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Table of Contents

SUMMARY

The objective of the report is to review user requirements for land and sea ice data and define the case studies to be conducted in the project. Requirements for satellite data to be used in the case studies have been identified, based on previous and ongoing user requirement studies. The case studies areas are also defined based on availability of satellite data over several years. The focus of the project will be in the western Russian Arctic, including Barents and Kara Seas, Franz Josef Land, Novaya Zemlya, Severnaya Zemlya area. The study area contains sea ice, icebergs and many glaciers and is well covered by satellite data over the last decades. Access to data from satellites, both from ESA, Russian Space Agency and other space agencies provides guidelines for what can be done in the project . The user requirements for providing more data on the cryosphere in this area are growing because of shipping, offshore operations, and the general interest in climate change data.

1 Introduction

Satellite Earth Observation (EO) data provides unique opportunities to Arctic climate process and changes. Use of EO data is beneficial in several climate-related scientific disciplines, providing methods for environmental monitoring, support to marine operations, resource management and contribution to education. In the international context, MAIRES will complement and support other GMES projects and systems developed for monitoring the Arctic climate system , such as (Arctic ROOS, http://www.arctic-roos.org), the *Global Climate Observing System* (GCOS), World Glacier Monitoring Service (WGMS)

Russia has long experience in Arctic research, including use satellite EO data. for sea ice, iceberg and land monitoring. Russian satellite and airborne remote sensing data have been used operationally for several decades by Russian research institutions.

During the ICEWATCH project (1995-1998), led by NERSC, the European (ESA) and Russian (RSA) space agencies cooperated for the first time to monitor sea ice in the Northern Sea Route by means of SAR data. The results from ICEWATCH and 16 years of cooperation have recently been published in both English and Russian translation in the book "*Remote Sensing of Sea Ice in the Northern Sea Route: Studies and Applications*" (Johannessen et al., 2007). Since 1991 NERSC has developed extensive cooperation with remote sensing scientists in Russia, in particular with scientists at the Nansen International Environmental and Remote Sensing Center (NIERSC) in St. Petersburg. In 2005, the cooperation with Russian scientists resulted in the award of the EU Descartes Prize in Earth Science for the CECA project (Climate and Environmental Change in the Arctic).

This report provides an overview of the user requirements for land ice, sea ice and iceberg monitoring data in the Russian Arctic, limited to the area shown in Fig. 1.

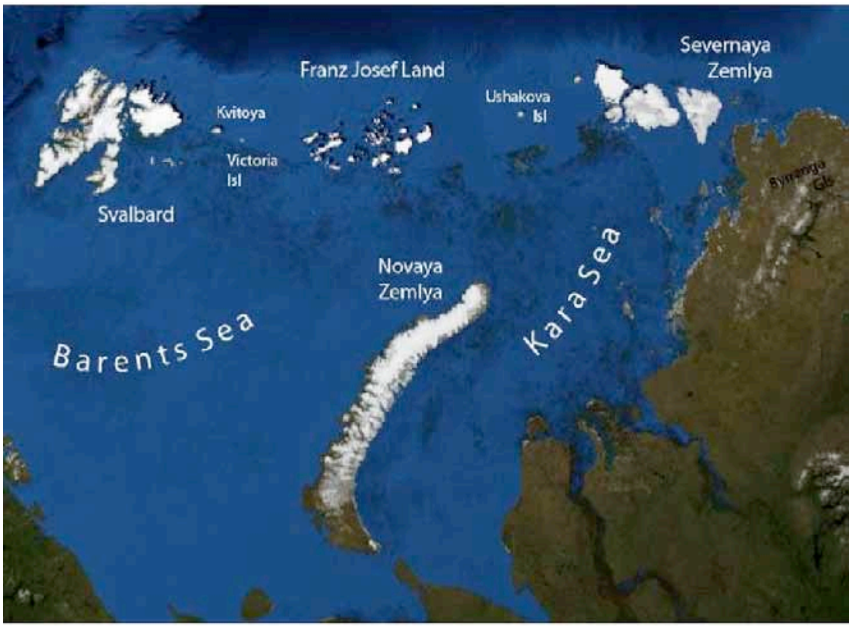

Figure 1. Map of the Barents-Kara region where the land ice areas are shown in white. The northern part of the region is ice-covered year-round, while in winter most of the Kara Sea and the north-eastern part of the Barents Sea is ice-covered.

2 User requirements for land ice data

2.1 Land ice variables

In accordance with the GCOS [1] requirements and by analogy with the "Water-Resources Investigations Report", the main tasks of glacier monitoring can be formulated as follows: to monitor spatial (geometric) and physical changes of the glacier surface, glacier motion, mass-balance and stream runoff to understand glacier impact on sea level change and Earth's water cycle, and improve the quantitative prediction of water resources, glacier-related hazards, and the consequences of global change (GCOS 2006, USGS 2000). The GCOS identified requirements for satellite-based glacier products and specified the list of glacier state variables including glacier area, topography, velocity, glacier dammed lakes, facies, snowline, accumulation and mass balance, which can be derived from satellite data. The support of *early-detection strategies* in global climate change observations is foreseen as main benefit from using such EO products.

Similar specifications were offered in the frameworks of "Operational Monitoring of European Glacial Areas" OMEGA FP5 EESD project (2001-2004) and further detailed in the INTEGRAL FP6 GMES project focused on glacier observations from European satellites (Sharov & Jackson 2007). Following the compromising idea on the meaningful performance under reasonable costs and time expenses we compiled the preliminary list of glacier state variables under investigation in the MAIRES project and determined the principal requirements to the glacier monitoring EO system directly achievable with spaceborne sensors, both optical and radar (Table 1).

Table 1. Preliminary list of glacier state variables and technical requirements (Sharov 2010)

Glacier state variables, units	**Temporal cycle**	**Resolution, m**		**Observing cycle, years**	**Expected accuracy**
		horizontal	**vertical**		
Area, km²	annual	50	-	5	5 %
Area change, km²/a	annual	25	-	5	1 – 2.5 %
Topography (extent & elevation), m	annual	50	1	2	50 m (horizont) 2 m (vertical)
Change in termini pos, m or m/a	annual	25	-	2	10 m/a
Elevation change, m or m/a	annual	50	1	1 - 5	0.25 m/a
Velocity, m/a or cm/day	seasonal	250	-	0.5	10 m/a, 2 cm/d
Calving velocity, cm/day or m/a	diurnal	250	-	0.5	2 cm/day
Velocity change or strain rate, m/a²	diurnal	500	-	1	1% (1 m/a²)
Accumulation, m	seas – ann	500	0.25	1	5 – 10 %
(Specific) Mass balance, m or kg/(m²·a)	seas - ann	500	0.25	0.5 – 1	0.20 m or 100 kg/(m²·a)
Macro-regional glacier inventory *	decadal	100	5	5	5% (omission & commission)
Supra-glacial and dammed lakes *	seas – ann	50	-	5	2.5 %
Glacier surface state, classes / facies *	diurnal	500	-	0.25 - 0.5	5 %

*) optional products

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[1] GCOS - Global Climate Observation System.

The glacier variables and technical requirements for their determination specified in Table 1 were determined in accordance with our collective expertise and precursor product experience. Asterisk (*) denotes optional products. Most values in Table 1 meet GCOS requirements[2], reflect modern capabilities of satellite EO systems and offer / promise substantial benefits. The proposed list of glacier variables and EO capabilities will be critically reviewed, enhanced and completed in a direct consultation with the relevant climate research community to provide a detailed and realistic specification of user requirements.

Recently, overall scientific needs for spaceborne glacier products as well as observational requirements and technical capabilities of European satellite missions were discussed at the ESA SEN4SCI Workshop in Frascati, Italy (March 2011). The SEN4SCI compilation of glaciological variables including state parameters for mountain glaciers and ice caps, sea ice and icebergs can be accessed at http://wiki.services.eoportal.org/tiki-download_forum_attachment.php?attId=95. Corresponding observational requirements for glaciers and ice caps are given in Table 2 (Rott & Nagler 2011).

Table 2. Observational Requirements for mountain glaciers and ice caps (after SEN4SCI).

Variable	**Spatial resolution**	**Temporal repeat**	**Accuracy**	**Sensor type**	**Maturity of techn.**
Glacier area	50 m (T), 25 m (G)	5 yr (T), 1 yr (G)	3% (T), 1% (G)	HROI	H
Surface topography	100 m (T), 30 m (G)	5 yr (T), 1 yr (G)	5m(T), .5m(G)	INSAR, HRSOI	H
Facies, snowline	100 m (T), 50 m (G)	1 mo (T), 10 d (G)	200m(T),50m(G)	SAR, HROI	H
Glacier dammed lakes	50 m (T), 15 m (G)	1 mo (T), 5 d (G)	50m(T), 15m(G)	SAR, HROI	H
Ice velocity	100 m (T), 50 m (G)	1 yr (T), 6 mo (G)	5%(T), 1%(G)	INSAR	H
Surface accumulation	500 m(T), 100 m(G)	1 yr (T), 1 mo (G)	10%(T), 5%(G)	SAR (Ku+X-band)	M
Ice thickness	200 m(T), 100 m(G)	10 yr	20 m	RES in situ, air-	NA

High similarity of the requirements specified in Tables 1 and 2 illustrates their reliability, usability and commodity.

2.2 Requirements for measurement accuracy

In general, the set of glacier variables under observation and technical requirements to their determination depends on the working scale of monitoring and can be defined by analogy with the information requirements for both topographic charts and thematic maps of glacial areas at a particular scale (Sharov 1997). In the MAIRES project, all data requirements are based on the leading principle of meaningful performance with regard to costs and time planning, and may vary depending on the study region, the exact user requirements and the resources available to the Consortium. A trade-off analysis will be carried-out to effect a compromise and to achieve a

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[2] Guideline for the Generation of Satellite-based Datasets and Products meeting GCOS Requirements

community consensus. For instance, there exist principal opportunity of using satellite radar and lidar data for monitoring the glacier surface state and supra-glacial and dammed lakes, which is included in the table for the sake of discussion, but won't be treated in detail in the project work, however, due to limited resources. There are no direct spaceborne determinations for the snowline position proposed either.

For the practical work in the MAIRES frames some specific technical parameters of glacier mapping including, but not limited to, the reference datum (horizontal and vertical), spatial resolution (grid size), horizontal spatial accuracy, vertical spatial accuracy and tachometric accuracy were determined in accordance with the Geospatial Positioning Accuracy Standards associated with terrestrial and hydrographic surveys that support glacier mapping.

The WGS 84 ellipsoid is chosen as the horizontal reference datum. Its relationship to national datum's and dimensions of the ellipsoids used will be accounted for. Differences among regional and national use of datum's will be treated under request. In the project work it is foreseen that vertical co-ordinate values will be referenced to the applicable chart datum and not to one of the geodetic vertical datum's. The Universe Transverse Mercator (UTM) projection will be accepted for producing glacier maps and value-added products.

Horizontal spatial accuracy is the two-dimensional circular error of data sets horizontal co-ordinates at the 95% confidence level. When geodetic satellite positioning methods are used to establish primary and secondary control points for glacier monitoring, the error don't exceed 1 or 5 cm at 95% confidence level respectively. In the MAIRES frameworks, a horizontal accuracy of 50 m while defining boundaries of large ice masses is believed to be reasonable for medium- and small-scale mapping of study glaciers. Otherwise, a 50 m horizontal accuracy in surveying glacier interiors with insignificant surface gradients could ensure the vertical accuracy within 1 - 2 m and is thus expedient. The SAR-altimetry co-registration accuracy is given as ± 1.2 pixel rms. In our practical work we shall account for the graphic accuracy requirement, i.e. horizontal errors should not exceed ± 0.25 mm[3] at map publishing scale.

Vertical spatial accuracy is defined by the one-dimensional linear error of depths at the 95% confidence level. Precise repeated surveys of evolving glacier surface and mass balance measurements require the vertical accuracy of 20–30 cm over a one-year interval. DGPS surveys of glacier elevation changes might provide accuracy of the order of one centimeter or better over one-week repeat time. Stake measurements, snow pit observations and manual probing of the snow pack should be performed with vertical accuracies of the order of 2–5 cm. The interpretation of ground penetrating radar profiles for the detection of the last summer surface foresees the accuracy of 10 cm, whereas an accuracy of 1 m is believed to be sufficient for recognizing deeper reflective layers (internal structure of firn, mapping of glacier facies). The accuracy of direct vertical measurements and contouring in glacial areas via satellite image data is usually much lower (10-20 meters at best). This is why the use of spaceborne altimetry data with the vertical accuracy of several *decimeters* is foreseen for enhanced geocoding, calibrating and mosaicking of glacier elevation and change models. In the practice, we will apply an approximate rule of thumb stating that the required vertical

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[3] Graphical precision of the printed map

accuracy should not be worse than 1/3 of the contour interval, while the vertical change error should not exceed 1/4 of the elevation change gradation.

Velocity accuracy. Sub-meter accuracy is required when measuring the position of ablation stakes to enable the definition of ice surface velocities from repeated annual surveys. Repeat-pass SAR interferometry enables the precise determination of daily glacier velocities in the areas where no direct measurements are possible. Relative velocity accuracy on the order of 6 mm/day or 2.3 m/year was reported to be achievable over extensive glacier sheets using ERS-1/2-SAR interferograms (Joughin et al. 1996). Still, this value looks to be somewhat optimistic and we define the tachometric accuracy of interferometric determinations over homogeneous glacier surface as 5 - 10 m/yr or 1 - 2 cm/day. When possible, the INSAR glacier velocities will be compared with correlometric results and direct glaciological measurements.

Spatial resolution*.* A 50 m grid size is believed to be small enough to support raster modelling of glacier surface topography and to study changes in the glacier extent, area and elevations. For particular areas and certain tasks, e.g. for observational mass balance and ice flow raster models, a larger grid size of 250 to 500 m is more than sufficient, whereas reference elevation models of poor mapped and extensive glaciers could be ideally used with a grid size of 100 m. According to photogrammetric standards the DEM posting should not be “denser” than 10 times of the standard vertical error.

2.3 Focus of the studies in MAIRES

The MAIRES project will be focused on studying typical arctic glaciers, both maritime and continental, where solid cartographic knowledge (standard topographic map series) and relatively comprehensive glaciological information are available for the generating and interpreting glacier change models, and comparing the output products with the results obtained from earlier studies by different techniques. Special emphasis is put on the involvement of the of long-term observational data collected at Austrian, Norwegian, Russian, Scandinavian and Swiss glacioclimatic and hydrological stations and observatories, such as Austfonna, Nagoorskoe, Krenkel, Feodorova, Golomyany, et al. and the use of these observations as “*anchor stations for calibration and validation of process models and satellite-derived glacier products*”.

In 3 years, MAIRES project will provide a complete contribution to detailed global glacier inventories (WGMS, NSIDC, IceGIS) regarding the dimensions of Arctic ice caps, tidewater and mountain glaciers and their changes, thus filling in approx. 20 % of available gaps. A standardized home-database of glacier measurements representing project outcomes and relevant datasets from parent projects on-line will be established, managed and linked to the WGMS. The project results will thus provide a solid basement for the design of an *active* approach to satellite-based world-wide glacier monitoring.

The proper selection of study glaciers will support the technical feasibility of satellite observations and enable the performance of inter-disciplinary geophysical research. Such strategy will ensure the comparability of ice products and will stimulate further methodological developments and studies of mutual variations in land- and sea ice thus leading to thorough understanding of climate change processes, broad and intensive use / exchange of EO data, and closer scientific interrelations within other research groups / projects.

The MAIRES study glaciers were selected so as

- to ensure the entire coverage of the study glaciers with ESA archival and new missions' data and the technical feasibility of space-borne interferometric, altimetric and gradiometric observations,
- to perform overall mapping of glacier state and changes at regional scales, without gaps wherever possible, and to fill the largest gaps in available world glacier inventories and international databases,
- to include glaciers of different size, elevation range, morphological type and dynamics, with different sensitivity to climate change and different history of surveys,
- to cover different climatic zones with different rates of environmental changes and socio-economic activities,
- to determine the glacier change signal along the extensive (circum-Arctic) latitudinal transect characterized with the largest gradient of solid precipitation and glaciation index,
- to accord the available expertise and to ensure the availability of external validation data and the homogeneous distribution of validation activities,
- to re-use existing databases, cartographic materials, documentation and infrastructure resulted from glacier-related EO projects, subject to suitable error terms, including the network capabilities of European glaciological stations,
- to cover main Cal/Val glacial areas related with the launch and operation of CryoSat-2 mission,
- to complement and not duplicate the efforts undertaken by ongoing activities,
- to stimulate further studies of mutual variations in land- and sea ice,
- to stay within the constraints of time schedule and cost.

MAIRES study glaciers are distributed among 3 distinct groups / regions:

1) large maritime ice caps and domes of insular Eurasian Arctic with mostly homogeneous topography, sporadic flow and strong change signal (*main macro-region*),

2) small- and medium-size tidewater glaciers (outlets) with fast flow and strong-to-medium change signal (*transitional region*),

3) well-studied mountain / valley glaciers and ice caps of the Eurasian (continental) Arctic and Scandinavia with strong change signal and the most comprehensive rows of observational data (*main validation region*).

The study region extends for approx. 2.200 km from Kvitöya, Victoria and Arthur islands in the west across Rudolph, Eva-Liv, Ushakova, Schmidt and Komsomolets islands in the north to Bennett and Henrietta islands in the east thus comprising the most distant and least studied ice caps in the Russian Arctic. The situation of insular ice masses close to the edge of summer minimum sea ice proved helpful in analysing spatial asymmetry of glacier accumulation signal. In total, three dozens glaciers and ice caps, some large and some smaller, were selected for detailed remote sensing studies in the MAIRES frameworks (Table 3). Several mountain and plateau glaciers from other parts of the Eurasian Arctic are represented in the list as a "reserve" and an optional development for further CryoSat-2 and GOCE-related studies. Glaciers with homogeneous topography are preferred. Approximately 20% of study glaciers are considered as "difficult" for satellite observations due to their small size, complex topography and/or irregular dynamics. Nearly each large glacier contains "difficult" parts. All study glaciers belong to the Northern Hemisphere in accordance with the natural distribution of “glaciers & ice caps” on the globe. Six glaciers specified in the list are included in the “Fluctuations of Glaciers”, v. IX and five – in its change part. Factual knowledge about land ice volumes and mass fluxes on most study glaciers is missing, although some data is available for separate ice caps in the Eurasian Arctic (e.g. Dowdeswell et al. 2004).

Table 3. List of MAIRES study glaciers

N	**Meso-Region**	**Name of Central Glacier**	Glacier Area, km^2	**Priority**	**Responsibility**
10	*Scandinavia*	*W. & E. Svartisen Ice Caps*	*221 + 148*	*high*	*JR*
11	*Ural*	*IGAN, Obruchev, MGU glaciers et al.*	*1 +*	*low*	*JR, IGRAS*
12	*Byrranga Mts*	*Toll Glacier et al.*	*29*	*medium*	*JR, MIIGAiK*
13	S Spitsbergen	Hornbreen-Hambergbreen et al.	179 + 144	medium	JR, IGRAS
14	S Spitsbergen	*Hansbreen* and Torelbreen	60 +	low	JR, IGRAS
15	W Spitsbergen	Kronebreen, Kongsvegen et al.	700 + 102	low, opt	MIIGAiK, JR
16	E Svalbard	Edgeøyjøkulen et al.	1365 +	medium	JR NERSC
17	E Svalbard	Barentsjøkulen et al.	571 +	medium	JR NERSC
18	***NE Svalbard***	***Austfonna & Storoyjokulen***	***8.100 +***	***high***	***JR, NERSC***
19	NE Svalbard	Vestfonna & Ahlmannfonna	2.500 +	low, opt	NERSC ?
20	***NE Svalbard***	***Kvitoyjokulen***	***690***	***high***	***JR NERSC***
21	**Victoria Island**	**Victoria Ice Cap**	**10**	**high**	**JR**
22	*W Franz Josef Land*	*Southern, Moon, Brousilov, Arthur etal.*	*2.150 +*	*medium*	*JR, IGRAS*
23	*C Franz Josef Land*	*Moscow IC, Sedov Glacier, et al.*	*980 +*	*high*	*JR*
24	***E Franz Josef Land***	***Tyndall, Windy ice caps et al.***	***1.890 + 727+***	***high***	***JR, MIIGAiK***
25	**N Franz Josef Land**	Rudolph-Middendorf, Eva-Liv, Hohenlo	**291 + 268 + 26**	**high**	**JR, IGRAS**
26	***N Novaya Zemlya***	***Northern Ice Cap***	***2.260***	***high***	***JR, MIIGAiK***
27	**Novaya Zemlya**	**Main Glacier Complex**	**approx. 20.000**	**medium**	**JR, MIIGAiK**
28	S Novaya Zemlya	Selected southern glaciers	600	low, opt	MIIGAiK, JR
29	***Ushakova Island***	***Ushakova Ice Cap***	***325***	***high***	***JR***
30	**NW Severnaya Zemlya**	**Schmidt Ice Cap**	**438**	**high**	**JR IGRAS**
31	***N Severnaya Zemlya***	***Academy of Sciences Ice Cap et al.***	***5.865 + 290***	***high***	***JR IGRAS***
32	***Severnaya Zemlya***	***Karpinsky, Vavilov, University et al.***	***2.561 + 1.805 +***	***high***	***JR NIERSC***
33	***Severnaya Zemlya***	***Matusevich Ice Shelf***	***252***	***high***	***JR IGRAS***
34	**S Severnaya Zemlya**	**Leningradsky Ice Cap et al.**	**1.704 +**	**high**	**JR**
35	*De Long Islands*	*Toll Ice Cap, Henrietta, Small et al.*	*82*	*high*	*JR MIIGAiK*
36	*Wrangel Island*	*Mountain glacierets*	*3.5*	*medium*	*JR MIIGAiK*

*) Validation glacial areas are marked in *italic*. The largest ice caps selected for GOCE applications are given in **bold**.

All study glaciers are entirely and repeatedly covered with ERS-1/2 interferometry, ICESat altimetry and GOCE gradiometry data. Russian state topographic and gravimetric maps, as well as reference elevation models are also available. Some data sets demonstrate low quality, e.g. low coherence value, however, and several additional datasets will be used as substitutes.

2.4 Interaction with modellers and other networks

Previously established links to experts proficient in global and regional climate / circulation models and glacier volume projections at the Max Plank Institute for Meteorology in Hamburg (Dr. D.Jakob), Geophysical Institute at the University of Alaska in Fairbanks (UAF, Dr. R.Hock,), University of British Columbia, Vancouver (UBC, Dr. V.Radic), Institute for Meteorology and Geophysics at the University of Innsbruck (IMG, Prof. M.Kuhn, Dr. E.Schlosser), Institute for Atmospheric and Climate Science, ETH Zurich (IACS, Prof. H.Blatter), and State Research Centre "Planeta" (SRCP, Profs. V.Asmus and A.Uspenskiy) in Moscow will be used for discussing, specifying and interpreting main MAIRES outcomes, both potential and real. In addition, available contacts to several European research institutes involved in studying the impacts of climate variability and change on glaciers and the consequences of these impacts for the climate system including the Alfred Wegener Institute for Polar and Marine Research in Bremerhaven (AWI, Prof. H.Miller), Central Institute of Meteorology and Geodynamics (ZAMG, Dr. W.Schöner) in Vienna, Centre for Polar Observation and Modelling, University College London (CPOM, Prof. D.Wingham), Institute of Geography, Russian Academy of Sciences in Moscow (IGRAS, Dr. A.Glazovskiy), Nansen Environmental and Remote Sensing Centre in Bergen (NERSC, Mr. S.Sandven), Norwegian Polar Institute in Tromsö (NPI, Dr. J.Kohler), Universities of Graz (IGR, Prof. G.Lieb), Innsbruck (IMG, Prof. M.Kuhn), Oslo (DGEO, Prof. A.Kääb), Toulouse (LEGOS, Dr. B.Legresy) and Utrecht (IMAU, Prof. J.Oerlemans) will be applied to expanding our links with global and regional climate modelling community. There exists a close link to the GeoForschungZentrum (GFZ) in Potsdam, sections 1.2 "Global Geomonitoring and Gravity Field" (Dr. F. Flechtner, Dr. C. Förste), 1.3 "Earth System Modelling" (Prof. M. Thomas), and 1.4 "Remote Sensing" (Prof. H. Kaufmann). A large group of climatologists and climate modelers who are involved in the ongoing international research projects SWIPA, GLACIODYN, CliC, Kinnvika and "Western Canada Cryospheric Network" will ultimately get an access to our data products and will take part in their discussion and verification.

Further consultations are planned with glacier cartographers at the Universities of Bern and Dresden (Profs. H.Zumbühl and M.Buchroithner) and with WGMS representatives at the Zurich University. Communication of MAIRES results will be to Dr. M.Zemp at WGMS. Data will also be deposited at the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado. Main project outcomes will be stored in on-line archives and made accessible to the broad scientific community, thus providing a sound supplement to existing glacioclimatic databases and atlases. The MAIRES team will actively participate in all activities organized and coordinated by ESA CCI. CCI bi-annual working meetings will be attended and used for discussing mutual variations of land- and sea ice in heterogeneous field of gravity. Key project documents will be made accessible for an open review by the CCI CMUG.

The MAIRES Consortium involves experts experienced in numerical modelling of glacioclimatic processes, who are aware about principal requirements on the content and due form of inputs to modern climate models. So we will be able to liaise with the user modelling community at "equal eye-level" and to ensure the glacioclimatic products developed are compatible with the needs of the CCI and correspond to the interests of wider climate research community. We learnt these interests during the whole previous work and know how to achieve a consensus in difficult cases.

In our practical work we will account for the spatial resolution and temporal scales of available and potentially applicable general and regional climate / circulation models such as UCMO HadCM3, CGCM3, REMO (for the Barents Sea) et al. and, on request, will tune similar parameters of some

GLACIS50 deliverables in order to match those scales. New contacts to the UK Meteorological Office, Hadley Center (MOHC) and Canadian Centre for Climate Modelling and Analysis (CCCMA) will be installed via ESA CCI-CMUG and Ice2Sea project for matching MAIRES products specifications with global & regional climate/circulation models and determining ways of using climate model outputs.

Presently, glaciers and ice caps are only treated in regional climate models, and further developments are related with improving the detailedness of numerical climate models / scenarios and providing reasonably accurate and entire spatial representations of glacier state and change at regional scales (Radic & Hock 2006, Huss et al. 2008a). In this concern, MAIRES products stimulate the two-way motion towards the optimal solution and are addressed to climate modelling and climate change assessment community. Our new map series, which continuously represent glacier changes at meso- and macro-level might mitigate some scaling problems in studying interrelations between atmosphere-, ocean- and glacier state variables.

Our combined gravity-altimetry-interferometry (GAIN) products might represent an interest for further developments of the atmosphere-ocean circulation models considering the acceleration due to gravity as horizontally variable. Several maps showing spatial interrelations / correlations between local intensity of solid precipitation, sea ice concentration, glacier change and gravity anomalies will be prepared for joint discussions with other CCI groups and system experts preparing for new EO missions, such as CryoSat-2, TanDEM-X and Sentinel-1.

3 User requirements for sea ice and iceberg data

3.1 Arctic shipping and offshore operations

The Arctic regions offer vast areas of hydrocarbon resources that have just started to be exploited. The Arctic Ocean is surrounded by continental shelves, where in particular the huge Siberian shelf covering the eastern hemisphere, extending from the Barents Sea to the Chukchi Sea. There is growing political interest for the Arctic Ocean and several countries have started investigations of the continental shelves. This implies that Arctic shipping can be expected to grow in the coming decades and the need for better ice monitoring and forecasting service will increase. A map of areas where ship traffic is expected to grow is shown in Fig. 2.

The ongoing changes in Arctic climate with increasing temperatures and decreasing sea ice cover have stimulated the interest for oil and gas exploration in several Arctic areas. A reduction of the sea ice area opens up the possibility to access new areas of the Arctic Ocean where hydrocarbon resources can be exploited and transported to the markets. The Barents and Kara Seas have seasonal sea ice cover as well as icebergs that put severe constraints on design and operation of installations and on transport solutions.

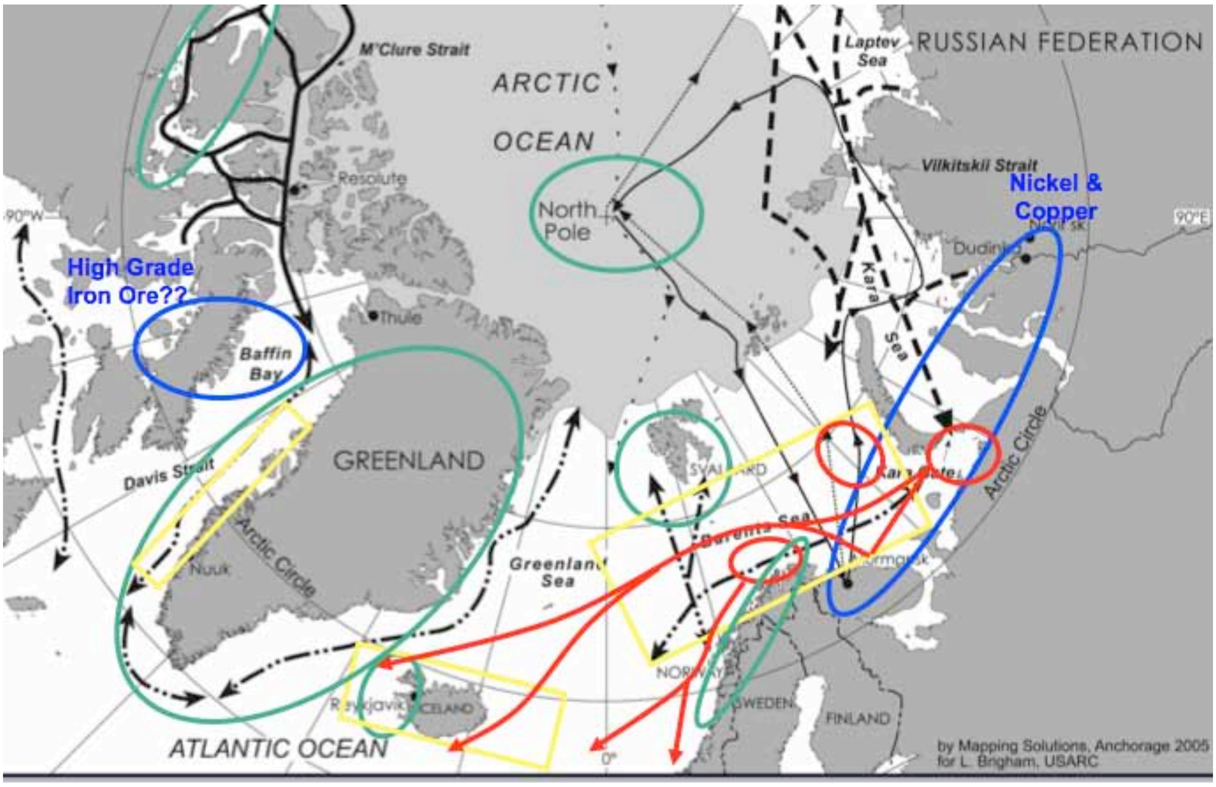


Figure 2. Araes with increasing ship traffic and offshore operations. Green circles: tourism, red circles: offshore operations, blue circles: mineral exploration (ref. L. Brigham).

Sea ice concentration, thickness, and pressure are the major direct factors influencing ice forcing on constructions and operations in ice areas. For offshore construction, the drift of ice as well as its thickness and mass are key parameters in calculation of ice loading. Maximum ice thickness is mainly determined by ridges and ice keels, formed when ice floes are pushed against the shore and can be piled on top of each other. In shallow waters, where depths are less than 20 m, ice keels can become grounded and ridges can build up to more than 10 m as a result of the drifting ice floes. In addition to the general ice conditions, it is very important to have specific data on these ice parameters in local regions where ice operations are planned. Oil companies usually need to collect region-specific data on sea ice parameters as part of the design phase studies for operations in Arctic areas. For offshore operations, there are two main situations that require different management of the ice. The first situation is in shallow waters (5 – 20 m) where constructions are built on the seafloor and designed to withstand the forces of the drifting sea ice. The sea ice is often attached to the seafloor and can be stationary for a long time. But stationary ice can start to drift due to strong winds and pile up ice blocks forming stamukhas. The other situation is when operations take place in deeper water covered with ice that is freely drifting and also icebergs can occur. Floating constructions and ships can operate if they are designed to withstand the ice forcing. In case of extreme ice conditions, the platforms can be released and towed away.

Icebergs drifting in the ocean are one of the most dangerous threats to offshore operations (Fig. 3). Icebergs are commonly found in the northern Barents Sea, around Svalbard and Franz Josef Land , in the Kara Sea, Laptev Sea and further east. In these areas, systematic monitoring of icebergs was conducted by Russian aircraft surveys for many decades, but in the last 20 years there have been no regular iceberg surveys in this area. In May 2003, surprisingly many icebergs were observed in the Shtokman area in the eastern Barents Sea. From ship radar observations, 109 iceberg and bergy bits were found in the area between 71 and 75 N and between 40 and 46 E. The largest iceberg was 190 by 430 m in horizontal extent and more than 50 m deep. Due to this event, the iceberg occurrence probability for the Shtokman area was re-calculated and triggered the oil companies to plan an iceberg monitoring and forecasting system for the area. Since the iceberg distribution can vary strongly from year to year, it is important to have good monitoring and tracking systems for the icebergs. Such systems are not in operation for most parts of the Arctic today. Extreme events can happen from year to year and there is no direct method to predict when and where icebergs occur and how they drift in the ocean.

Figure 3. Iceberg drifting in packice north of Svalbard

The requirements for sea ice observations have been defined by the IGOS Cryosphere Theme Report (2007) and are summarized in table 4.

Table 4. Requirements to measurements of sea ice variables from satellite sensors

Parameter	C/T/O	Measurement range		Measurement accuracy	Resolution		Satellite data
		Low end	High end		Spatial	Temporal	
Extent/Edge	C			15 km	15 km	1 day	AMSR, VIR, SAR, AUV
	T			10 km	10 km	1 day	CMIS
	O			5 km	1- 5 km	1 day	CMIS
Concentration	C	15 %	100 %	5 – 20 %	15 km	1 day	AMSR, VIR, SAR, AUV
	T	0 %	100 %	< 10 %	15 km	1 day	
	O	0 %	100 %	< 5 %	10 km	1 km	CMIS, SAR, AUV
Leads/polynyas	C	0 %	100 %	5 -20 %	15 km	1 day	AMSR, SAR
	T						
	C	0 %	100 %	5 %	10 km	1 day	MODIS, PM, AUV
Thickness	C	0 m	10 m	0.5 m	0.5 km	0.5 year	IceSat, oper. Ice charts, IMB, AUV
	T						
	O	0 m	10 m	0.1 m	25 km	1 month	Satellite altimeter, IMB, AUV
Motion	C	0 km/day	100 km/day	5 km/day	25 km	1 day	AMSR, SAR buoys
	T	0 km/day	100 km/day	3 km /day	25 km	1 day	SAR
	O	0 km/day	100 km/day	1 km/day	1 km	1 day	More frequent SAR, improved MIZ data
Snow depth on ice	C	0 cm	100 cm	10 – 20 cm	15 km	1 day	AMSR, Scat
	T	0 cm	100 cm	5 cm	10 km	1 day	CMIS
	O	0 cm	100 cm	2 cm	5 km	1 day	CMIS
Melt onset and duration	C	1 day	365 days	4 day	15 km	1 day	AMSR, Scat
	T	1 day	365 days	2 day	15 km	1 day	
	O	1 day	365 days	1 day	10 km	1 day	
Surface characterisation	C	0 %	100 %	10 &	1 km	1 day	MODIS, not operational
(albedo, melt ponds, temp.)	T	0 %	100 %	10 %	1 km	1 day	
	O	0 %	100 %	1 – 5 %	0.5 km	1 day	
Ridge height, concentration	C	0 m	10 m				SAR
	T	0 m	10 m	2 m			
	O	0 m	10 m	1 m			
Volume / Mass flux	O	0 km3/day	X km3/day	1 km3/day	25 km	1 day	Derived from motion, thickness and conc.

C: current capabiity, T: target requirement, O: Objective requirement

3.2 *User institutions*

According with main objectives of Task 1 contacts with Russian potential users and stakeholders are establishing and define their product requirements and case studies of sea ice and icebergs for the application area - the Eurasian Arctic, substantially in the Barents and Kara Seas. The list of potential users includes as well as traditional users and some new presented in Table 5.

Table 5. List of Russian potential users of satellite information for monitoring of Arctic sea ice and icebergs in the Eurasian Arctic *(as per February, 2012)*

№	Organization, country, city	Contact person	Position	Phone +7…./ +7 fax
1.	AARI Arctic and Antarctic Research Institute (Roshydromet) Russia, St. Petersburg	Frolov Ivam Yevgenyevich	Director	(812) 352 15 20 / (812) 352 2688
2.		Brestkin Sergey Vladimirovich	Head of Ice - Hydrometeorgocal Information Center	(812) 337 31 13
3.		Mironov Yevgeny Uarovich	Head of Ice forecast dep.	(812) 337 31 28
4.		Smirnov, Vladimir Grigoryevich	Head of Ice Remote Sensing dep.	(812) 337 31 30
5.	Atomflot (icebreakers) Russia, Murmansk	Babich Nikolay Grigoryevich	Head of Navigation Dep.	(8152) 481 189
6.	Company “Norilsk nickel“ Russia, Moscow	Gorshkovskiy Anatoly Grigorievich	Head of department	(925) 507 13 65 gorshkovskiyag@nornik.ru
7.	Public corporation “LUKOIL”, Russia			Fax: +7 495 627 4881 corpcom@lukoil.com
8.	Close corporation “TRANSAS“ - TRANsport SAfety Systems St.Petersburg, Russia			(812) 325-31-31 (812) 325-31-32
9.	Main administration of the navigation and oceanography, NAVY			(812) 327-19-34 / (812) 323 32 80
10.	Krylov institute Russia, St.Petersburg	Orlov Oleg Pavlovich	First deputy Director, head of department	(812) 127-95-95
11.	CNIIMF Central Research Institute of the Russian Federation Marine Fleet Ministry	Semanov Gennadi Nikolaevich	Head of department	(812) 271 10 15 semanov@cniimf.ru
12.	“Planeta”, Roshydromet	Krovotyntsev Vladimir Anatolievich		(495) 200-42-10; (499) 252 37 17 / (499) 252 66 10
13.		Trenina Irina Stepanovna		(495) 200-42-10
14.	ROSHYDROMET, Moscow			(499) 252-14-86

15.	Northwestern Hydromet, St. Petersburg			(812) 323-66-19 (812) 328-09-62
16.	Northern Shipping Company, Arkhangelsk			(8182) 637-333 / (8182) 655-309
17.	Northwestern Department of Roshydromet			
18.	Murmansk Hydromet			(8152) 47 25 49; (8152) 47 27 26
19.	Center of Hydromet. Information			(8152) 47 24 06
20.	VNIIOKEANGEOLOGIYA - All-Russia Research Institute of the Ocean Geology and Mineral recourses, St Petersburg			(812) 11-14-70
21.	JSC “TNK-BP”; Moscow			
22.	"Gyprorybflot" (Research and Design Institute of the State Committee on Fisheries of the RF), St.Petersburg	Chernook Vladimir Il’ich	Deputy Director	(812) 312-52-58, 312-76-21 / (812) 314-60-36;
23.	“Shtokman Development”			
24.	Sevmorneftegaz			(499) 550-30-02(499) 550-30-03
25.	Sovkomflot (overseas transport)			(495) 660 40 00 / (495) 660 40 99
26.	Center of the Arctic Remote Sensing, Northern (Arctic) Federal University after M.V.Lomonosov, Arkhangelsk	Koposov Sergey Genned’evich	Director	+7 921-721-02-59 (8-8182) 41-28-95
NEW POTENTIAL USERS				
27.	JSC “ROSNEFT”			
28.	Arkhangelsk sea harbor administration			
29.	Center of nature management environmental protection, Arkhangelsk			
30.	JSC “Gasprom space systems”			
31.	“National Park “Russian Arctic”			

The major potential users of sea ice and iceberg information are the following: Marine Operations Headquarters of Rosatomflot (former Murmansk Shipping Company - MSC), Murmansk, Russia; Shtokman Development AG, Moscow, Russia; 40th State Research Institute of salvage operations, diver's and deep-water works of Ministry of Defense of Russian Federation; TRANSAS Company (a worldleading developer and supplier of a wide range of software and integrated solution and hardware technologies for transportation industry); Arctic and Antarctic Research Institute (AARI); Murmansk Department for Hydrometeorology and Environmental Monitoring and others.

These users need substantially sea ice information in operative mode (time delay should not exceed several hours) for supporting navigation and offshore activity on the shelf. Marine operations headquarters of Rosatomflot is interested in receiving raw SAR images, interpret these images themselves and uses them for planning routes of navigation in the Arctic and for solving tactical tasks of navigation in the ice. AARI prepares composite weekly ice charts for the Arctic and is interested in development of automatic interpretation technique for their composition (automatic classification, ice drift retrieval, etc.). TRANZAS works on including sea ice and hydrometeorological information as a layer in their electronic maps. The products, developed in the project, will be the input for electronic maps. A major part of defined users is to different degree involved in activity, connected with exploration of Shtokman gas deposit. Shtokman Development AG particularly needs charts of iceberg distribution. In the frames of a project a several case studies will be conducted, when the developed products will be delivered to the users, which will estimate their quality and provide a feedback on their usefulness. In the frames of these case studies charts of iceberg distribution will be delivered to Shtokman Development; ice classification and drift products will be delivered to AARI; charts of polynyas – to Rosatomflot. All products will be delivered to TRANZAS for adaptation to electronic maps and to 40th State Research Institute of salvage operations – for their general assessment. User involvement into the project consists of receiving the products, generated in the project, their use for implementation of their work and studies and providing feedback.

In the MAIRES work we could take in account that in Russia was developed and use now a special system for providing of sea ice information for practical use subject to function (dedication), time and spatial coverage and resolution. There are three kinds of ice maps:

- General ice charts are preparing regularly during all ice period and characterized by large coverage (hundreds km) and not high time resolution (at an average 10 days or less). Use for study of space-time background conditions (monitoring), and for long-term and short-term ice forecasts;
- Scientific and operational ice charts are preparing accord to special user tasks for support of ice navigation, fishery, safety of a sea oil fields etc. As a rule such charts has a less coverage and more high time resolution than General charts. In operative mode the time delay should not exceed several (few hours;
- Special ice charts are preparing under special cases from time to time if need to get an ice distribution with very high accuracy and detailing, for instance by search-and-rescue activity and for engineering problem decision, namely construction of roads on the ice cover, monitoring of ice conditions etc.

The general user requirements to the ice satellite products are the following: regularity, i.e. independence on weather and light conditions: high-resolution: operative use and their correspondence to real ice conditions and characteristics. For this purpose their validation is necessary, so additionally available nonsatellite data (from aircrafts and in situ measurements) will be needed for validation of satellite products. The validation will be continuously based on comparison with field data from the expeditions, icebreaker reports on ice conditions, data from polar stations and analysis by experts.

Under the foresaid we can determine some type and characteristics of initial satellite information that we have to use for output of some satellite ice products are most important for potential users.

The most important ice parameters for users could be: ice edge, ice type distributions, polynyas, fractures, icebergs distributions, ice drift fields, thickness of the sea ice etc. Necessary to say that no only one method permits to derive all listed characteristics from satellite images, so we will clarify possibilities of some methods to meets user requirements here below separately subject to different methods. Case studies for the project will be defined on the bases of availability of satellite and in situ validation data

3.3 Definition of case studies

3.3.1 Sea ice classification on SAR images using a Neural Network algorithm

A multilayer feed forward Neural Network (NN) algorithm is developed for the Arctic sea ice classification during the winter period. The algorithm can be applied to ENVISAT Advanced Synthetic Aperture Radar (ASAR) images using extracted backscatter coefficients and image texture features. Based on the visual interpretation of ASAR images, a neural network is trained for the classification of the first year (FY) level and rough ice and multiyear (MY) ice. The algorithm validation is done using Arctic and Antarctic Research Institution (AARI) ice charts and ice expert visual analysis. The backscatter coefficients for the major sea ice types at HH–polarization and 23° incidence angle, as well as angular dependencies of the backscatter for young, first-year and multiyear ice types are derived from calibrated ENVISAT ASAR Wide Swath Mode (WSM) images. A methodology is developed for the backscatter angular correction for the predetermined incidence angle for obtaining range independent contrast for the same ice types. The backscatter coefficient data sets for various Arctic winter sea ice types at HH–polarization and 23° incidence angle are derived from Envisat ASAR image analysis.

Case studies will be conducted in the Arctic Ocean, the Barents and Kara Seas for winter period. Maps of ice diustribution will be composed and validated using optical images.

User request for ice charts: product content and specification

1. Type of ice chart (operational chart – every 2-3 days, general chart – once a decade for sea ice monitoring and special chart – high resolution for small regions investigation: Fram Strait or port area and etc);
2. Region of interest (northern Barents Sea, Svalbard area, northern Kara Sea, high Arctic);
3. Ice chart product: sea ice types (FYI thin or level, FYI def, FYI thick), ice\OW edge, fractures and polynias;
4. Time (winter – ice types, ice\OW edge, fractures and polynias, summer – ice\OW edge);
5. Projection (standard product is Polar Stereographic projection, it could be converted into Mercator projection for navigation or ARCGIS system);
6. Resolution (depends on ice chart type: 300 m or 1050 m for operational, general chart: 300 m or 1050 m or less, special chart – 150 m resolution or higher);
7. Coordinates (grid data of latitude and longitude);
8. Format of the provided data (output in MAT-files or NetCDF format or GeoTiff).

Automated sea ice classification process: Neural Network\Bayesian algorithm

The Neural Network (NN) automated sea ice classification includes the following stages (Fig. 4):

- Absolute ENVISAT ASAR image calibration to obtain *sigma0* values;
- Correction of angular depending effect on WSM ASAR images - backscatter values are changed with incidence angle increasing (~ 16 – 42 degree along the swath) for same sea ice types;
- Calculation of textural features for corrected ASAR image;
- Image classification: the textural characteristics and mean *sigma0* have to be used as input parameter for already trained NN;
- Conversion NN classification result according to users requirements.

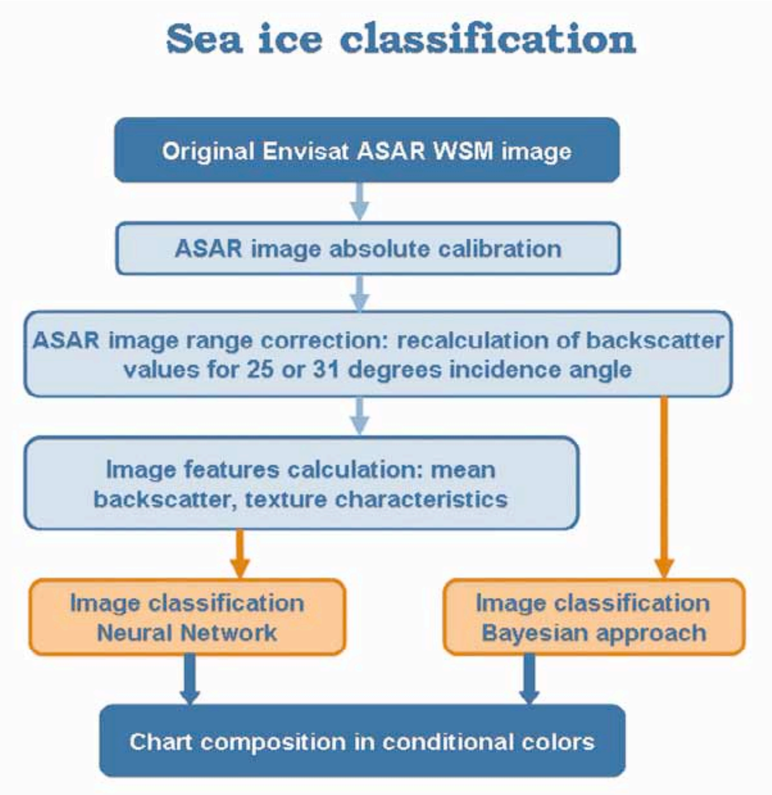


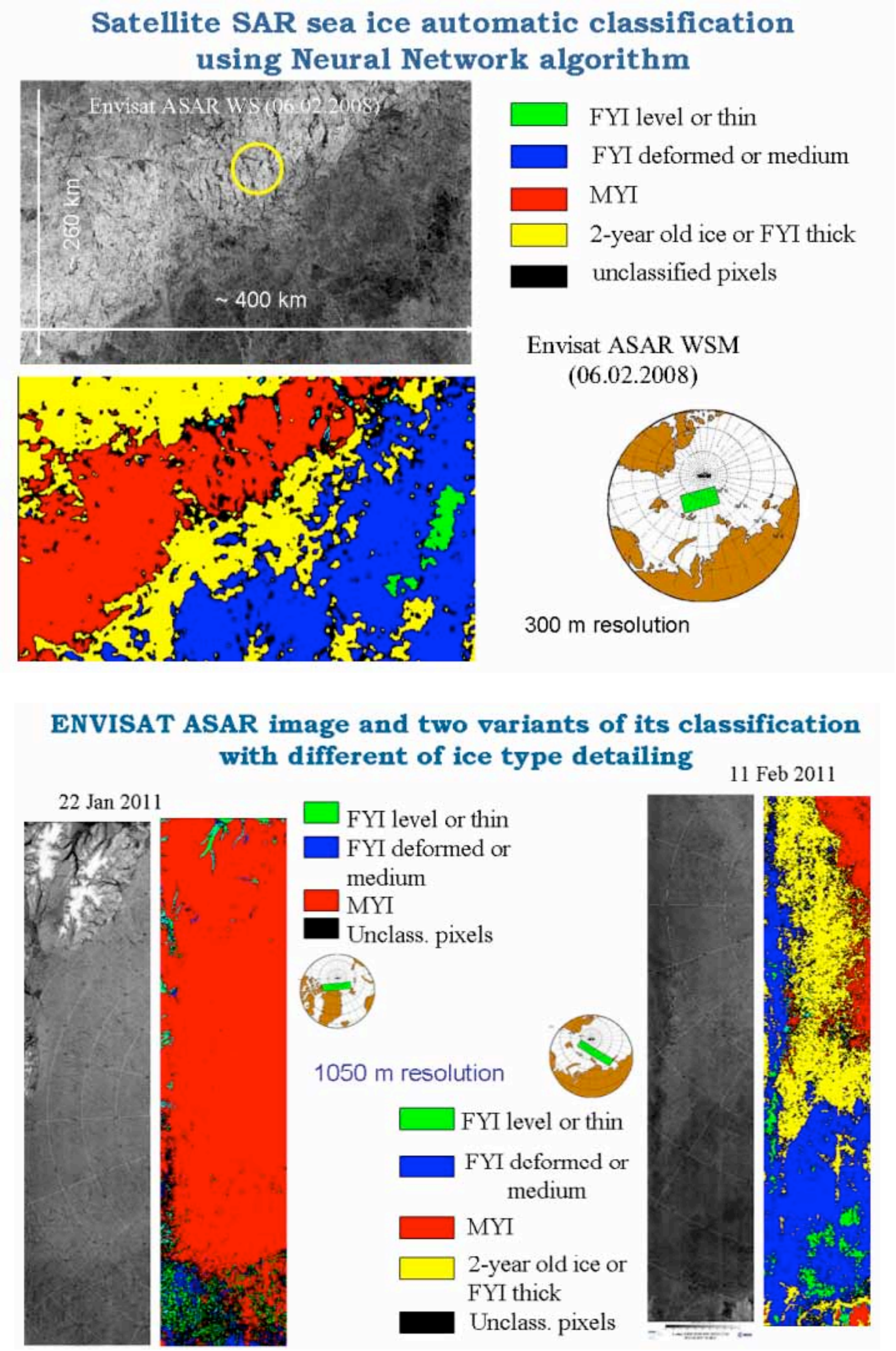
Figure 4. Sea ice classification process.

In case of Bayesian approach application:

- Absolute ENVISAT ASAR image calibration to obtain *sigma0* values;
- Correction of angular depending effect on WSM ASAR images - backscatter values are changed with incidence angle increasing (~ 16 – 42 degree along the swath) for same sea ice types;
- Image averaging for speckle reduction: corrected image is filtered by averaging in a sliding window, that removes the effect of noise;
- Image classification: the mean *sigma0* have to be used as input parameter for Bayesian approach using a priori probabilities of sea ice types in the Central Arctic, estimated from knowledge of ice conditions, and conditional probabilities of these ice types, assessed early from calibrated ENVISAT WSM images;
- Conversion classification result according to users requirements.

Classification of sea ice types

According to users requirements ice charts may be presented with different resolution and have a different time or area of cover. Examples of classification are shown in Figs. 5 and 6.

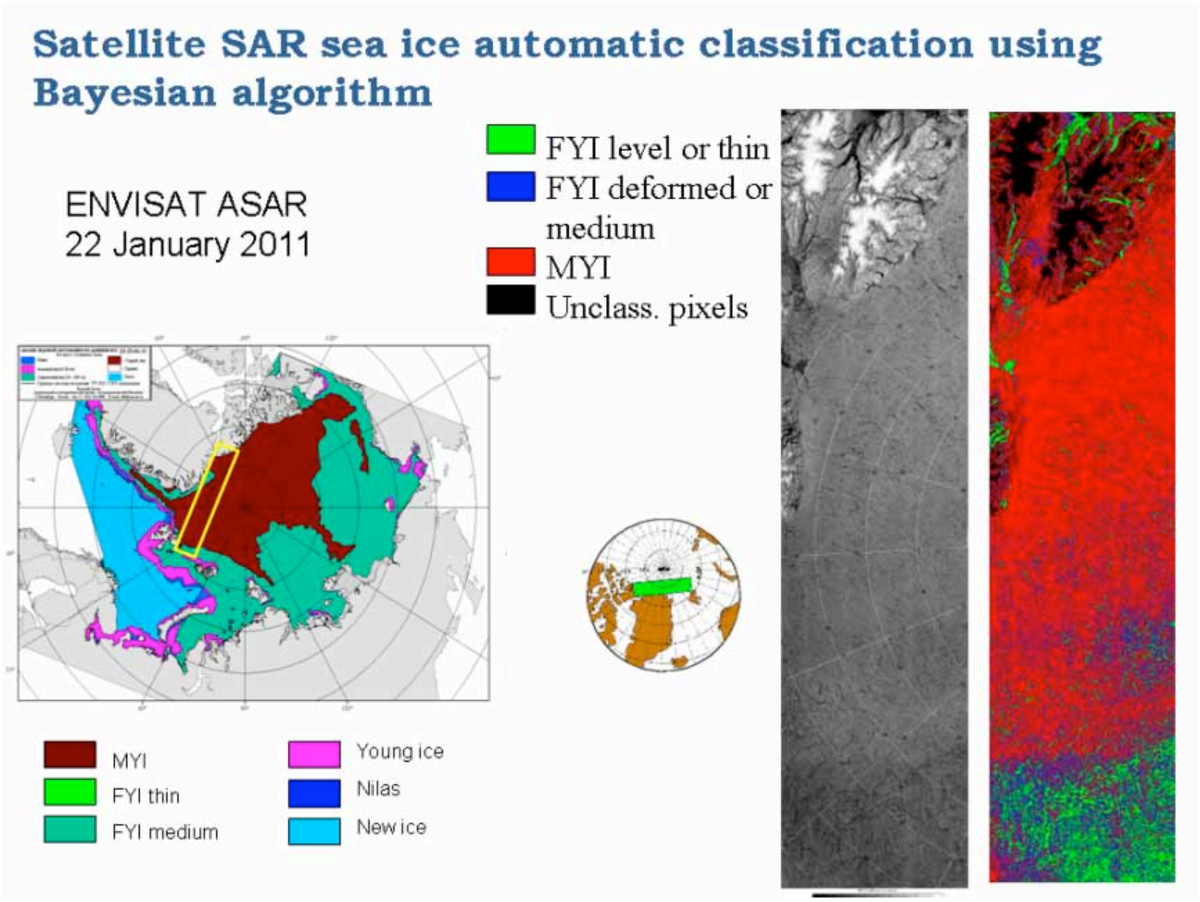


a) b)

Figure 5. Result of NN automated classification: a) small image fragment with 300 meters final resolution; b) full ENVISAT ASAR image scene with different sea ice type number (general sea ice types for the Central Arctic on the left figure and more detailed thick sea ice on the right) with 1050 meter final resolution.

Bayesian classification algorithm recognizes major ice types in the Central Arctic: FYI level, FYI deformed or thick and MYI. A priori probabilities of level FYI, deformed FYI and MYI appearance in the Central Arctic, estimated from knowledge of ice conditions, and conditional probabilities of these ice types, were assessed due to investigations from calibrated ENVISAT WSM images (Fig. 6).

A comparison with AARI ice charts shows that Bayesian algorithms reasonably recognize major ice types in the Central Arctic.

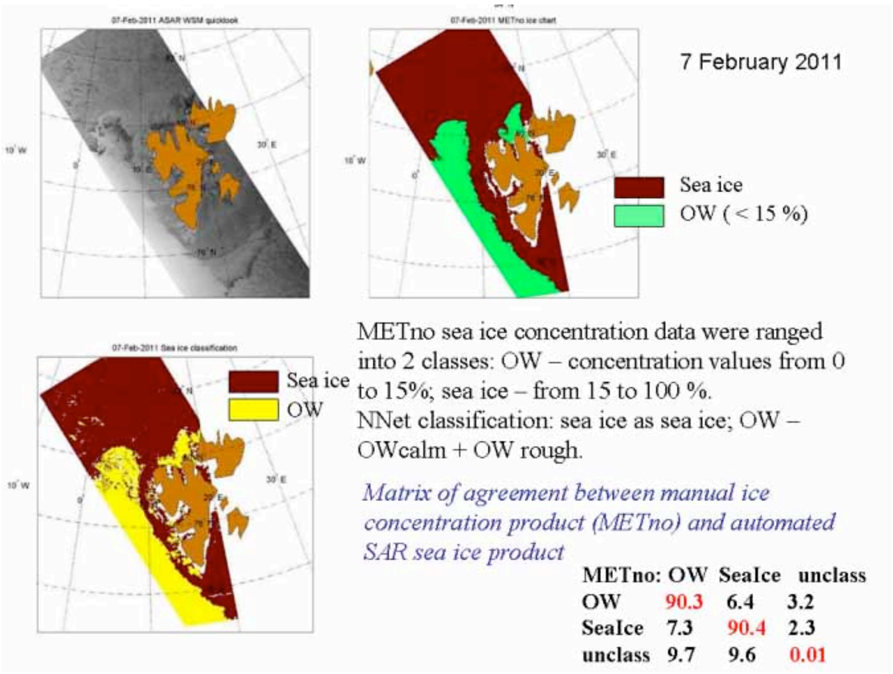


a) b)

Figure 6. Result of Bayesian automated classification: a) general ice chart manually developed in AARI for 21 – 23 January 2011; b) full ENVISAT ASAR image scene: corrected image and the result with 3 sea ice types with 300 meter final resolution.

Discrimination between Open Water and Sea ice

An algorithm for sea ice edge-OW detection has been developed using NN approach. The Arctic SAR sea ice edge\OW detection product is based on ENVISAT ASAR images together with a coarser ice concentration product from AMSR-E. The SAR data during prepossessing are averaging to a spatial resolution of 525 m x 525 m in pixel. AMSR-E data is interpolated into same grid (Fig. 7).



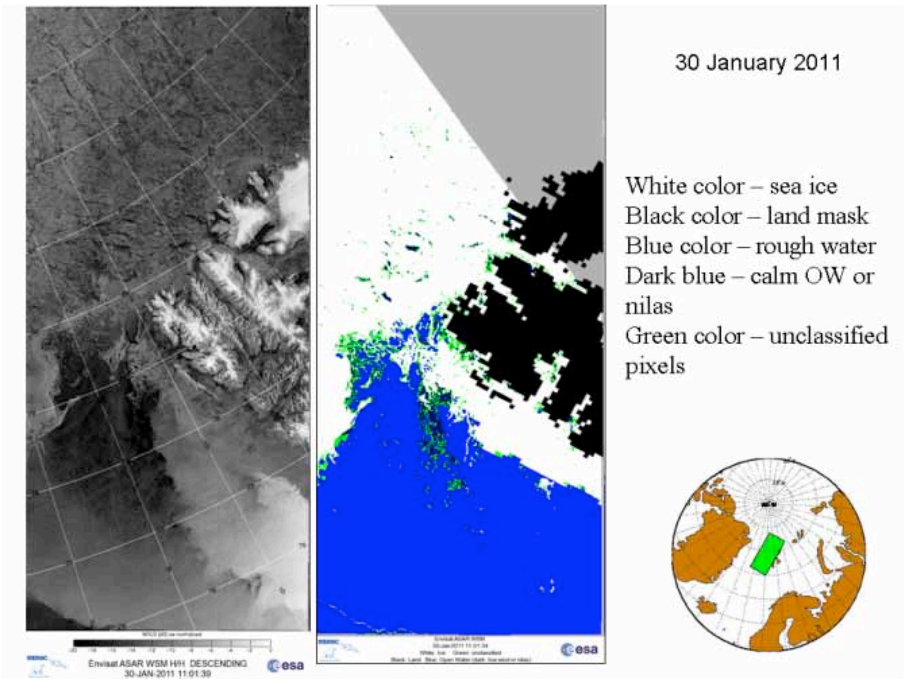
7 February 2011

METno sea ice concentration data were ranged into 2 classes: OW – concentration values from 0 to 15%; sea ice – from 15 to 100 %.
NNet classification: sea ice as sea ice; OW – OWcalm + OW rough.

Matrix of agreement between manual ice concentration product (METno) and automated SAR sea ice product

METno:	OW	SeaIce	unclass
OW	90.3	6.4	3.2
SeaIce	7.3	90.4	2.3
unclass	9.7	9.6	0.01

a)



30 January 2011

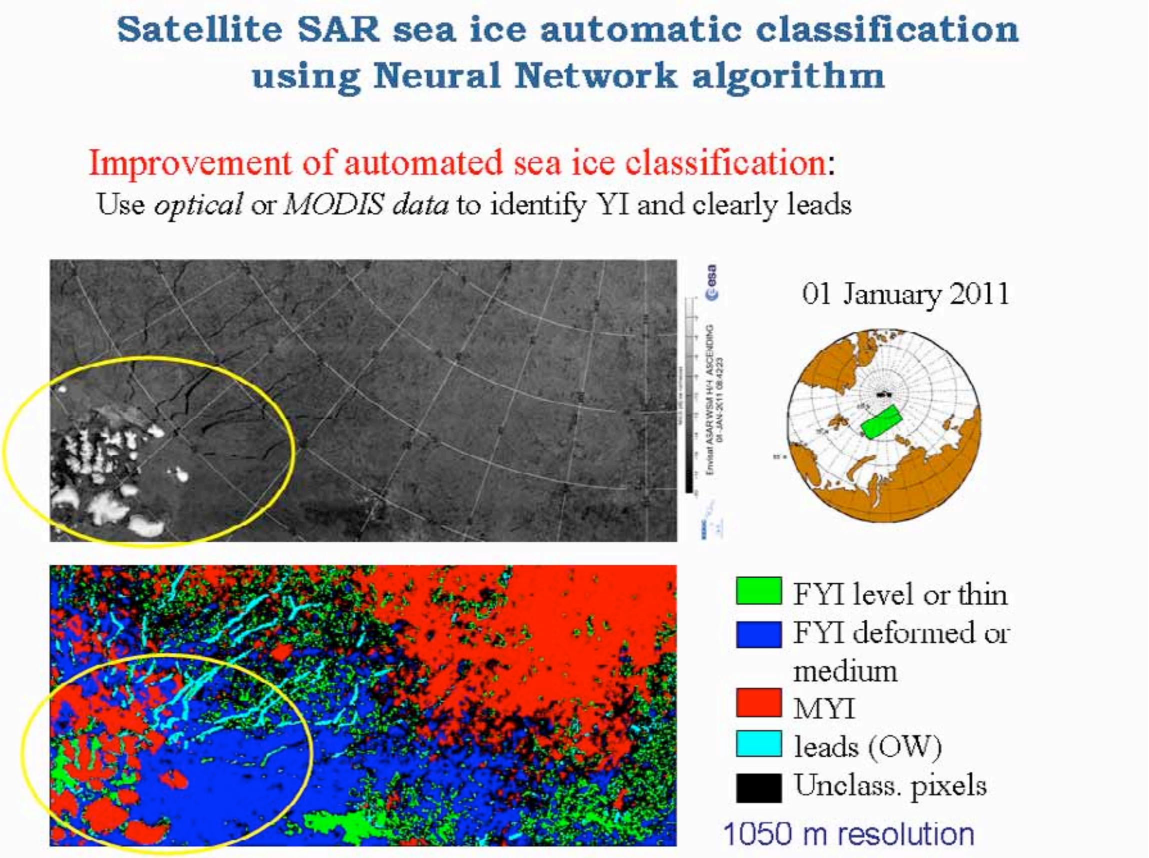
White color – sea ice
Black color – land mask
Blue color – rough water
Dark blue – calm OW or nilas
Green color – unclassified pixels

b)

Figure 7. Automated classification of Open Water - Sea Ice edge: (a) Corrected ASAR scene acquired 7 Februrary 2011, upper right – collocated subset of a manual ice concentration product of Met.no for the same day; lower figure – classification product. SAR OW\ice edge product are compared with a manual ice concentration product of Met.no: main diagonal (red colored) of presented error matrix shows the percentage of agreement between areas of the same classes. (b) Operational product – the lead (with open water) are presented here.

Automated classification improvements

Lack of young ice (YI) as individual class cause the NN classification errors: some areas of young ice may be classified as FYI deformed (Fig. 8 – yellow circles). NN also has several problems: leads in thin and level FYI and cracks. We can improve classification and increase sea ice types according to user's requirements using additional MODIS or other ***optical*** data (polynias, YI, nilas). Using Alternating Polarization mode of ENVISAT ASAR will also improve the sea ice classification.



Satellite SAR sea ice automatic classification using Neural Network algorithm

Improvement of automated sea ice classification:
Use *optical* or *MODIS data* to identify YI and clearly leads

01 January 2011

🟩 FYI level or thin
🟦 FYI deformed or medium
🟥 MYI
🟦 leads (OW)
⬛ Unclass. pixels

1050 m resolution

Figure 8. Automated sea ice type's classification using NN: a) upper – corrected full ENVISAT ASAR image scene acquired 1 January 2011; b) classification result with 3 sea ice types (1050 meter final resolution). Yellow oval shows the classification error: according visual analysis the YI zone was classified as FYI deformed.

Sea ice thickness

Ice thickness will be retrieved from Cryosat-2 measurements of ice freeboard (level-2 data) using developed empirical relations between ice thickness and ice freeboard. Obtained ice thickness values will be compared with *in situ* measurements of ice thickness at North Pole-38 and North Pole-39 drifting stations. It is expected that CryoSAt level-2 data becomes available during 2012.

Icebergs distribution and Iceberg detection

Methods for detection and monitoring of icebergs using new high-resolution SAR images from ENVISAT, RADARSAT-2, TerraSAR-X, visible images from SPOT, ASTER, and from Russian satellites Monitor-E will be demonstrated. The focus of case studies will be on the calving areas around Svalbard, Franz Josef Land, Novaya Zemlya and Severnaya Zemlya. The methods will cover three situations of iceberg location: (1) in open water, (2) in fastice, and (3) in drifting sea ice.
Icebergs will be detected by means of use of automated algorithms as well as by analysis of the satellite images. Validation will be done using database of iceberg observations.

Examples of iceberg detection in optical images in the Franz Josef Land area is shown in Fig. 9, where ASTER images on 20 April, 09 May and 18 June 2005 were analysed. The three images show that the fastice area around the islands did not change much in the period and that most of the icebergs were located in the fastice area. Icebergs embedded in the fastice are stationary as long as the fastice is not moving. Detection of these icebergs is more feasible because the background is generally homogeneous and time of observation is less critical. It is noteworthy that many icebergs can also be detected in open water between the fastice and the drifting ice, especially on 18 June.

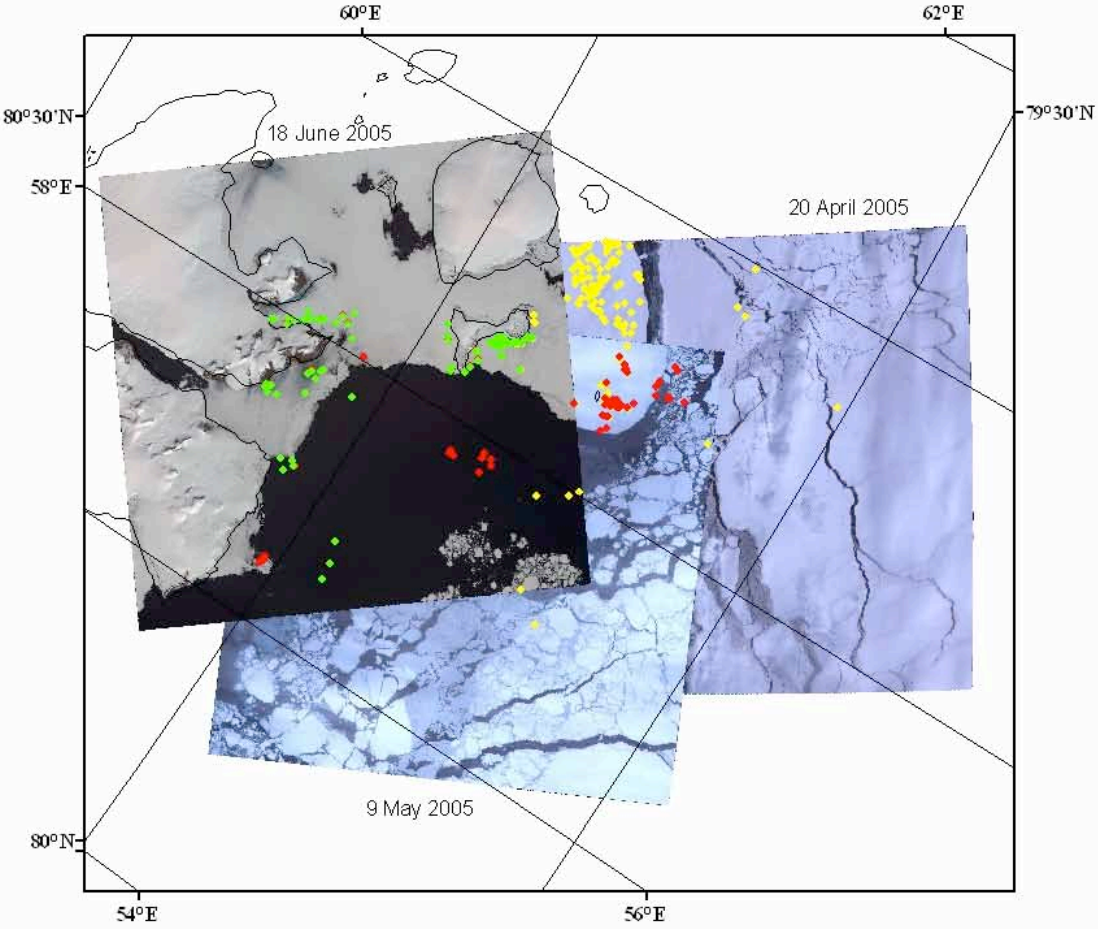


Figure 9. Composite of three ASTER images centred at 80 N and 58 E, in the southern part of Franz Josef Land. The dots indicate location of icebergs from image analysis on 20 April (yellow dots), 09 May (red dots) and 18 June (green dots).

Ice drift fields

In general mode we will use information which was collected as MAIRES data base: Pathfinder daily fields (all seasons 1979-2006, 25 km) – about 2000 points with values for each daily field (20 000 000 vectors); IFREMER SSMI/AMSR-E data (3 daily, winter season, 1991-2011) – about 1000 points with values for each daily field (700 000 vectors); and buoy data (NP, ITP, IAPB, …) - since 1937. An advanced statistical algorithm, namely vectorial-algebraic approach will use for getting some statistical characteristics of drift fields. The vectorial-algebraic approach allows us to significantly compress the initial information and most adequately describe the vector time series of full-scale and model data restricted by a set of statistical characteristics in the invariant form.

In scientific (and operational) mode as well as in special mode we will use drift data derived from SAR images using manual and automatic algorithms.

4 Concluding remarks

The report has reviewed the general requirements for observation of land ice, sea ice and icebergs based on previous and ongoing studies, especially regarding use of satellite data. The report has also identified many users of data and products derived from satellite data, from individual insitutiions and companies to international organisatins and global climate programmes. Definition of case studies has been done based on user requirements as well as data surveys. Access to data from satellites, both from ESA, Russian Space Agency and other space agencies provides guidelines for what can be done in the project. The report has also demonstrated examples of satellite analysis that will be done in the project and disseminated to users.

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