# *CryoLand*

## *Copernicus Service Snow and Land Ice*

***Collaborative Project funded by the European Union under the 7th Framework Programme***
***Project Number: 262925***

# Final Report

# Objectives, Main Achievements, S & T Results and Foreground, Impact and Exploitation

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# Executive Summary

In the FP7 project CryoLand services on snow and land ice monitoring have been developed and implemented in order to match the needs of a broad user community. The products and services build upon data from a variety of Earth Observation satellites. They are ready to fully exploit the potential of the new European Copernicus Sentinel satellite constellation. Fully validated products on snow cover, glaciers and lake/river ice from local to continental scales, conforming to the INSPIRE/GEOSS standards, are delivered to the stakeholders in near real time. In CryoLand concepts and tools have been also developed for operational Copernicus Snow and Land Ice Services, including the option to extend the services to global monitoring of snow and ice.

The CryoLand services on accurate and timely observations of snow and land ice by means of satellites are supporting many environmental and resource management activities in Europe. Seasonal snow cover and glaciers are important resources, supplying major parts of Europe with fresh water for human consumption, agriculture, hydropower generation, and other economic activities. On the other hand, there are natural hazards directly or indirectly arising from snow, glaciers and lake / river ice, including avalanches, snowmelt floods, water outbreak from glacier lakes, and ice jams on rivers. The users of the CryoLand services include organisations operating in the field of water resources management, hydropower production, energy trading, natural hazards mitigation, transportation, construction activities, climate monitoring and modelling, weather prediction, agriculture, tourism, and environmental agencies.

Specifications for snow and ice products and for the CryoLand Geoportal were elaborated together with the CryoLand User Group, comprising more than 60 organisations from 15 European countries and Greenland, and 3 European Institutions. The primary snow products are pan-European and regional maps of snow extent (including fractional coverage) from optical satellite data (MODIS, future Sentinel-3), maps of melting snow from imaging radar (Radarsat-2, Sentinel-1), and low resolution maps of snow water equivalent (from microwave radiometry). Regional snow products, optimized for the users' needs, include spatially detailed maps of snow extent from optical satellite data for the Alps, Scandinavia and the Baltic region and snowmelt area for mountainous regions derived from radar imagery. Lake and river ice products for northern Europe are generated in near real time from optical satellite data and radar images. The primary lake / river ice products are the extent and concentration of lake ice, and ice cover on rivers. Glacier services, operating on user request, have been provided for various glacier regions using high resolution satellite imagery (SPOT-5, Quickbird, Ikonos, Landsat, Sentinel-2). Products include glacier area and outlines, maps of snow/ice areas on glaciers, ice surface motion, and glacier lakes. Within CryoLand products on glaciers in the Alps, Scandinavia, Greenland, Kyrgyzstan, and Bhutan were generated for individual users. Several of the services are being carried on after the lifetime of the project, in order to enable a smooth transition to upcoming Copernicus pan-European snow services.

The developed services and methods are capable to immediately utilize data from the various satellites of the European Copernicus Sentinel satellite constellation. The first satellite, Sentinel-1A, was launched in April 2014. Demonstration products on snow cover and glaciers have been generated already in the ramp-up phase after satellite launch. The Sentinel satellite missions will offer an excellent and comprehensive database for climate monitoring and operational applications with long-term continuity.

In order to ensure timely and efficient delivery of CryoLand snow and land ice products, a powerful service infrastructure has been developed and implemented, based on interoperable and standardised Web services. It enables interactive viewing, selection and downloading of single products and time series, and provides also automatic download options for operational user applications. The CryoLand products and services are freely accessible at the CryoLand project Web page http://www.cryoland.eu.

CryoLand Services were advertised at many international conferences. The dissemination activities have been supported by more than 50 printed articles and oral presentations. In several dedicated sessions user organisations were trained on access to the services and the integration of the products into various application environments. Dissemination Workshops with more than 50 participants were held in Oslo and in Innsbruck in 2014, attracting also new user organisations. The CryoLand project partners elaborated an exploitation plan, taking into account existing users as well as the attraction of new customers, outlining a commercial business model, and planning extended exploitation activities within the project consortium and with users.

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# 1. SUMMARY DESCRIPTION OF PROJECT CONTEXT AND OBJECTIVES

## 1.1 Background

Snow and land ice are key elements of the water cycle and are important resources, supplying major parts of Europe (but also in many other regions in the world) with water for human consumption, agriculture, hydropower generation, and other economic activities. The presence of snow and ice affects the radiation and energy balance of the Earth's surface and has an important role in regulating the climate on Earth. Seasonal snow is present in Europe for 30 days to more than 150 days in Alpine regions and for 150 to 300 days in Scandinavia. Therefore, accurate characterisation of snow extent and snow conditions is important for weather prediction and climate monitoring. The variations at daily to seasonal time scales are superimposed to long term trends for all the parameters of the land cryosphere which have been observed during the last decades and are attributed to climate change. Glaciers are located in mountain regions, but they are having wider socio-economic impact as resource as fresh water supplies, especially during warm dry periods, providing headwaters to several large river systems in Central and Eastern Europe which transport water downstream into lowland regions where water is needed for human water consumption, irrigation etc. UNEP (2007) reports that 1.5 to 2 billion people are living in regions, where reduced water flow due to retreat of the seasonal snow cover and glaciers could cause major water shortages. Beside this, glaciers and especially their temporal changes give also an important insight into climate Change.

Various natural hazards are directly or indirectly related to the seasonal snow, glaciers and lake / river ice, including snowmelt flooding, droughts, avalanches, river ice jams and related floods, etc. Seasonal snow has also an impact on the availability of water for irrigation and agricultural activities. Snow load is an important safety and operation issue concerning construction activities for buildings, hydropower reservoirs and power lines. Additionally, transport and logistics are affected by snow conditions in the European regions of seasonal snow cover; this includes such economically important activities as timber collection from woodlands, where the presence of snow enables the manoeuvring of forestry machinery and wood transport.

Snow, lake ice and river ice are characterized by high temporal variability. At short time scale the extent and properties of snow cover and freshwater ice are driven by meteorological events. The year to year variability of these cryospheric parameters is also very high. Due to this high spatial and temporal variability, satellite sensors are the optimum tool for snow and ice monitoring. Accurate observations of snow cover extent and physical properties are not only of interest for climate change research, but are of great socio-economic importance. Snow and glacier melt is a dominating source of runoff in many parts of northern Europe, as well as in the Alps and other European mountain ranges.

The FP7 project CryoLand addressed the continuous and accurate monitoring of snow, glaciers, lake ice and river ice, a theme which is of high socio-economic relevance to the European citizen. A self-sustainable service was developed and implemented in order to support the better management and realisation of a wide range of economic and ecologic activities related to snow and land ice being major natural resources and essential elements of the environmental and climate system. CryoLand capitalized on the high investments in the space sector made in Europe and world-wide by utilizing data from the flagship of the European Earth observation satellites, the Sentinel satellite family.

## 1.2 Objectives

The primary CryoLand project objectives were to develop, implement and validate an operational sustainable service for monitoring snow and land ice as a Downstream Service within Copernicus in a value added chain with the Land Monitoring Core Services. CryoLand provided geospatial products on the seasonal snow cover (snow extent, snow mass, melt state), glaciers (area, snow / ice extent, ice velocities, glacier lakes), and lake / river ice (extent) derived from Earth observation satellite data in response to user needs. Processing lines and service infrastructure for various product types were adapted to match the user needs. Snow and land ice products at near-real time delivery were supplied with pan-European coverage, as well as with national and regional coverage in Europe and on other continents as required by the users.

To reach the overall aim several sub-objectives were specified:

- **Definition of a framework and specifications for the snow and land ice monitoring services and products based on requirements of users from different application fields**. The objective was to define in detail the products and services needed by specific user groups as well as by individual clients. The user needs were collected in workshops, a web survey and by direct consultations and took into account previous and other satellite snow and land ice monitoring activities. This guided the development of geospatial infrastructure, of snow and land ice products and of related services in the project.
- **Design, development and implementation of a system for CryoLand services with interoperability of the infrastructure by compliance with INSPIRE and GEOSS.** CryoLand was implemented on top of existing Web service environments (decentralized business process architectures) supporting the publication, provision and chaining of geospatial data services according to INSPIRE and GEOSS und integrating Copernicus Land Monitoring Core Services.
- **Design, development and implementation of Internet based interfaces to integrate the geospatial infrastructure developed in the project, in order to allow for efficient user interaction and access to the products**. User information services offering interactive maps, search and order functions via Web browsers were designed in a corporate “CryoLand

Geoportal". The objective was to provide virtually centralised access to services provided by the cooperation among partners for the delivery of products at different levels of geophysical product generation and of Enterprise System Interfaces for CryoLand service integrations into external user applications.

- **Augmentation and improvement of the portfolio of snow and land ice products and services tailored to specific customer needs.** The objective was to develop and validate products and processing lines for tailored snow, glaciers and lake / river / ice products and services as requested by user groups and individual users.
- **Development and implementation of tools for integration of snow and land ice products from satellite data with non-space-based data (in-situ measurements, model output) in order to improve the quality of the CryoLand services**. The aim was to develop, implement, and validate tools for integrating data and products from different sources and to make them accessible through the CryoLand Geoportal. This included tools for the integration of CryoLand products into hydrological and glaciological process models.
- **Support and train users for accessing and using the CryoLand Geoportal and Products.** The objective was to inform and train the users in the frame of workshops, training sessions or bilateral trainings, on the access and use of the CryoLand Geoportal and products and support the integration of CryoLand Services into their applications.
- **Perform thorough testing, validation and qualification of the snow and land ice monitoring system in pre-operational environment**. The objective was to perform full end to end system tests of the various components of the CryoLand system and verification in pre-operational environment.
- **Development of tools for utilization of Sentinel satellite data for snow and ice monitoring services**. The aim was to prepare the software and processing lines for generating snow, glaciers and lake / river ice products using EO data from Sentinel-1 (SAR), Sentinel-2 (high resolution optical) and Sentinel-3 (medium resolution optical) satellites. After operationalisation Sentinel satellites will provide the main EO data for running the services.
- **Preparation and initiation of a self-supportive operational snow and land ice monitoring system:** A final objective of the project was the transition to an operational self-supportive snow and ice monitoring service before the end of the project by running full performance demonstration of the system, by promotion and dissemination work. The project aimed to perform demonstration of the services during 2 winter periods.

## 1.3 Acronyms

| | |
|---|---|
| AOI | Area Of Interest |
| API | Application Programming Interfaces |
| CRS | Coordinate Reference System |
| EC | European Commission |
| EO | Earth Observation |
| ESA | European Space Agency |
| ETL | extract, transform and loading |
| FSC | Fractional Snow Cover |
| FTP | File Transfer Protocol |
| GCOS | Global Climate Observing System |
| GEOSS | Global Earth Observation System of Systems |
| GIS | Geographic Information System |
| GLIMS | Global Land Ice Measurements from Space |
| HTTP | Hypertext Transfer Protocol |
| IGOS | Integrated Global Observing Strategy |
| INSPIRE | Infrastructure for Spatial Information in the European Community |
| LIE | Lake Ice Extent |
| MODIS | Moderate Resolution Imaging Spectroradiometer |
| OData | Open Data Protocol |
| OGC | Open Geospatial Consortium |
| REST | Representational State Transfer |
| RIE | River Ice Extent |
| SAR | Synthetic Aperture Radar |
| SCAW | Wet Snow Covered Area |
| SOS | Sensor Observation Service |
| SWE | Snow Water Equivalent |
| TM | Thematic Mapper |
| TOI | Time Of Interest |
| URL | Uniform Resource Locators |
| WCS | Web Coverage Service |
| WFS | Web Feature Service |
| WMS | Web Map Service |

# 2. S&T RESULTS / FORE GROUNDS

## 2.1 Requirements and Specifications of Snow, Glaciers and Lake / River ice Products and Services

An important role in the project was the establishment of links to potential users of the CryoLand system. The interaction with the user group was important not only for assessing requirements and tailoring products and services to user needs, but also to encourage and support users in the exploration and evaluation of the CryoLand system, and eventually contribute to a future interest in the CryoLand system.

CryoLand applied multiple approaches to obtain requirements on products and services from the users from a wide application field, which guaranteed that the products and services match the user needs. Figure 2.1 gives an overview of the methods applied to derive the user requirements. First the specifications of products and services of previous user surveys and user recommendations for snow, glacier and lake/river ice products and services as specified by international working groups and organisations as well as from projects carried out since 2000, including GCOS, IGOS, EC and ESA projects were reviewed.

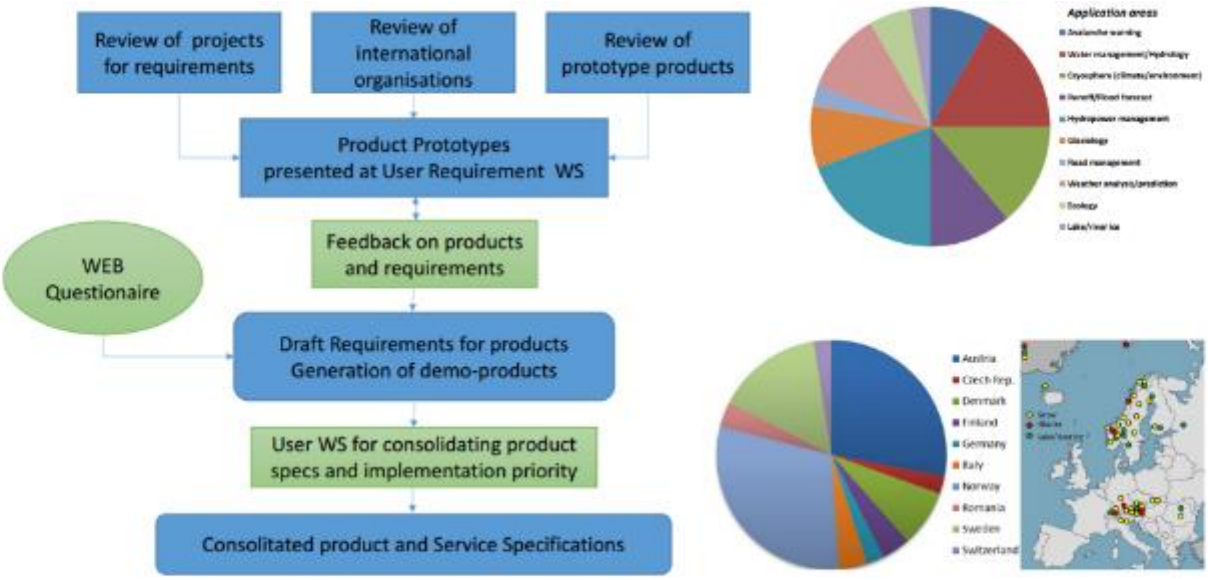



Figure 2.1: (left) Approach for consolidated requirements and specifications for snow and land ice products and services. (right-top) application fields of user (right bottom) nationalities and location of the users that responded to the user survey.

The preliminary product and service requirements were presented and discussed at 4 user requirements workshops held in Vienna, Oslo, Helsinki and Bucharest in May and June 2011. Parallel a web survey was initiated asking for input on the organisation itself, the present use of snow and ice information in their application field, specific requirements for various products and technical information on services and interfaces. The User Group was officially formed after the user requirement questionnaire following the initial workshops held in the first period of the project. Users involved in this process formed the core of the CryoLand user group, where further organisation joined during the life time of the project.

The product specifications were consolidated at a User Coordination Meeting held in May 2012 in Stockholm. The basis for the workshop was a first CryoLand Pilot Snow Service running for the period February to March 2012. The updated products and services were provided to users in the second Pilot Services held in the period December 2012 to June 2013, which enabled the users to test and evaluate the concept of the CryoLand System and to provide feedback to Service developers. At the Interim User Validation Workshop, held in Copenhagen in June 2013, users provided feedback and a first evaluation of the services which was used for final adjustment of the services and products. The user group interaction was concluded by the 2 Dissemination workshops held in Oslo and Innsbruck in October and December 2014, respectively.


Figure 2.2: Left: Map of Europe with origin of CryoLand user group and the location of the User workshops. Right: impression from one of the user workshops and one of the training sessions.

In preparation for the demonstration phase in winter 2013/14 the CryoLand team organized and held user trainings at various places in Europe (Norway, Finland, Austria, Romania, Sweden) for accessing and downloading CryoLand products and they supported the various users for integrating CryoLand Services in their applications. The user support also includes a written user guideline ("CryoLand for Newbies") and extensive help documentation at the CryoLand data portal.

The CryoLand User Group included in total more than 60 organisations from 15 nations in Europe (Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Italy, Norway, Romania, Slovenia, Sweden, Switzerland, and United Kingdom) plus Greenland, and 3 European Agencies (Figure 2.2). A core group of about 30 individual users have been actively involved in the evaluation of the CryoLand system, presenting their experiences at the workshops held by the project. The data download statistics indicated additional user activity in Australia, Belgium, Canada, China, Estonia, France, Germany, Japan, Kenya, Switzerland, Taiwan, and United Kingdom. The national institutes, universities and private companies represents user interest within space/remote sensing, environmental protection, weather and hydrological services, climate change, natural hazards, infrastructure, and energy/hydropower.

## 2.2 CryoLand System Architecture and Interfaces

The CryoLand System Architecture and the Interfaces of the geospatial infrastructure were designed in a way to match the system requirements collected during the user workshops but also to follow the guidelines of international standards like INSPIRE / GEOSS and OGC and, in the case of glacier products, the GLIMS specifications. This allows the user to access the CryoLand products and datasets online in a seamless way, and the direct integration of the provided products and datasets into the user's application system (e.g. GIS, modelling environment, etc.).

The system and geoportal design was based on the infrastructure, data-interface requirements and the product specifications collected and consolidated in the user workshops and contributions from CryoLand partners. This phase was followed by the definition of the required Internet Interfaces and Functionalities to fulfil the user requirements but also to ensure that CryoLand used advanced technologies providing a modern geospatial infrastructure anticipating future needs. The definition and the architectural software design of the Network services of CryoLand has been documented in detail in the Architectural Design Document.

The implemented CryoLand System built on widely proven Open Source Software Tools (e.g. Python, MapServer, GDAL, PostgreSQL/PostGIS, EOxServer, etc.). These tools were complemented by new implementations to cover system requirement of the user, which were not covered by pre-existed software tools. This includes also the set of software routines implemented to innovatively integrate existing Open Source software tools to form the CryoLand Server System.

A design decision towards the full exploitation and implementation of OGC web service standards for all external interfaces has been agreed upon. For the internal product exchange between project partners and the CryoLand Server, the FTP protocol has been chosen as already established distribution channels existed between the CryoLand partners. The processes between the CryoLand Product and Service Providers and the CryoLand Project Server have been fully automated. Once a product was made available by the Product Provider the product was automatically collected, registered and pre-processed to optimize viewing experience in the webGUI. The high degree of automated data handling led to an overall high availability of the CryoLand Service interfaces since the beginning of its operation. The setup of the CryoLand Service Network is shown in Figure 2.3.

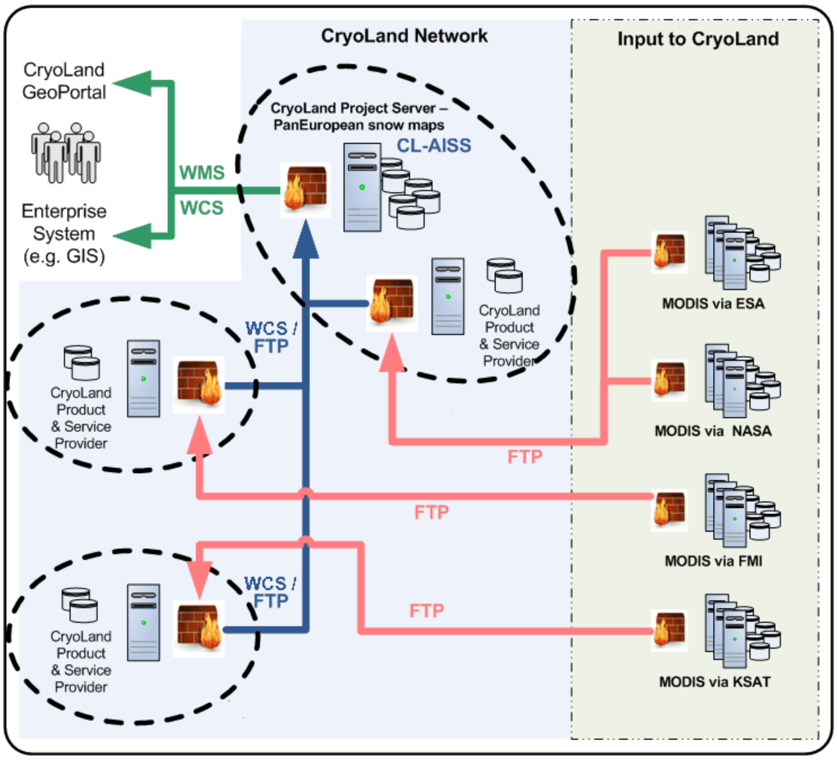



Figure 2.3: Service Network for the operational Snow and land ice services Service (CryoLand GeoPortal) utilizing a central data provisioning node.

In order to enable potential users to evaluate CryoLand products and services as early as possible the consortium initiated an additional effort and started with an early operation of the prototype system and products already in the winter season 2011/2012. This early setup of the CryoLand service was intended primarily for internal testing of work-flows and as a limited, first evaluation access point for certain users. It allowed to gather first user responses and helped to evaluate, streamline, and verify some of the requested user requirements. Additional input from the users was included in version 1 of the software release.

Starting with March 2012 the ***CryoLand GeoPortal Version 0.9*** was brought online and is since then fully accessible for anybody interested in Snow and Land Ice Information Products over the Pan-European region. The GeoPortal access offers fully interoperable interfaces based on the internationally widely used OGC standards WMS and WCS. As indicated in Figure 2.3 two access points, both based on these OGC services were made available:

- a webGUI providing a viewing/portrayal (WMS) and downloading service (WCS), mainly intended for direct interactive usage
- an access for Enterprise usage (e.g. for direct data integration into customers GIS or modelling environments), mainly intended for customers who either need to access large volumes of data (e.g. longer time-series) or need regular access (e.g. daily dataset) to test the services in a pre-operational environment.

To provide initial support to customers for usage of the Enterprise access point demonstration scripts (in python, or IDL) were provided to users. The specifications a user can provide to customize the CryoLand products of interest include

- selection of the desired Dataset Series
- selection of the desired Area Of Interest (AOI)
- selection of the desired Time Of Interest (TOI)
- selection of the desired output file-format
- selection of the desired output coordinate reference system (CRS, projection)

The user provided information is integrated into the WCS request and the GeoPortal generates the customized datasets on-the-fly and provides them to the user. During various User Workshops this functionality of the CryoLand GeoPortal, of automatizing and customizing the access has been demonstrated and received wide positive interest in the user community. Automatizing and customizing access to geospatial information (and remote sensing images) data products has been recognized as innovative and very helpful, especially by users with regular data needs or the requirement to analyse a time-series of a product.

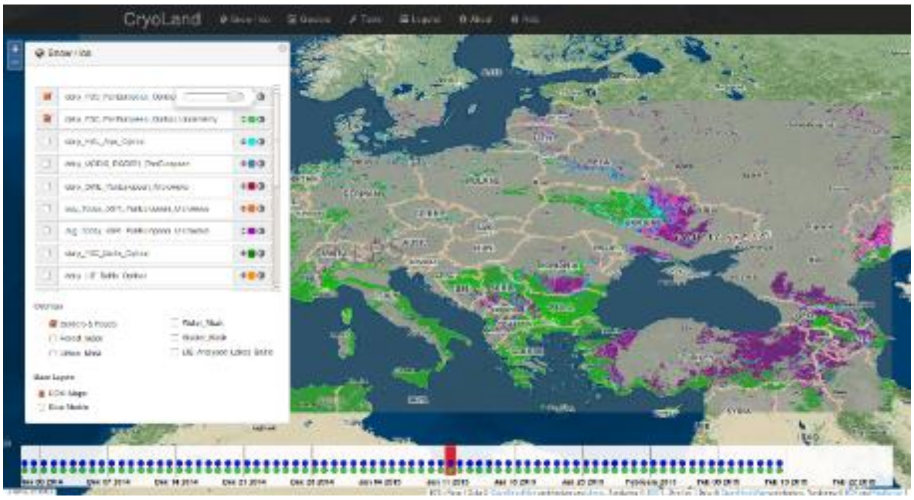
Despite the consolidated user requirements the webGUI interface of the GeoPortal has undergone three development and release cycles which where all influenced by user experience and user feedback (mostly collected during user workshops). This finally resulted in a lean, agile and highly streamlined webGUI with an optimized interface.

In April 2013 the CryoLand team, following a request by EEA, decided to immensely extend the time period for which Pan-European snow products. This resulted in a considerable increase in the number of datasets to be provided via the CryoLand GeoPortal causing performance problems at the server and the interfaces alike. CryoLand provided three daily datasets starting from 1 November 2000 and the project team agreed to extend the production of these products also after the official end of the project in January 2015 until 2016/17. The additional requirements for the larger number of products demanded an update of the GeoPortal (server and webGUI). Concurrently the initially offered OGC interfaces (WMS and WCS) had to be changed to utilize the EO Application profile of the corresponding service (EO WMS and EO WCS) since the result generated by a basic WMS-GetCapabilities exceeded 16MB and the time effort for such a request easily reached 20 minutes. This was caused by the fact that the basic WMS standard was not designed for such a number of datasets. Therefore, the EO-Application protocol has been standardized to take care of these cases. The upgrade of the Server and webGUI and the general utilization of the EO-Application profile (EO WMS and EO WCS) resulted in a significant performance boost.

The final upgrade of the CryoLand Server improved the performance in handling large data sets and updated the navigation on the Geoportal webGUI interface. Especially the selection of time series of products has been optimized. The webGUI (shown in Figure 2.4) was extended by the following features:

- Zoomable Time-Slider - for pleasant navigation
- Dataset indicators – zoom to dataset extent
- Refined Dataset grouping, together with overlay masks
- Datasets intuitively sortable in layer menu
- Streamlined download procedure
- Additional output file formats
- Additional output projections
- Capability to store/reload AOIs as GeoJSON files
- OGC support optimized to EO-WMS and EO-WCS

By 31 January 2015 the CryoLand System contained about 20.000 snow, glacier and lake / river ice products.



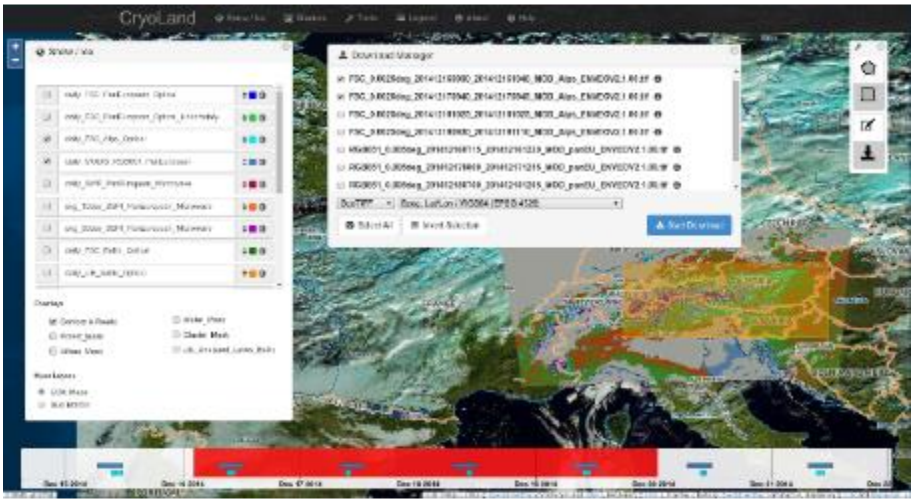




Figure 2.4: Top: CryoLand GeoPortal webGUI showing Snow/Ice Layer selection. Bottom: CryoLand GeoPortal webGUI showing AOI and TOI selection and Download Manager widget.

## 2.3 CryoLand Snow Products and Services

The snow products generated and delivered in the project are based on optical (radiometer) and microwave (synthetic aperture radar, SAR, and passive microwave radiometer, PMR) satellite imagery. The snow variable retrieval approaches are using single, dual and multi-sensor algorithms. The project partners have been working on advanced retrieval methodologies in many years and made important contributions to innovative algorithms. The project consortium stands internationally at the leading edge of this development. The specifications of the CryoLand Snow Products were defined in close collaboration with the CryoLand user group and are summarized in The product portfolio includes pan-European snow products from medium resolution optical and passive microwave radiometer data provided daily in near real-time. Regional fractional snow cover products were generated for

Scandinavia, Central Europe (Alps) and Baltic Sea region for local and regional users. Beside snow extent from optical data also maps of the snow conditions (wet snow) were specified using SAR data especially for mountain regions. These products were generated applying algorithms adapted to the characteristics of the region (topography, forest, etc.). Prototype products of snow surface wetness and snow surface temperature from optical satellite data were generated for southern Norway.

Table 2.1.

The product portfolio includes pan-European snow products from medium resolution optical and passive microwave radiometer data provided daily in near real-time. Regional fractional snow cover products were generated for Scandinavia, Central Europe (Alps) and Baltic Sea region for local and regional users. Beside snow extent from optical data also maps of the snow conditions (wet snow) were specified using SAR data especially for mountain regions. These products were generated applying algorithms adapted to the characteristics of the region (topography, forest, etc.). Prototype products of snow surface wetness and snow surface temperature from optical satellite data were generated for southern Norway.

Table 2.1
The main characteristics of the snow products provided by CryoLand.

| *Product type* | *Approx. spatial resolution* | *Frequency, Period* | *Coverage* | *Latency time* | *EO sensors* | *Status* | *Provider* |
|---|---|---|---|---|---|---|---|
| Snow extent, pan-European | 500 m | Daily, full year | 35N – 72 N 11W – 50E | < 1 day | MODIS, Sentinel-3 | Operational | ENVEO/ SYKE |
| Snow Water Equivalent (low res) pan-European | 10 km | Daily, dry snow season | 35N – 72 N 11W – 50 E | < 2 day | SSMI/S, AMSR2 | Operational | FMI |
| Snow extent, regional – Alps | 250 m | Daily, full year | Alps/central Europe | < 1 day | MODIS, (Sentinel-3 ) | Operational | ENVEO |
| Snow extent, regional - Baltic including Finland | 500 m | Daily, melting period | Baltic Sea area | < 1 day | MODIS (VIIRS) | Operational | SYKE/FMI |
| Snow extent, regional - Scandinavia | 250 m | Daily, melting period - full year | Scandinavia | < 1 day | MODIS/ Radarsat-2, Sentinel-1/-3 | Operational | KSAT/NR/ NORUT |
| Wet snow area | 100 m | Daily, full year | Scandinavia | < 1 day | Radarsat-2, ASAR (archived), Sentinel-1 | Operational | Norut/KSAT |
| Wet snow area | 100 m | Daily, melting period | Alps | < 1 day | ASAR (archived), Sentinel-1 | Demo Products with Envisat, Sentinel-1 | ENVEO |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Snow Surface Wetness | 1000 m | Daily | Scandinavia | <1 day | MODIS, Sentinel-3 | Demonstration product | NR |
| Snow Temperature of Surface | 1000 m | Daily | Scandinavia | <1 day | MODIS, Sentinel-3 | Demonstration product | NR |

The ***Pan-European Fractional Snow Cover (FSC)*** is a homogenized product for large areas, jointly developed by the CryoLand team. The product is based on medium resolution optical satellite data from Terra MODIS (Sentinel-3 in the future) and extends from Scandinavia in the north to northern Africa in the south, and from Portugal in the west to the Caspian Sea in the east (from 72°N/11°W to 35°N/50°E). The algorithm compensates for the effects of the forest and estimates the below-tree FSC. The product, and an associated accuracy estimation per pixel, have been provided daily with 0.005° spatial resolution (approx. 500 m).

The Snow Water Equivalent (SWE) product is based on the combination of satellite-based passive microwave radiometer and ground-based weather station data applied in a SWE model. Nimbus-7 SMMR (1980–1987), DMSP SSM/I (1987 to present) and Aqua AMSR-E are the main data sources. Non-mountainous areas within the pan-European domain were covered by the CryoLand implementation of the SWE service. The pan-European domain SWE maps have been provided with 0.1° spatial resolution (approx. 10 km).

Reprocessing of pan-European fractional snow cover product and the snow water equivalent product back to 2000 has been done in order to support European users.

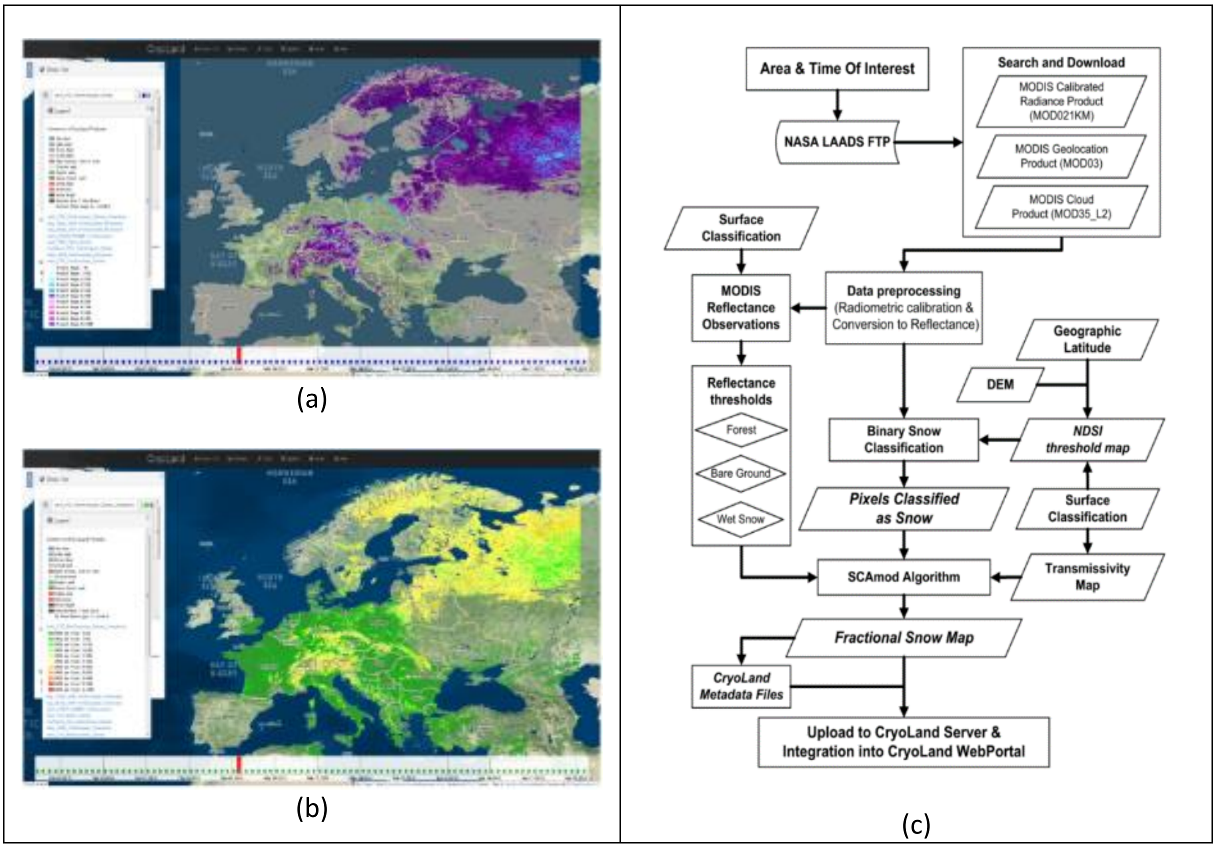



Figure 2.5: (a, b) Fractional snow cover and uncertainty map for the pan-European region, 4 March 2013, (c) processing line for generating Pan-European snow extent product.

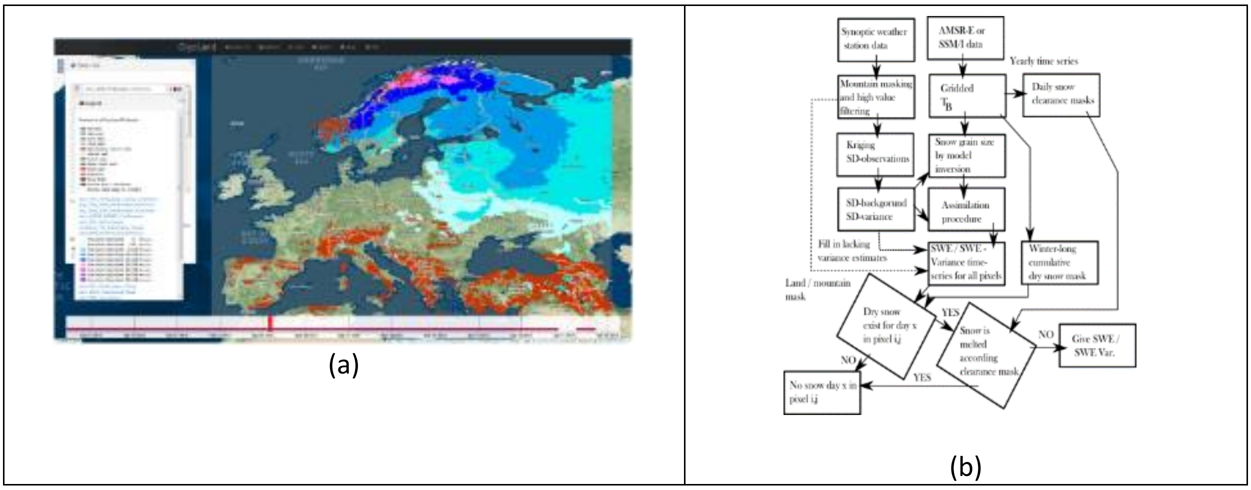



Figure 2.6: (a) Pan European Snow Water Equivalent Map, on 4 March 2013; (b) processing line for generation of the Pan-European snow water equivalent product.

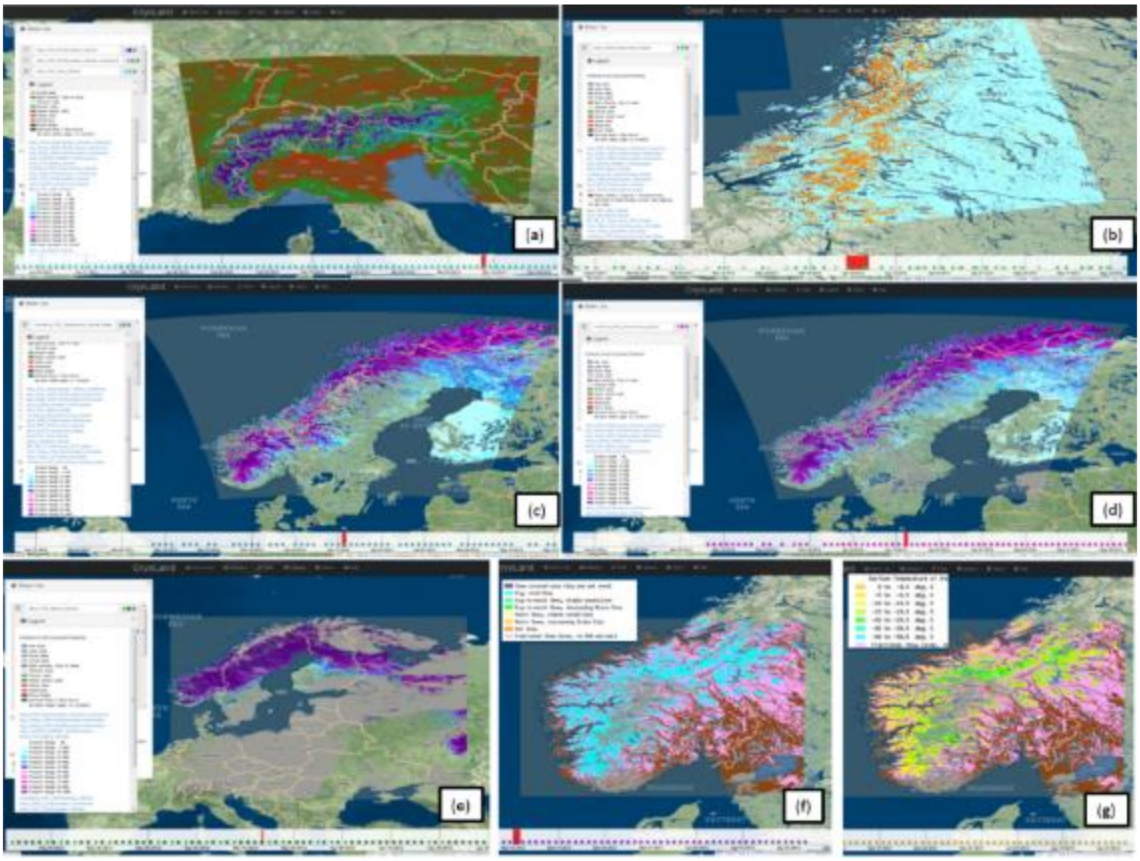


Figure 2.7: Regional snow products. (a) fractional snow cover products for the Alpine area from optical satellite data, (b) wet snow cover product for Scandinavia using radar satellite data, (c) fractional snow cover product for Scandinavia using optical and radar data, (d) fractional snow cover product for Scandinavia using multi-temporal optical satellite data, (e) fractional snow cover product for the Baltic Sea region from optical satellite data, (f) snow surface temperature for southern Norway from optical satellite data, (g) snow surface wetness for southern Norway from optical satellite data. Products (a) to (e) run operationally, products (f) and (g) were pilot services needing further evaluation activities.

## 2.4 CryoLand Glacier and Lake River Ice Services

**Glacier products** were generated and provided on users' demand for their particular areas of interest. The glacier product portfolio included glacier outlines, snow and ice areas on glaciers, glacier lake extent, and ice surface velocity on glaciers. Table 2.2 summarizes the specifications for the glacier products generated and provided within CryoLand.

Table 2.2:
Specifications of CryoLand glacier products.

| *Product type* | *Coverage* | *Spatial Resolution* | *Latency time* | *Sensor* | *Status* |
|---|---|---|---|---|---|
| Glacier outlines | ENVEO | 0.5 m – 10 m | SPOT, Landsat, Ikonos-2, Formosat-2, Quickbird | Selected Areas | Operational (on demand) |

| | | | | | |
|---|---|---|---|---|---|
| Snow / ice area on glacier | ENVEO | 0.5 m – 10 m | SPOT, Landsat, Ikonos-2, Formosat-2, Quickbird | Selected Areas | Operational (on demand) |
| Glacier lakes | ENVEO, GAMMA | 1 m – 30 m | SPOT, Landsat, Ikonos-2, Formosat-2, TerraSAR-X, Sentinel-1A | Selected Areas | Operational (on demand) |
| Glacier ice surface velocity | GAMMA, ENVEO | 3 m – 50 m | TerraSAR-X, (historical) ERS-1/-2, Sentinel-1A | Selected Areas | Operational (on demand) |

For the product generation very high resolution optical and radar satellite data were used, which were ordered especially according to user needs and received through the Data Warehouse system of EC. The applied processing lines for the glacier products generation available at ENVEO and GAMMA are in general operational, but were adapted to the very high resolution satellite imagery, which enabled the products generation with a high spatial accuracy. The products, meeting the internationally accepted format standards for glacier products identified by the Global Land Ice Measurements from Space (GLIMS) project, were directly provided to the interested users. In Figure 2.8 examples of glacier products generated on user demands from very high resolution satellite data and delivered to interested users are shown.

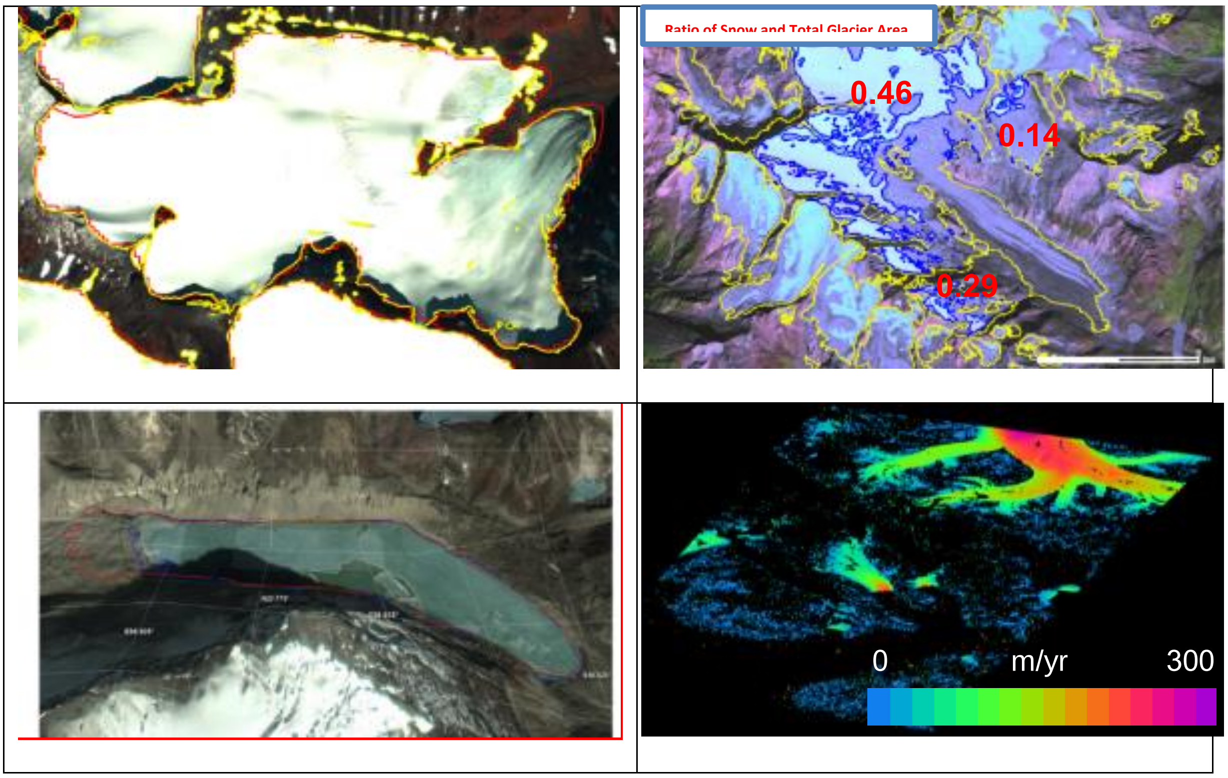



Figure 2.8: Examples of glacier products generated by ENVEO and GAMMA on user requests. Upper left: glacier outlines on a glacier in Jotunheimen, Norway, from a Quickbird-2 scene with 4 m pixel size of 27 August 2012 (yellow) compared to glacier outlines derived from a Landsat scene of 2004 with 30 m pixel size. Upper right: glacier outlines and snow and ice areas on glaciers in the Glocknergruppe, Austria, from a SPOT-5 scene of 1 September 2009. Red numbers indicate the ratio of the snow areas to the total glacier

areas of selected glaciers, which can be used as indicator for a glacier's mass balance. Lower left: change detection of a glacier lake extent in Nepal from TerraSAR-X scenes with 3 m pixel size of 2009 (blue) and 2010 (green), and from a Sentinel-1 scene with 20 m pixel size of 2014 (red). Lower right: ice surface velocity of glaciers in Spitsbergen, Norway, from TerraSAR-X scenes with 3 m pixel size of December 2012.

**Lake Ice and River Ice Services** were provided by the project partners SYKE and NORUT. Table 2.3 summarizes the specifications of these services.

Table 2.3:
Lake and river ice product coverage, projection and latency time.

| *Product type* | *Coverage* | *Grid / Projection* | *Latency time* | *Sensor* | *Status* |
|---|---|---|---|---|---|
| Lake ice extent (4 classes) | Regional (Baltic) | Lat/Lon / WGS84 | < 1 days | MODIS/Terra, Sentinel | Operational |
| River ice extent | TBD | Lat/Lon / WGS84 | 3 days | High res. SAR (1-30 m) | on user request and data availability |
| Lake ice extent | TBD | Lat/Lon / WGS84 | 3 days | High res. SAR (1-30 m) | on user request and data availability |
| Flood Inundation Area | TBD | Lat/Lon / WGS84 | 3 days | High res. SAR (1-30 m) | on user request and data availability |

SYKE has renewed its Lake Ice algorithm and accordingly the products. Previously the lake ice was mapped with Snow on Ice algorithm, which provided fractional snow cover over lake ice. The difficulty with the earlier algorithm was in distinguishing between snow and clear ice or snow-ice partially covered with snow. Another algorithm providing binary ice extent was in development stage. Based on these two prototype products an advanced algorithm, providing information on four classes (full snow cover, partial snow/white ice, clear ice and open water) was developed. The method uses Terra/MODIS 250m reflectance data as input. In the development phase, the extensive in-situ monitoring network of SYKE was exploited. The method can also be transferred easily to other optical satellite sensors. SYKE conducted in-situ observations of ice cover, ice thickness and thickness of snow cover over lake ice at several sites in Finnish inland waters. Finding the reference reflectances for the algorithm was based on comparing time series of MODIS/Terra reflectances to the snow thickness over selected monitoring sites.

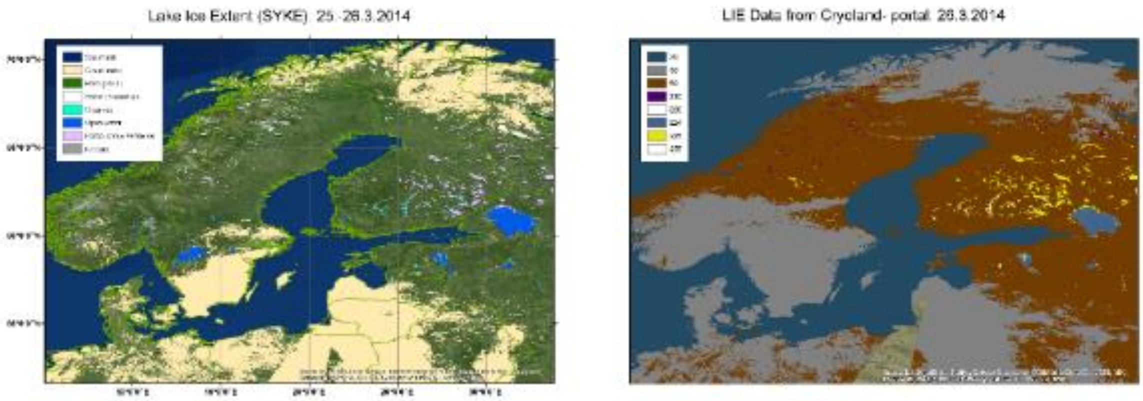



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Figure 2.9: SYKE's Lake Ice Extent data example from 25 – 26 March 2014, as seen in the CryoLand Portal (right) and in a standard GIS program (left).

An improved automated processing line for SYKE's Lake Ice Extent with Optical EO Data product has been created. The new processing line arrangement has been implemented in collaboration with FMI. Automated pre-processing of optical EO data for the Lake Ice Extent product was performed at FMI. This includes cloud detection from MODIS/Terra data (500m and 1km channels) to create the cloud mask. The MODIS/Terra 250m channel 2 (841 – 876 nm) was used for lake ice interpretation. The generated product was passed on to SYKE'S processing chain where it was packaged and further distributed via web-services and archived. The initial validation of the product gave overall accuracies of 86% and 74% for two high-resolution datasets from Landsat TM and SPOT-4, respectively.

For the Lake Ice Extent with SAR Data, River Ice Extent and Flood Inundation Area products NORUT has completed automated processing chains in IDL utilizing processing tools for SAR geocoding and classification, along with a long series of in-house NORUT developed processing tools (image reading, geocoding, classification, product export, etc.). The main step in the processing chain for the lake Ice Extent product from SAR Data is the lake ice classification module. This module uses state of the art imaging processing algorithm to identify pixels that are covered by ice and pixels not covered by ice (binary classifier).

River ice extent (RIE) is a product derived from SAR images that gives a binary classification (ice / open water) of river stretches. The classification algorithm for RIE is the same as the lake ice extent algorithm, but since rivers are more narrow, higher resolution SAR data (<25m or better) are preferred as they provide more accurate products. The automated algorithm for flood inundation area detection depends on accurate maps for water bodies. Areas outside the water bodies are subsequently classified into water or not-water based on the same statistical algorithm that is used for lake ice classification. First examples of lake ice maps using Sentinel-1A data was produced in January 2015 during the ice development period. (Figure 2.10).

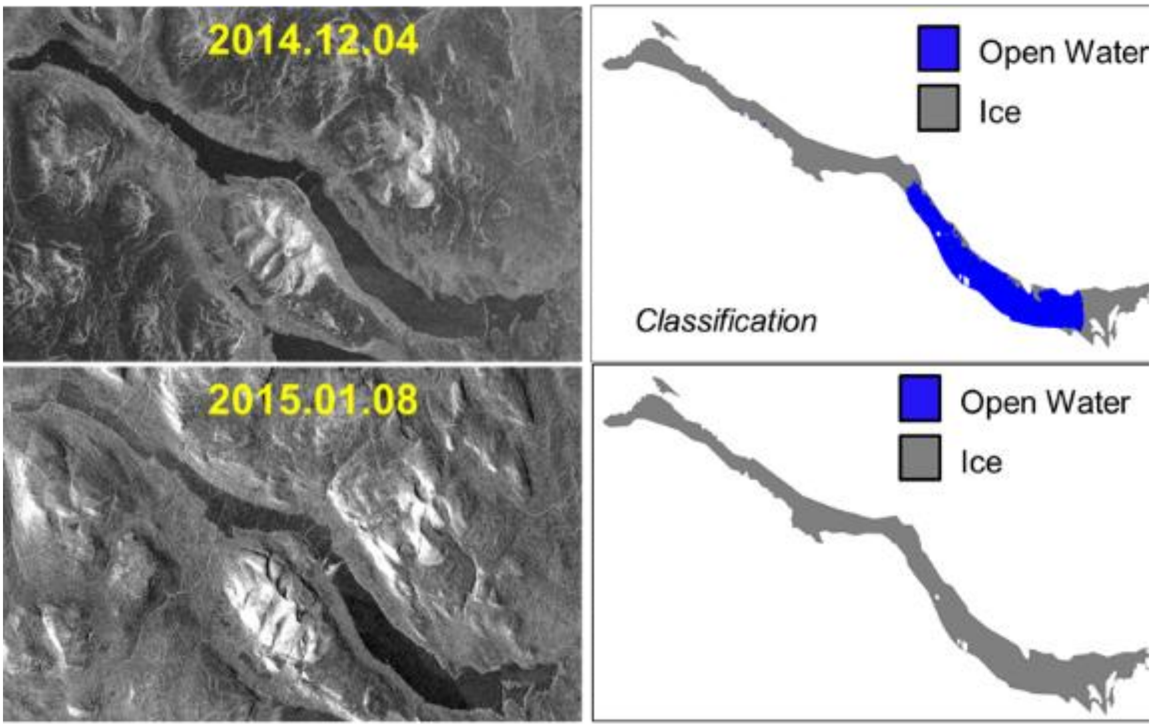



Figure 2.10: Sentinel-1A: Lake ice maps from Altevatn, Norway (Based on S1A VV-VH). The images are acquired during the lake ice formation period and during the polar darkness period in this region.

## 2.5 Integration of In-situ data into CryoLand Services

In-situ data was an essential part of the development of CryoLand services and in the generation of products. The wider use of in-situ data required that the data sets were available through standardized interfaces following a harmonized data model. These requirements meet also the principles of the INSPIRE directive. In CryoLand, recommendations for commonly used data model and standard interfaces were elaborated. The acceptance and wider implementation of the recommended data model requires national and institutional level discussion and decisions.

The CryoLand data model and interfaces follow the specifications of the INSPIRE directive, which strongly supports and provides guidelines for the interoperability of spatial datasets. The defined data model is capable to store single in-situ measurements (e.g. snow height at a certain location at a certain time), but also modelled values and their representative spatial features. Starting point of the development of the data model was carried out by analysing the current snow monitoring in CryoLand partners' Institute. The description of snow course networks and current data models were obtained from SYKE, Meteo Romania, and SMHI. Based on a brief study concerning delivered metadata the snow course data contain at least the information of snow depth, snow water equivalent, snow density and snow cover in the area (patchiness) at a certain time. Snow courses were identified by its name and idcode. Location information was known for a representative point, but location information of snow courses was available for multiple points along a track.

The proposed CryoLand data model, shown in detail in Figure 2.11, was designed to store snow information. Beside the mandatory attributes, additional attributes widen the information of the site if available. The code lists can be extended to include other phenomena if needed. The measuring methods and description of the sensor varies by different data providers and need to be described in the procedure table. The defined CryoLand data model and guidelines for harmonization were and are important for the users of in-situ data, but also for the provider of the data. The data model and the interfaces for accessing in situ data within CryoLand were documented in Deliverable D7.1 - Description of Data Models, Guidelines for Harmonizing and Publishing Datasets.

Table 2.4 summarizes the guidelines and recommendations for providing snow parameters to the CryoLand portal. The parameter list has been specified to support the implemented CryoLand products, but can be extended for upcoming products. For each parameter a recommended unit, the describing feature, the sensor type, the data type of the measurements and the short description is given. For several parameters, key words were defined.

The proposed data model was tested by transforming SYKE’s snow course data into the CryoLand data model. The overall harmonisation process including the ETL (extract, transform and loading) process to be used by data providers.

Spatial location is crucial information connected to in-situ measurement data. Usually measurements take place each time at same locations. When the coordinates of these sampling points are known, a spatial data set can be created using this information and then publish via WMS (Web Map Service) and WFS (Web Feature Service) interfaces. These standard interfaces allow easier access to data. WFS provides access to vector-based geographic features encoded in GML. It enables among other things querying the data based on coordinates and attributes of features. The data on WFS interface can be exploited as an input data source for analysis processes, which require to use this kind of data. Using WFS, the data can also be exported to the user's computer in a different format like ESRI Shapefile, if the user’s application is capable to import that. In addition to visualization and querying spatial features and their attributes the user might like to query observations and get for example time series of observations. SOS (Sensor Observation Service) interface was developed for sensor data, but it can be also used for publishing other kind of observation data.

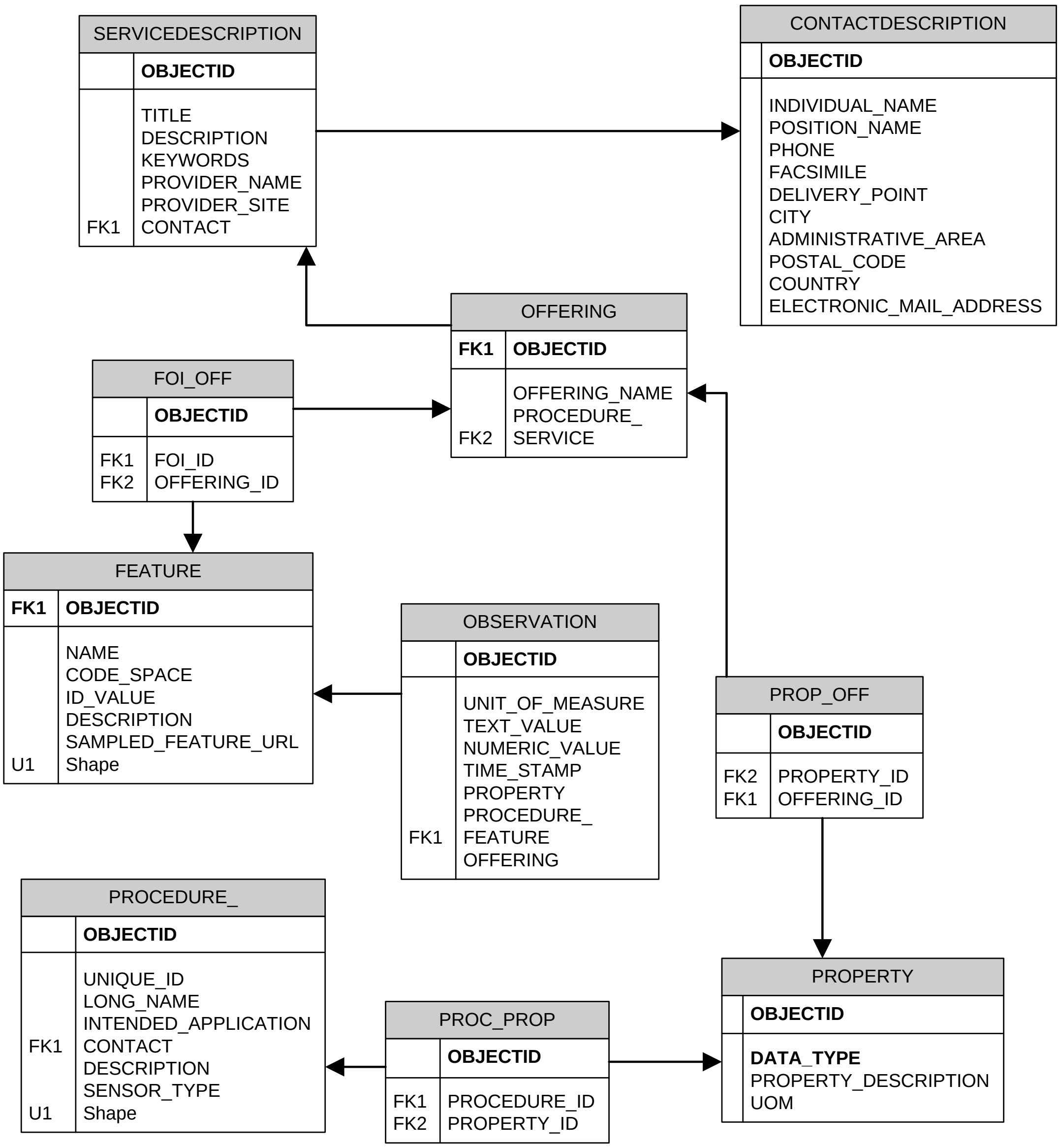



Figure 2.11. The CryoLand data model.

Table 2.4
Requirements and guidelines for the attribute values

| *Measured property* | *observation. unit_of_measure* | *feature. description* | *procedure. sensor_type* | *property. data_type* | *property. property_description* |
|---|---|---|---|---|---|
| snow depth | cm | environment* | measuring instrument** | numeric | snow depth |

| ***Measured property*** | ***observation. unit_of_measure*** | ***feature. description*** | ***procedure. sensor_type*** | ***property. data_type*** | ***property. property_description*** |
|---|---|---|---|---|---|
| snow water equivalent | mm | environment* | measuring instrument** | numeric | snow water equivalent |
| snow density | kg/m³ | environment* | measuring instrument** | numeric | snow density |
| snow patchiness | % | environment* | measuring instrument** | numeric | snow patchiness |
| Snow surface temperature | °C | environment* | measuring instrument** | numeric | Snow surface temperature |
| Snow surface wetness | %vol | environment* | measuring instrument** | numeric | Snow surface wetness |

** Keywords (Code list): Open place (tundra, grassland, steppe, agricultural), Open place in forest, Pine-intensive forest, Spruce-intensive forest, Deciduous tree-intensive forest, Swamp/Mire, Bare rock (over tree-line), Mountainous terrain (unforested; unglaciated), Average of mixed types*

*** Keywords (Code list): Snow balance, Snow cylinder (large), Snow cylinder (small), Snow stake, Shovel (small), Shovel (large), Ultrasonic sensor, Snow pillow, Gamma-ray detector, Visual observation, Thermometer*

In the CryoLand project spatial locations of Finland's snow courses were published via WMS and WFS. Also the SOS interface was implemented for observational data of them. The publishing was based on following software: MS SQL Server, ArcGIS for Desktop, ArcGIS for Server and SOS extension for ArcGISServer. The implementation process in SYKE is described in Deliverable D7.1 Description of Data Models, Guidelines for Harmonizing and Publishing Datasets. Besides the above described commercial software used in SYKE, there are also different Open Source software tools available, which are widely used for publishing data via WMS/WFS interfaces (GeoServer, MapServer, degree, etc.) and SOS interface (52N-SOS-3.2.0 etc.). Spatial data can likewise be stored in Open Source relational database management system like PostgreSQL/PostGIS.

## 2.6 CryoLand System Validation and Quality Assessment

The validation and testing activities performed for the CryoLand services and products were defined based on the general objectives and structured according to the Reference Model of Open Distributed

Processing (RM-ODP1) (ISO/IEC 10746-1:19982). This model is an international standard for designing open, distributed processing systems. It provides an overall conceptual framework for building distributed systems in an incremental manner. The key fundamental aspect of this model is that it provides a framework for assessing system conformance with the initial requirements. In the model, the viewpoints (a view is a representation of a whole system from the perspective of a related set of concerns) identify the top priorities for architectural specifications and provide a minimal set of requirements to ensure system integrity. They address different aspects of the system and enable the 'separation of concerns'. Hence, it was identified as a viable approach for identifying the requirements to be validated and verified.

The CryoLand system testing and validation activity was coordinated by NMA. Using the general RM-ODP1 recommendations, the team structured and documented a CryoLand oriented set of procedures, principles and models for system validation and qualification. The documentation was complemented with the feedback and requests received during the User Validation Workshop, held in Copenhagen on 5 June 2013. For an independent assessment of the CryoLand system, relevant user communities (15 experts from 9 institutions) have been introduced long before the start of the CryoLand qualification phase. Several meetings and interactions have been conducted in the second half of the project period. The scope was to create a team of professionals that were willing to use the test procedures and tools prepared for the system validation and qualification. The team had a one day face to face meeting at the NMA headquarters. Hands-on workshops were given by CryoLand project members to learn the testing team members how to operate the CryoLand system and how to use the testing infrastructure. In the following months, the testing team provided feedback using two methods:

- Performing predefined test procedures;
- Perform overall system evaluation based on questionnaires and interviews.

The test procedures had the following structure:

- Purpose;
- Test platform;
- Actions to be performed;
- Expectations to be verified;
- Status after execution: OK if the final result corresponds with the defined expectation, KO otherwise;
- Feedback: text description of the encountered problems.

Each Test Procedure contained a number of Test Cases specific for each method of access. All Test Cases need to be executed in the order specified in the Test Procedure, as they are usually connected one with another and assure a normal execution flow for the user operations. If specified, the pre-requisite of a Test Case must be respected; otherwise a false KO may be generated. A web tool was used to define the test cases and gather the results for each individual test case. A fully automated testing procedure (autotest) for the CryoLand software modules was developed and run automatically after every change which has been submitted into the system repository, as well as prior to any release version. In the end, a total of 991 test cases were defined for the entire functionality of the CryoLand system:

- automatic tests: 919
- manual test cases: 66
- integration cases: 6 test cases

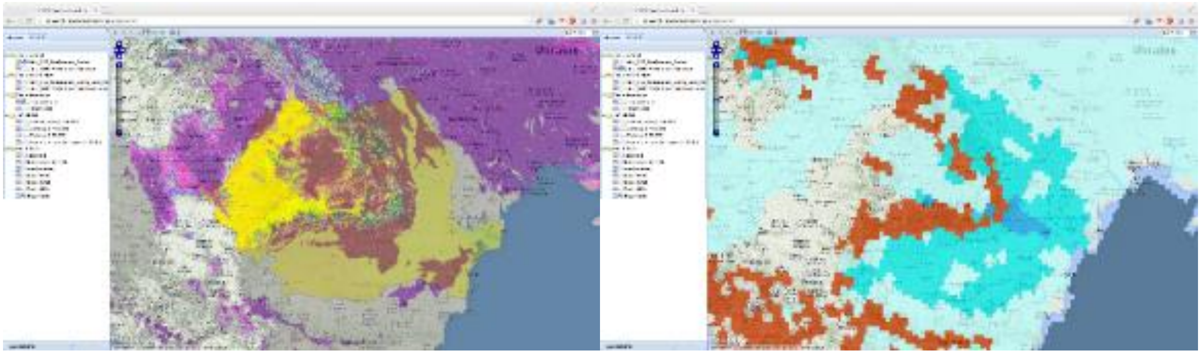
A total number of 990 OKs were obtained:

- automatic tests: 766 test cases OK, 153 test cases OK but skipped (regarding functionalities disabled on purpose)
- manual test cases 65 OK. Minor errors on one test case regarding a browser specific error that does not affect the normal behaviour of the geoportal.
- integration cases: 6 tests cases OK. Some very minor errors/warnings/slow system responses that do not affect the normal behaviour of the system were registered.

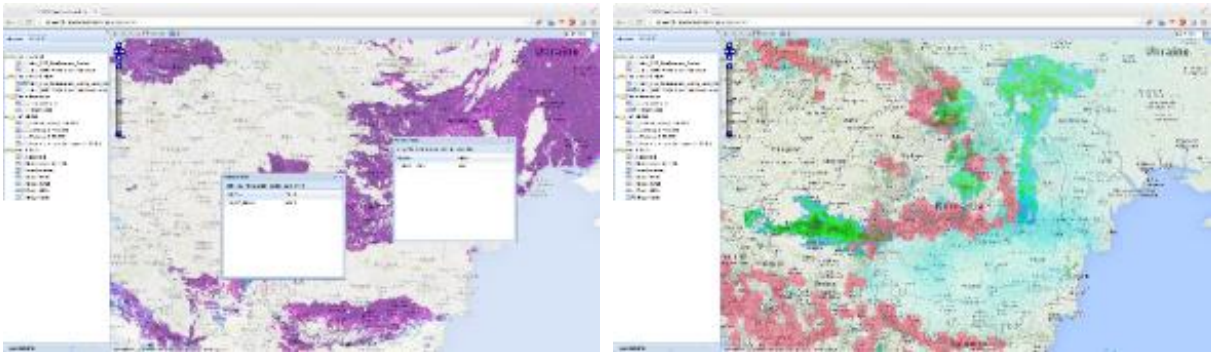
Therefore, the global status of the verification gave a percentage close to 100% of OK results. The registered errors were mostly minor errors, the global functionality of the system was the one defined and planned in the initial project documents. A number of upgrades were implemented after the initial results of the testing phase, based especially on the feedback received from the users (e.g. new functionalities and improvements of the GeoPortal WebGUI). The full description of the process is the subject of the deliverable D8.2 (Final System Qualification of Services and Acceptance).

For demonstration purposes, a technical integration of CryoLand data services with NMA existing geoportal (hosting mainly climatic and meteorological forecast data) was setup. Conceptually, the main CryoLand service has been seen as a “mother service” and the NMA as a lighter “child service”, focussed on a specific geographic area, with domain specific functionalities. The CryoLand snow products were integrated using two methods:

- Directly, by connecting to the main CryoLand EO-WMS service. This approach was used for product visualization.
- Indirectly, some products were mirrored on the NMA server. This approach was used mainly for data processing and other operations not permitted by the CryoLand service (e.g. product reprojection to Stereo70, the official Romanian coordinate system).



(a) (b)



(c) (d)

Figure 2.12: Examples for integration of CryoLand products into a user's system: (a) Integration of the CryoLand FSC product with the NMA hourly temperature map (b) Direct CryoLand SWE product integration. The product is reprojected on the fly to Spherical Mercator projection by the CryoLand Service in order to be able to overlay the data on top of popular mapping services like Google Maps and OpenStreetMap.(c) Integration of the CryoLand SWE product with the NMA radar mosaic. (d) Interactive query of the CryoLand FSC product values.

## 2.7 Snow and Land Ice products from Sentinel-1 Data

CryoLand Services were developed and implemented for using Sentinel data as main input for their services. The Sentinel satellites are a new family of missions specifically for the operational needs of the Copernicus programme. Each Sentinel mission is based on a constellation of two satellites to fulfil revisit and coverage requirements, providing robust datasets for Copernicus Services. These missions carry a range of technologies, such as radar and multi-spectral imaging instruments for land, ocean and atmospheric monitoring. CryoLand Services were designed to make finally use of data from Sentinel satellites.

CryoLand Services were designed to make finally use of data from Sentinel satellites.

| | | |
|---|---|---|
|  | Sentinel-1<br>Launched: 3.April 2014 | Sentinel-1 is a two satellite constellation with the prime objectives of Land and Ocean monitoring. The mission provides C-Band SAR data continuing ERS-2 SAR and Envisat ASAR. |
|  | Sentinel-2<br>Launch:Q3 2015 | Sentinel-2 is a high resolution optical land monitoring mission, and will be composed of two polar-orbiting satellites. |
|  | Sentinel-3<br>Launch: Q1 2016 | Sentinel-3 is composed of three satellites, operating multiple sensors. Relevant for CryoLand services are the medium resolution optical sensors SLSTR (Sea and Land Surface Temperature Radiometer) and OLCI (Ocean and Land Colour Instrument). |

Within the timeframe of CryoLand project the first satellite of the Sentinel satellite series, Sentinel- 1A, has been launched in April 2014. Commissioning Phase was successful and ended in early October 2014. Thereafter the Sentinel-1 Scientific Data Hub, a rolling archive hosting the data of the last 2 months, became operational. Within CryoLand it was possible to take advantage of the first Sentinel-1 data that were made available through the Science Data Hub in October and November 2014. As Sentinel-1 is an active radar sensor, only products that are based on SAR data could be produced. For the products depending on Sentinel-2 and Sentinel-3 preparatory work was done using existing sensors with similar characteristics.

The Sentinel-1 based services for snow and glacier products were implemented and tested. The main snow product was the extent of wet snow from multi-temporal SAR data. The glacier products cover glacier velocity products as well as glacier lake outline maps of Europe, Himalayas and Antarctica.

The Sentinel-1 Scientific Data Hub was the only access for Cryoland Partners to get Sentinel data (ESA, 2012, 2013a, 2013b). The Sentinel-1 Scientific Data Hub Rolling Archive maintained at least the latest 2 months of products for download via HTTP. No data tasking or ordering is possible through the data hub. The Scientific Data Hub has a web interface that allows browsing the archive and an Open Data Protocol (OData) interface for machine-to-machine data catalogue access. OData was used for the creation and consumption of REST (representational state transfer) application programming interfaces (API), which allowed resources, identified using uniform resource locators (URL) and defined in a data model, to be published and edited by Web clients using simple Hypertext Transfer Protocol (HTTP) messages. At this stage the ground segment is in ramp up phase, that means only limited data is made available.

The status Sentinel-1 SAR data acquisitions for the period 3 October 2014 to 31 January 2015 is shown in Figure 2.13.

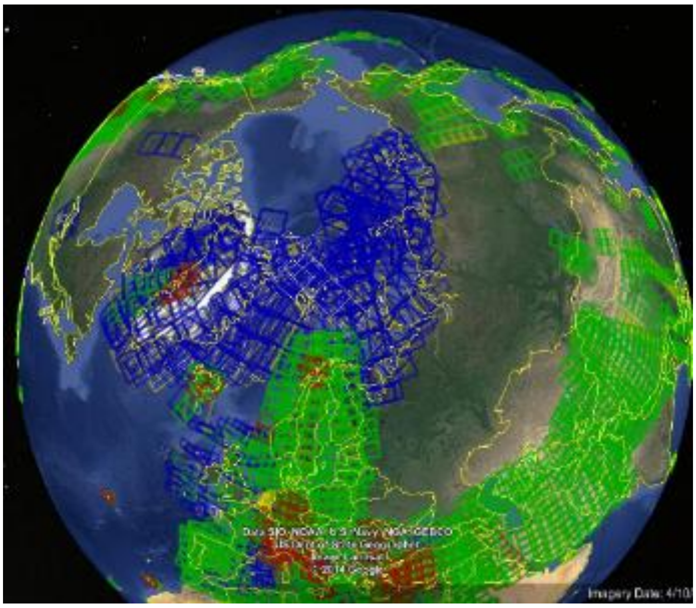


Figure 2.13: Google Earth visualisation of Sentinel-1 data frames acquired in the period since 3 October 2014 to 31 January 2015. Red frames indicate Single Look Complex (SLC) data, blue indicates ground range detected images (GRD) in extended wide-swath mode (EW) and green ground range detected images in interferometric mode (IW).

**Wet snow maps** (SCAW product) are generated from time series of SAR following an algorithm from Nagler and Rott (2000). The method applied hinges on using a reference SAR image acquired under dry conditions (either snow free or snow covered). The method segments wet snow by applying a threshold (typically -3 dB) on the ratio between the current SAR image and the reference data. Within CryoLand processing lines for wet snow products were implemented at Norut within the GSAR software environment and within ENVEO's wet snow processor.

Several pairs of 12 day repeat pass Sentinel-1 images over different locations in Europe were processed and analysed by Norut. In order to simplify processing at this stage it was decided to geocode all images to 50 m resolution. The EU DEM was used for precision geocoding. At present time with limited data it was decided to use several sources of data for inter-comparison with the wet snow map, and also to evaluate the reference dataset. The sources used were modelled snow conditions for Norway (from http://www.senorge.no), meteorological data (temperature, precipitation, snow depth), MODIS based snow cover maps and wet snow map from other high resolution SAR satellite data. In Figure 2.14 the inter-comparison of wet snow maps in Svalbard, Norway, derived from Radarsat-2 and Sentinel-1 scenes, each acquired on 3rd October 2014, is shown. The mean temperature (http://yr.no) was +4ºC on 3rd October and –10ºC on 14th December. This is consistent with melting snow conditions on 3rd October in the areas that were snow covered. Due to late snow this winter, the main part of the wet snow can be found at glaciers. The increased wet snow cover extent from Sentinel-1 compared to the wet snow extent from Radarsat-2 is probably due to the different acquisition times of Radarsat-2 and Sentinel-1 scenes; the Radarsat-2 image was acquired in early morning, at 06:14 UTC, the Sentinel-1 scene only in the afternoon, at about 15:20 UTC.

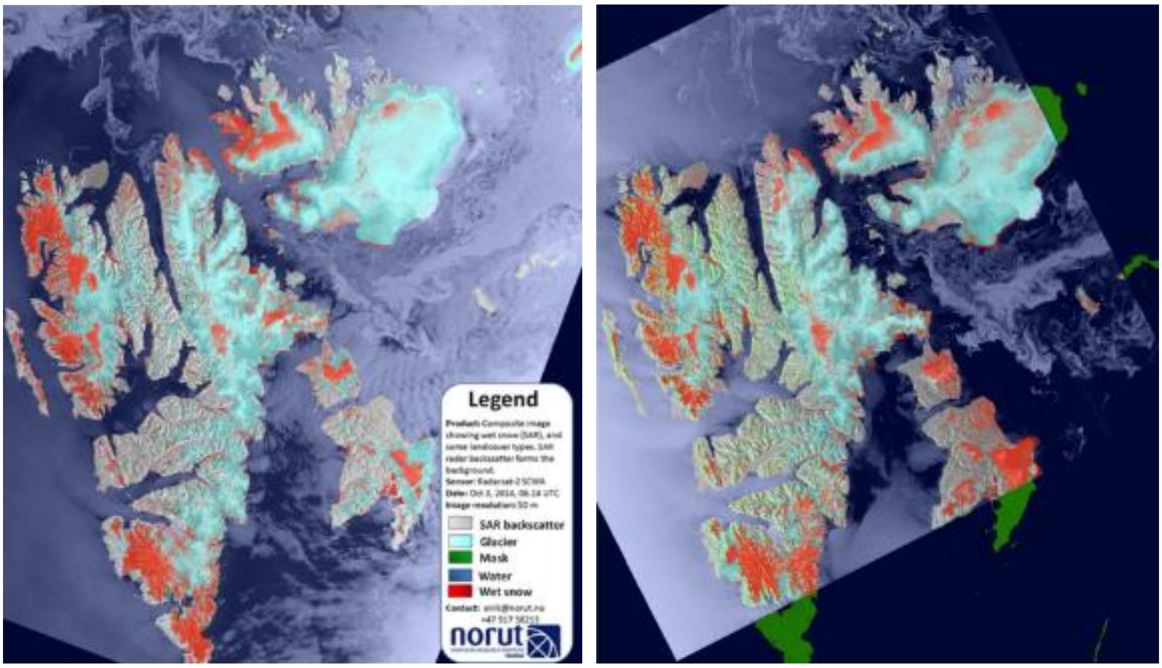



Figure 2.14: Wet snow map for Svalbard, from Radarsat-2 (left) and Sentinel-1 SAR (right) data, acquired on 3 October 2014 at 06:14 and 15:20 UTC, respectively. (Red – wet snow; background - Sentinel-1 SAR amplitude image).

The principal method to measure **ice flow velocity** of fast moving glaciers and over longer time intervals is offset tracking (OT). This method determines the surface velocity field by detecting and tracking identifiable features that move with the ice (e.g. crevasses) and that remain stable in sequential pairs of co-registered images. OT represents a method that delivers two components of the velocity vector (in slant range and along track direction) and is less sensitive or insensitive to temporal decorrelation of the radar signal than InSAR, although at lower accuracy. Two OT processors were available within CryoLand, the GAMMA OT processor and the ENVEO OT processor. The GAMMA glacier velocity processor is based on SAR offset-tracking procedures (Strozzi et al., 2002) and the methodology developed within ESA Glaciers_cci (Paul et al., 2013). Preliminary examples and validation of ice surface velocity maps on glaciers from Sentinel-1 data were generated by GAMMA and ENVEO for Arctic and Antarctic Glaciers. Results were validated against existing velocity information and the quality of the co-registration by matching stable ground. Existing information included the Greenland Ice Sheet Velocity Map from InSAR Data by Joughin et al. (2010) and the Ice Velocity Map from Rignot et al. (2011). Figure 2.15 shows the ice surface velocities derived from

Sentinel-1 data of 10 and 22 September 2014 along central west coast of Greenland and in particular the Upernavik area.

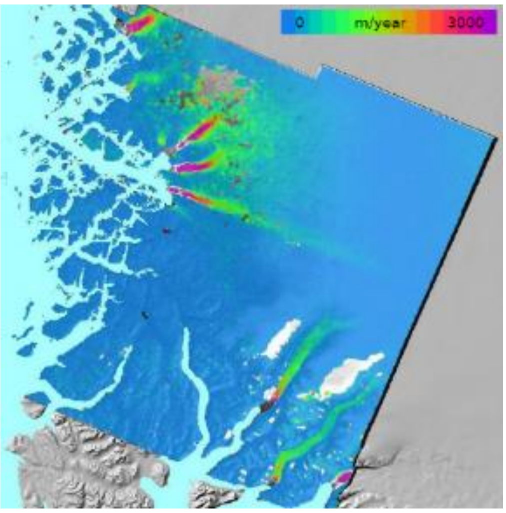



Figure 2.15: Example for ice velocity map from Sentinel-1 SAR data, covering outlet glaciers (main glacier Upernavik) of West Greenland.

**Glacier lake extent products:** Among glacier hazards, glacier lake outburst floods (GLOF) are especially devastating and represent the glacial threat with the farthest potential reach, up to hundred kilometres and more downstream of the glacier lake that burst out. Typically, glacier lake outbursts are a part of complex chain reactions and process interactions, for instance when sudden slope failures above a lake cause impact waves that trigger destabilization of a lake dam that would otherwise remained stable. The CryoLand glacier lake mapping service provided outlines of the glacier lake under observation for selected dates. The service has been run upon user request and the products were directly delivered to the user. The methodology is based on the very low backscatter coefficient of smooth water surfaces compared with other land types. Two glacier lake mapping processors were available within CryoLand, the GAMMA processor (Strozzi et al., 2012) and the ENVEO processor. The quality of the products was assessed by comparison with the DEM and if applicable earlier products or other auxiliary data. Within the CryoLand project Sentinel-1 glacier lake maps were produced for lakes in Greenland and the Himalayas. Figure 2.16 shows the Lumding Tsho glacier lake and the Lake Tininnilik in West Greenland. The different outlines show the lake extent at different dates derived from Sentinel-1 and TerraSAR-X revealing the lake increase due to the glacier retreat.

Figure 2.16: (Left) Time series of lake outlines of Lumding Tsho glacier lake, green - TerraSAR-X April 2009, magenta – TerraSAR-X October 2009, green – TerraSAR-X May 2010, red - Sentinel-1, 19 October 2014. (Right) Outlines of lake Tininnilik in West Greenland, mapped from Sentinel-1A IWS scene of 19 October 2014 (yellow). Red outlines indicate the lake extent mapped from the Landsat 8 scene of 27 August 2014. The amplitude image of the Sentinel-1 scene is used as background.

Operational **Fractional Snow Cover** monitoring is currently usually based on single sensor approaches. The synergistic usage of the spectroradiometer 'Ocean and Land Colour Instrument' (OLCI) and the 'Sea and Land Surface Temperature Radiometer' (SLSTR) on board of the future Sentinel-3 will provide a new data base enabling an improved snow monitoring and snow and cloud discrimination system. Processing lines for mapping fractional snow cover and improving the cloud screening based on these new sensors have been developed and tested by ENVEO using synergistically archived Envisat MERIS and AATSR data, which have very similar spectral and geometric characteristics as the instruments on-board of Sentinel-3. The resulting snow maps have a significantly improved spatial resolution, and the synergistic usage of the two sensors enables an improved snow and cloud discrimination, which is a critical issue for an operational snow monitoring service.

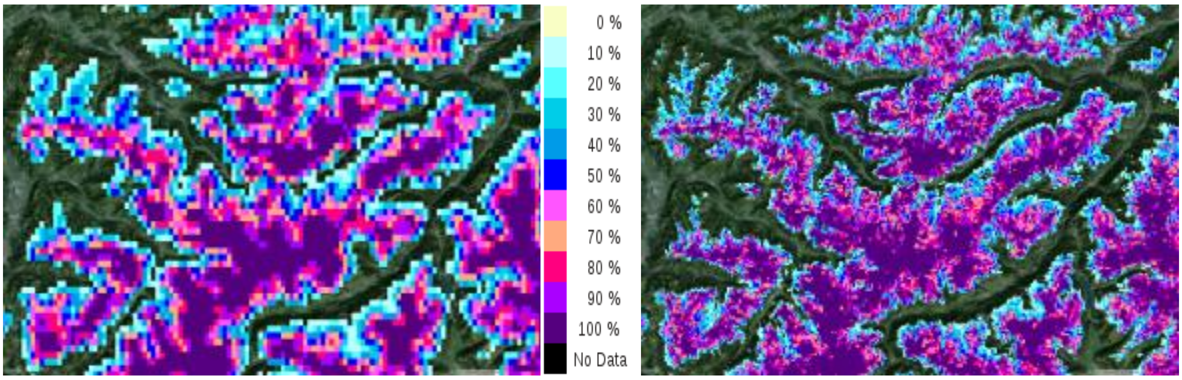



Figure 2.17: Fractional snow extent maps of the Alps, derived from ENVISAT AATSR only (left) and from synergistically use of ENVISAT MERIS and AATSR data (right), with similar characteristics as Sentinel-3 SLSTR and OLCI.

## 2.8 Integration of CryoLand Services into hydrological runoff models

One of the main user applications of satellite based snow information was in hydrological models for stream flow predictions and hydropower reservoir management. In general, snow (and ice) data can be integrated in hydrological models either through calibration and evaluation procedures for model development, or for model state initialization in forecast simulations using so-called data assimilation. In both cases, the raster based satellite information need to be transformed into the spatial representation used in the hydrological model, which usually is sub-basins representing the catchment area of a specific point in the watershed. The satellite snow information can further be used to calculate sub-basin averages or distributions as function of for instance elevation, aspect, and vegetation type, which is then compared to the equivalent model variables.

The integration of CryoLand Product and Services in hydrological modelling was assessed using the hydrological model HYPE developed and operated at the project partner SMHI for basins and sub-basins in Sweden. A template production chain was developed, including automatic scripted download from the CryoLand Geoportal, pre-processing of the satellite products into time series of hydrological sub-basin averages, assimilation of satellite snow data in the hydrological model, and publishing of the model output on WMS interfaces following the CryoLand data model (Figure 2.18). The suggested processing chain has been developed with the CryoLand products and services and the SMHI hydrological models in mind, but could easily be adapted to other combinations of products from satellite data and hydrological model systems.

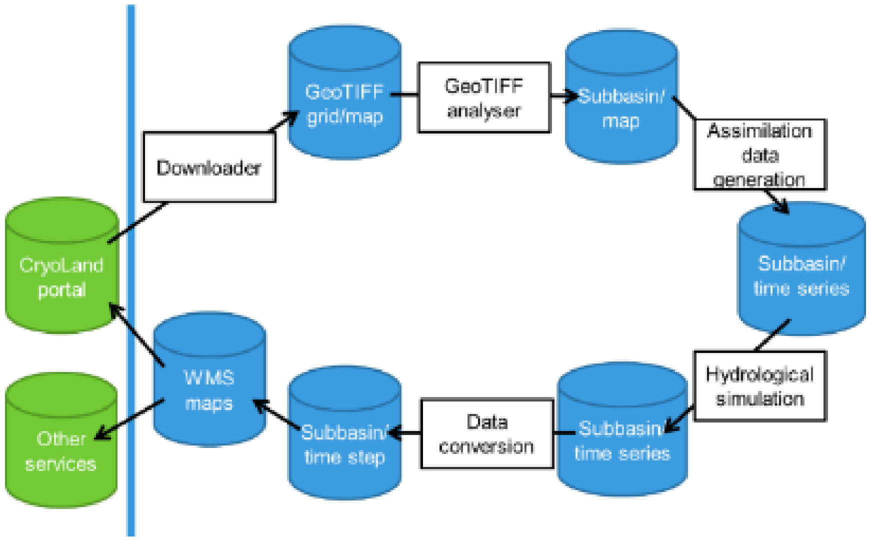



Figure 2.18: An overview of the processing chain required for transforming and integration of CryoLand products from satellite data in hydrological model simulations.

The Swedish application of the HYPE model (Strömqvist et al., 2012) is used operationally by SMHI for simulation of the water quality and together with the HBV model (Hydrologiska Byråns Vattenbalansavdelning; Bergström, 1995) for the operational flood forecasting. The current version (S-HYPE 2012) has 36693 sub-basins with a median size of 18 km², and covers the Swedish mainland, all major islands along the coast and contributing areas in Finland and Norway. A routine for data assimilation has been implemented based on the Ensemble Kalman filter method (Evensen, 1994).

Simulation and data assimilation experiments were conducted with the objective to compare the CryoLand SWE and FSC products with the S-HYPE model, and to assess impact of assimilation of the satellite products on the snowmelt runoff simulations, respectively. The Pan-European FSC and SWE products, as well as the Scandinavian multi-temporal and multi-sensor FSC product were included in the study, using data from the second Pilot Service 2011-2013. The results showed firstly a good agreement between the S-HYPE model and the Pan-European SWE products in the major inland part of Sweden, except for the mountainous region in the north-western border to Norway and along the east-coast (Figure 2.19).

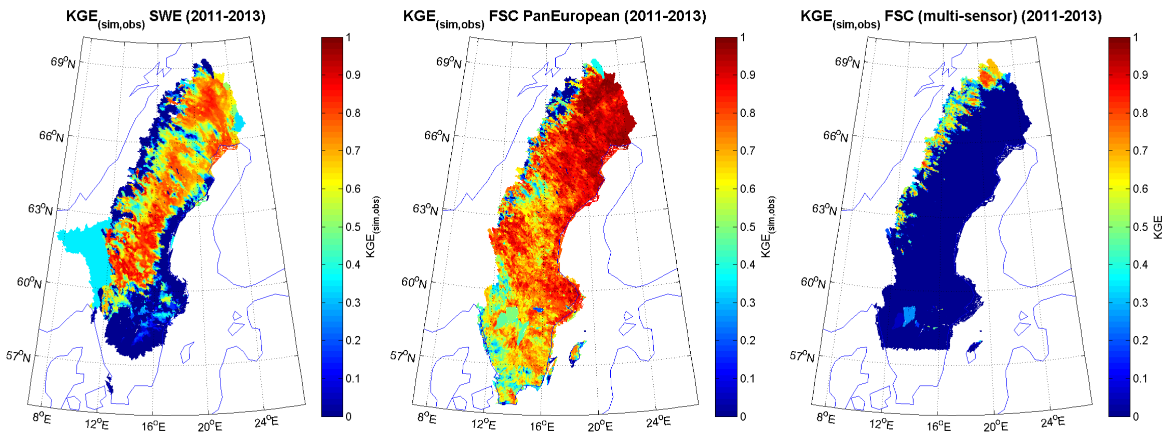



Figure 2.19: Comparison of S-HYPE model simulations versus the CryoLand Pan-European SWE (left), FSC (middle) and Scandinavian Multi-sensor multi-temporal FSC products using the Kling-Gupta model efficiency index KGE (Gupta et al., 2009) over Sweden for the years 2011-2013.

The discrepancies can most likely be attributed to issues in the microwave based satellite product related to spatial variability of snow in the mountains and influence of the sea along the coast. The Pan-European FSC product and the model simulations compared well with the model simulations in most of Sweden, except for the most northern alpine parts. The multi-sensor/multi-temporal FSC product on the other hand was in good agreement with the model in the mountain areas, but underestimates largely the maximum snow cover in the forest areas, which constitutes the larger part of Sweden. The differences in the agreement between the simulated FSC and the two satellite products were logical, since the Pan-European optical FSC product takes into account the effect of vegetation, and the Scandinavian multi-sensor FSC product has been optimized to correct for shading and clouds in the Scandinavian mountain areas.

The impact on the simulation of stream flows by assimilation of the CryoLand snow products was studied in smaller river basins representing non-regulated rivers in different parts of Sweden. The Pan-European products SWE and FSC improved and reduced the performance of the stream flow simulations in about 1/3 of the experiments, respectively. The largest improvement was achieved in a sub-basin to the Tornionjoki river basin above the tree-line in northern Sweden. The largest reduction in the stream flow simulation performance was experienced in the sub-basin in the central eastern coastal area, where the initial comparison of the CryoLand snow products from satellite data and the S-HYPE model indicated large biases. The assimilation experiments illustrated both the potential of satellite snow data for improving hydrological model simulations/forecast and some typical problems related to systematic biases and other errors in the satellite data.

# 3. POTENTIAL IMPACT AND DISSEMINATION

## 3.1 Potential Impact

The CryoLand service on accurate and timely observations of snow and land ice by means of satellites is very relevant to supporting environmental and resource management activities in Europe. Accurate information on extent and properties of the seasonal snow cover, of glaciers, and of lake and river ice is important for many socio-economic activities, as well as for climate change monitoring.

The seasonal snow cover and glaciers are important resources, supplying many parts of Europe with water for human consumption, agriculture, hydropower generation, and other economic activities. The presence of snow and ice strongly changes the radiation and energy balance at the Earth's surface, so that accurate characterization of the snow and ice cover is crucial for improved numerical weather prediction. Moreover, several natural hazards are directly related to snow and glaciers including avalanches, flooding from sudden snowmelt or from the outbreak of glacier dammed lakes, and ice-jams on rivers. Additionally, snow cover in boreal forest and sub-arctic zone has a significant effect to transport and logistics, e.g. to the timber collection from the woods. The snow load is an important safety and operation issue concerning constructions, such as buildings (roofs) and power lines.

Thus the snow and land ice services developed in the project are of high relevance to

- Water resources management (Irrigation, water quality, water supply
- Hydropower energy production, energy trading
- Natural hazards mitigation (snow and glacier related floods, avalanches)
- Transportation (roads, rivers, lakes) and construction activities
- Insurance and re-insurance industry
- Climate monitoring and modelling
- Numerical weather prediction
- Carbon accounting and biodiversity
- Living conditions of northern indigenous people
- Ecosystem management
- Agricultural management
- Tourism

## 3.2 The Relevance of CryoLand To EU Strategies and Directives

The services developed in the project are not only of interest for users at national level, but also have great potential to support EC policies related to water supply and quality, renewable energy, agriculture, traffic, natural hazards, and climate change.

*DG ENV and EEA: Water* Information System for Europe (WISE). Water supply from snow and ice is crucial for river basin management, groundwater recharge, and water quality in many parts of Europe.

*DG ENER:* European Strategic Energy Technology Plan - SET. Climate protection requests to make the most efficient use possible of the available energy sources. Hydropower is by far the dominating renewable source for electricity. Improved information on snow and glacier runoff is needed for increasing the efficiency of hydropower production.

*DG ECHO and EEA*: The Community Civil Protection Action Programme. Significant improvements for hazard forecasting can be expected from the CryoLand Service: Snow cover information is essential for forecasting avalanches and snow-melt related floods. Up-to date glacier information is important for predicting and mitigating floods in high alpine regions. Glacier dammed lakes may cause sudden floods, and the increased glacier runoff in warm summers tends to amplify floods caused by rainfall in Alpine basins. Snowmelt floods in Nordic rivers may be aggravated by ice jams.

EEA: Support of Environmental Policy in Europe. Snow cover is relevant for Water quality and water availability and has an important function in surface/atmosphere exchange processes, thus being very relevant to air pollution control.

*DG AGRI:* Rural Development Policy. Snow melt water is essential for agriculture in many parts of Europe

*DG CLIMA:* European Climate Change Programme (ECCP). Adapting to Climate Change: Snow and glaciers and lake / river ice are sensitive indicators for climate change.

*DG ENTR – European Space Policy - Copernicus*: CryoLand aimed at developing a service based on EO data, which is of high socio-economic relevance to the European citizens. This is a key objective of Copernicus.

# 4. DISSEMINATION AND EXPLOITATION

During the CryoLand project all partners have taken part in the exploitation activities. As part of this the CryoLand partners were in contact with users and potential future customers of snow and land ice products developed and provided within CryoLand. In general all the CryoLand-partners will continue work actively to increase interest, knowledge and demand for satellite derived snow information to further extending the user group, either it is among the public bodies, commercial partners or R&D partners. SMHI as one of the users which during the CryoLand project has started to use CryoLand-products as part of their normal operations to support prediction of flood warning, water management and also for hydropower customers.

The stakeholders may be graded in *key stakeholder* ("champions", key funding partners), *important stakeholders* (typically governmental support or partly funding), and *others*. The stakeholders may act as user of data or service, funding source, governmental regulator, organisation defining industry standards, or as a general supporter of the service benefitting from service.

**Identified Key stakeholders are** Large hydropower companies. **Important stakeholders include** Hydrological services, Energy traders, Meteorological services, Environmental agencies. **Others** include Avalanche warning centres, Road, Railway and River Authorities, Climate monitoring institutions, Geotechnical & Construction companies, Ecologists, Reindeer herders, Recreation (e.g. fishery, skiing), Forestry companies

Results of CryoLand-project were found appropriate to carry on in 3 different business models, as described in Figure 4.1:

- **Public Union Model:** Pan-European Snow Service within Copernicus Land Monitoring Services
- **National / Regional Model**: Regional products developed serving support of governmental mandates based on public funding (internal department budgets and resources)
- **Commercial service:** Downstream snow products and services provided on commercial basis, e.g. for hydropower companies and governmental agencies

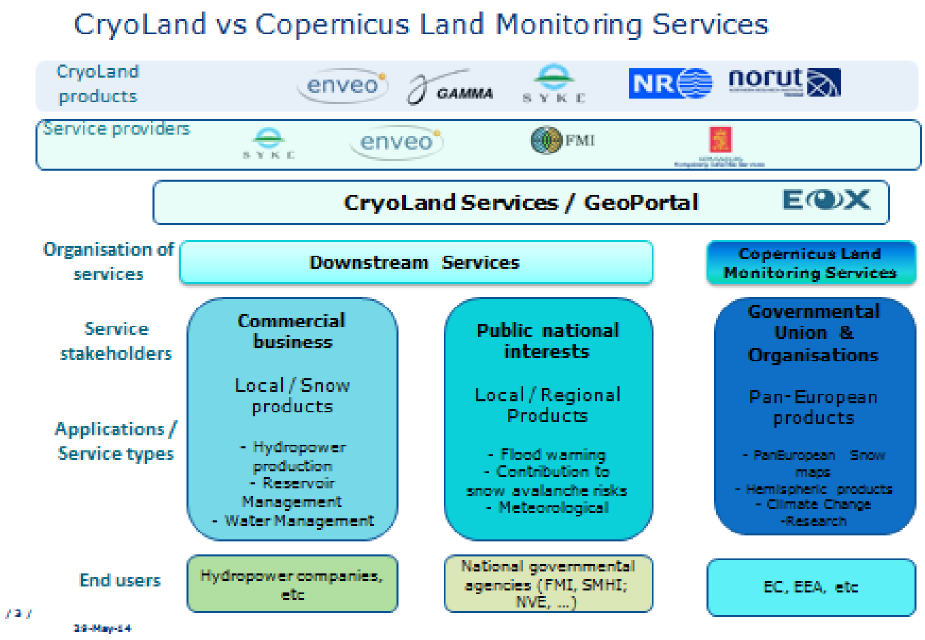



Figure 4.1: Business model classes for CryoLand Services.

Three models were applied to serve the three service stakeholder groups, where one group exists and the two others have to be established. SYKE and FMI will use the (public) national/regional model to improve services to the people of Finland. As part of the second model Snow and glaciers have to be included as services in the Copernicus Land Core services, which is an ongoing process where partners and the CryoLand project have given input to EC how these services could be established and operated. The third model suggested addresses snow monitoring products and services which are regarded as mature enough to be run operationally. User interest is significant, and hence assumed having a potential commercial basis for the operational service provider organisations willing to take risk.

During the CryoLand development and demonstration period, there has been strong interest in the products from close to 100 different user organisations, both from commercial and governmental institutions. Especially the provided snow monitoring services generated high interest among innovative hydropower companies, representing the main commercial market. Governmental authorities, which had already been involved in EO based snow monitoring, demonstrated the benefit of using these products e.g. in flood forecasting, especially at the Finnish and Swedish institutions.

The potential market has been divided into following user segments, where focus is commercial operation of snow monitoring services:

- Hydropower companies, and other actors in the hydropower market
- Energy brokers, analysis and consultancy services
- Public authorities responsible for water and energy management
- Meteorological Offices (and other organizations doing Numerical Weather Predictions)

- Geotechnical Engineering Companies

The proposed services have several documented significant advantages for the potential users. However, the user barriers have to be overcome by adaption and integration opportunities into user environment and systems to be compliant with existing run-off models used in the industry.

Main users with interests in using CryoLand products, where main focus is snow products, could be shortly summarized as follows:

- **Public national bodies** – national responsibility and funding serving national interests, especially flood warning
- **European level** – European initiatives like EFAS, also involving national public bodies in providing flood and drought warning, funded by public European instruments.
- **Industry / commercial companies** – Some companies in the start-up phase to serve hydropower users with FSC and SCAW products, trying to develop mechanisms to integrate results into existing hydrological models being used as industry standards.
- **Meteorological institutes** – continue using the CryoLand products for intercomparison and validation activities with their NWP model output, and research on options for snow product integration into meteorological and radiative models is ongoing. Glacier products from satellite data as provided by CryoLand will be a supplementary dataset for climate studies, providing information with an added value for many remote and hardly accessible regions worldwide.
- **R&D institutes** – continue to use results gained in the CryoLand project to improve algorithms, and develop new systems based on the general knowledge and infrastructure acquired during the CryoLand project. Trying to achieve the goal of improved spatial resolution of SWE-product, when new appropriate sensors will be available; this is to be used as base for improved services also within the other sectors.

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