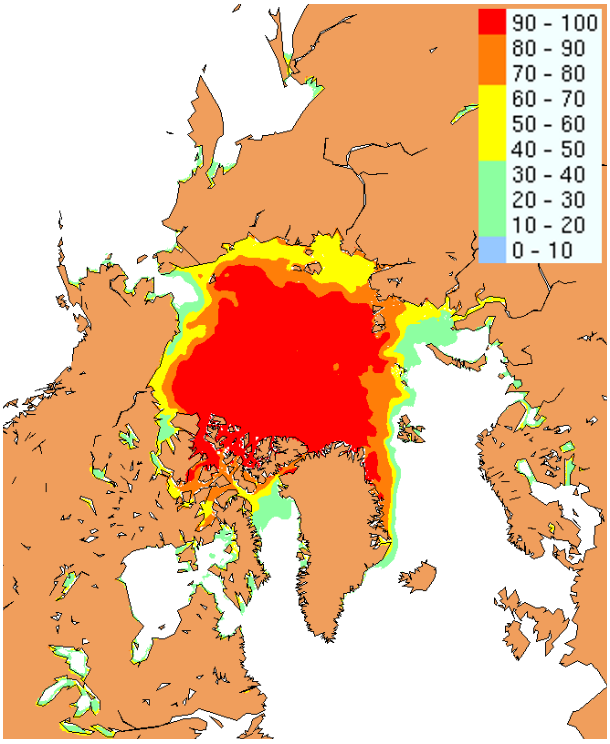

Figure 2. Average sea ice concentration for October 2000

5. SUB-SERVICE FOR SNOW

There are three planned spatial snow products:

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

While the first product has grid resolution of 10 km, the two others will most likely have grid resolution of 5 km. There will be at least daily products and monthly aggregated products. In addition there will be a selection of climate-change indicator products. The time series starts in 1987 for PMR (SSM/I) and in 1982 for optical (AVHRR). The processing chain is operated by METNO and developed by METNO and NR in collaboration.

CryoClim Phase 2 has developed a prototype sub-service for global SCE products based on PMR, while Phase 3 will do the same for optical data. Both phases will deliver current products as a service. The ultimate goal is to develop a novel algorithm for a multi-sensor product based on PMR and optical data. If this development is successful, a daily 5 km resolution multi-sensor product on SCE will for the first time be available. The intention is to draw on the best features of PMR and optical data for snow cover retrieval and combine these features in an optimal way in a multi-sensor algorithm. A multi-sensor algorithm for optical and SAR data is already developed by NR [7] and a Bayesian approach is applied in the OSI SAF sea ice algorithm [4], so the goal of achieving this for optical and PMR is not far-fetched. A comparative analysis of the products from the three sub-services will then be carried out in Phase 4, complemented with retrieval and analysis of user experiences of the services. A final decision will then be taken on which sub-service that will be continued operationally, which most likely is the multi-sensor service.

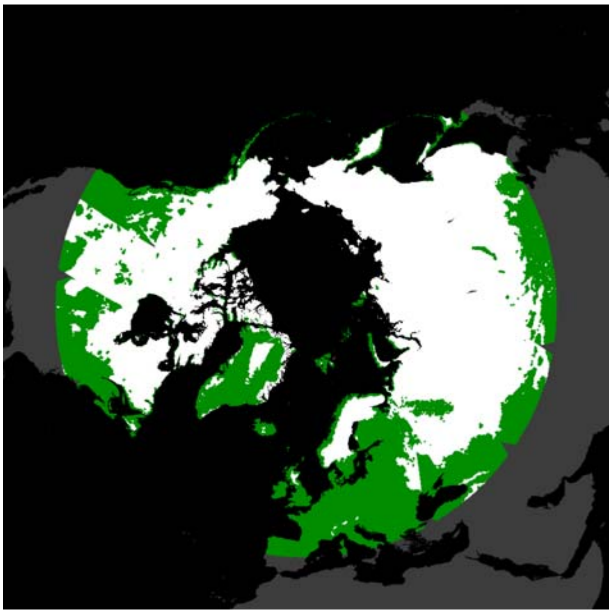

Figure 3. Current SCE product based on SSM/I for 1 March 2010 showing dry snow. Snow is shown as white in the map

In the Phase 2 a passive microwave snow extent retrieval algorithm was implemented and used to derive a climate dataset based on SSM/I data covering the time period 1987 to present. One weakness of the PMR methods is detection of wet snow. In the melting season with the presence of sunlight optical data can provide a very good complementary data source. Therefore the ultimate goal of the CryoClim snow cover algorithm is a multi-sensor PMR and optical approach.

6. SUB-SERVICE FOR GLACIERS IN MAINLAND NORWAY

The glacier products are:

- Glacier Area Outline (GAO)
- Glacier-dammed Lake Outline (GLO)
- Glacier Periodic Photo series (GPP)

The products are based on Landsat (or possibly also other optical satellites as ASTER), air-borne sensors, topographic maps, and terrestrial photography. For each Landsat scene (or image from other optical sensor) the glacier products GAO and GLO are derived. A time series of GAO and GLO will be based on Landsat TM satellite images ranging back to 1984. Topographic maps and aerial photographs will be used to extend the GAO and GLO time series prior to 1984. For the products retrieved from satellite sensors the algorithms are implemented and validated against maps and orthophotos when available, which also are used to tune the algorithms. The spatial resolution of both GLO and GAO are ~30 m. The products have potential to be used for glacier change detection and will be used to derive climate indicator products when time series of products have been produced.

The GLO product can be extended with information on previously detected jökulhlaups and potential hazardous glacier lakes in mainland Norway. A separate layer in the CryoClim web portal can also be derived to show this information. The GLO dataset can also be used to map potential hazardous glacier-dammed lakes by more detailed GIS analyses.

The GPP product (time series of glacier photographs: terrestrial and airborne imagery without geo-referencing) will be used to illustrate glacier changes for selected glaciers where photo series are available for use.

Figure 4. Mapped glacier area outline (GAO) and glacier lake outline (GLO) for a subset from Folgefonna, south-west Norway

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 [8]. The results confirmed that the applied method was robust and highly accurate for extracting glacier outlines in the test area. The ratio image method was therefore chosen in CryoClim for mapping GAO of all glaciers in mainland Norway. In Phase 2 of the CryoClim project, the method was used for all glaciated areas in mainland Norway.

The new GAO product derived through CryoClim will be delivered to GLIMS (Global Land Ice Measurements from Space) - a project designed to monitor the world's glaciers primarily using data from optical satellite instruments (www.glims.org), Results from two regions in mainland Norway, Jotunheimen and Svartisen, are already included in the GLIMS database.

7. SUB-SERVICE FOR GLACIERS IN SVALBARD

The glacier products are:

- Glacier Surface Type (GST)
- Glacier Balance Area (GBA)

The products are based on SAR C-band data from ERS-1, ERS-2, Envisat and Radarsat. The spatial resolution is 30 m, and the time series will start in 1992.

The CEC FP5 EuroClim project developed two methods for glacier monitoring on Svalbard [9, 10]. The first method uses the extent of the firn area on the glacier to observe changes for a particular glacier. Since the firn area extent is dependent on the combined influence of several previous years, a change in its size smoothes out annual mass-balance variations and rather shows long-term trends on the glacier.

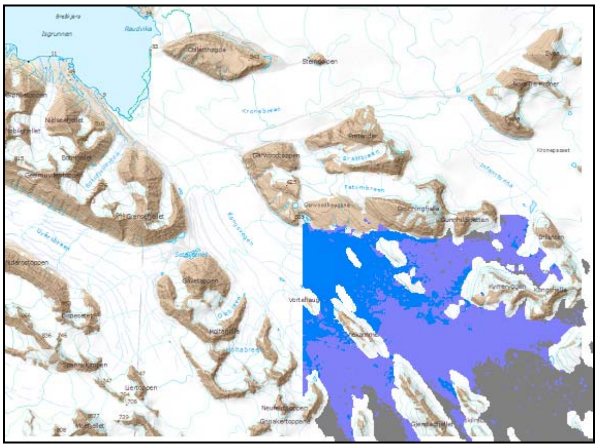

Figure 5. Glacier surface type of the upper part of Kongsvegen (blue – ice, violet – superimposed ice, grey – firn, transparent – no classification area)

The second method was discovered when attempting to make operational the firn area algorithm. Applying a k-means classification in three clusters on the glacier surface resulted in one zone on the higher parts of the glacier where the variation in areal extent correlates remarkably well with the glacier's annual mass balance. This is because the snow from the accumulation area influences the k-means classification. Thus, on glaciers where mass-balance values are available, new mass-balance values can be predicted solely from SAR images. However, the method was only tested on selected glaciers on Svalbard. In the CryoClim project the SAR method for mass balance monitoring is validated more extensively on other glaciers.

8. DISCUSSION AND CONCLUSIONS

The CryoClim project develops new operational services for long-term systematic climate monitoring of the cryosphere. The current project includes development of services for sea ice and snow products of global coverage and glacier products covering Norway (mainland and Svalbard), see Tab. 1. The project is also aiming for an expansion where new products for glaciers in the Alps and the Greenland ice sheet are included. The system and services are designed to be integrated into the international system of systems for global monitoring (GEOSS) – the part of the system aimed for climate monitoring.

The project is carried out in four phases. Phase 1 (2008) prepared the ground for a successful development of an operational monitoring system and service in phases to follow. Phase 1 identified the user needs, developed a first design of the system, developed a demonstrator of the system and climate demonstration products, promoted the initiative, established contacts with key users and other key organisations, and developed a work plan for the main project. The table below gives an overview of the currently foreseen products to be provided by the CryoClim service.

Phase 2 (April 2009 – March 2010), developed the first (incomplete) version of the web service, completed the sub-service for sea ice, developed the passive microwave component of the snow sub-service, made the first full glacier product coverage for mainland Norway based on optical data and validate SAR-based algorithms for glacier monitoring in Svalbard.

Phase 3 and 4 will complete the sub-services, produce the full time series of cryospheric products and establish fully operational production to regularly update the product sets. The web service will be completed with an operational backend system and a web service with a portal and machine-readable interfaces.

Our ambition is that CryoClim, including the web-based service and the new and accurate climate products, will represent a significant contribution to the very important task of monitoring the development of the climate on our planet.

Table 1. Current product portfolio. The column ECV refers to the Essential Climate Variables (ECVs) as defined by GCOS

ECV	Name	Coverage	Frequency	Grid res.	Time span	Prov.
	Sea Ice					
O.1	SIC - Sea Ice Concentration	Global	Monthly	10 km	1979-present	EUMETSAT/ METNO
O.1	SIE - Sea Ice Edge	Global	Monthly	10 km	1979-present	EUMETSAT/ METNO
	Snow					
T.3	SCE - Snow Cover Extent (PMR)	Global	Daily	10 km	1987-present	METNO
T.3	SCE - Snow Cover Extent (optical)	Global	Daily	5 km	1982-present	METNO
T.3	SCE - Snow Cover Extent (multi-sensor)	Global	Daily	5 km	1982-present	METNO
	Glacier – Norway					
T.2.1	GAO - Glacier Area Outline	Norway	1-30 years	30 m	1930[1]/1984-present	NVE
	GLO - Glacier-dammed Lake Outline	Norway	1-30 years	30 m	1930[1]/1984-present	NVE
T.2.1	GPP - Glacier Periodic Photo	Norway	Annual[2]	N/A	1980-present	NVE
	Glacier – Svalbard					
T.2.1	GST - Glacier Surface Type	Svalbard	Annual	30 m	1992-present	NPI
T.2.2	GBA - Glacier Balance Area	Svalbard	Annual	30 m	1992-present	NPI

[1] Time span depends on availability of maps and mapping dates will also vary for each region.

[2] Frequency dependents on the available imagery for each glacier. Only for selected glaciers and in recent years series of annual photos

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