SEN4SCI (Sentinels for Science) – Assessing Product Requirements for the Scientific Exploitation of the Sentinel Missions

Project final document:

'The science needs for land & solid Earth Sentinel 1-2-3 products'

For the European Space Agency edited by:
Zbyněk Malenovský (RSL-UZH/UTAS).
Approved and released by:
Michael Schaepman (RSL-UZH).
Contribution:
Zbyněk Malenovský (RSL-UZH/UTAS), David Small (RSL-UZH), Glenda García-Santos (RSL-UZH), Josef Cihlar (ZEMKON), and Michael Schaepman (RSL-UZH).

Abstract

The main objective of the SEN4SCI European Space Agency (ESA) project is an assessment of product requirements for the scientific exploitation of the Global Monitoring for Environmental Security (GMES) Sentinel 1-2-3 missions. The following tree complementary approaches were used to identify the Sentinel-based products that are needed to support current activities in land and solid Earth research: i) an Internet search for relevant research programs and projects and their documentation review, ii) an international SEN4SCI scientific workshop devoted to the scientific potential of Sentinel 1-2-3, and iii) a public Internet discussion forum for scientific experts.

In the first approach, the intensive Internet documentation search and literature review was carried out to find out the important land and solid Earth research programs and projects and to synthetize their requirements on data, products or other information obtained through satellite observations. Documentation review of about 70 research programs and projects all over the World resulted in a document listing goal and threshold observational requirements of 30 land and 17 solid Earth scientific variables deliverable from space. The following up gap analysis pointed out, which sensor aboard of the Sentinel 1-2-3 missions and other synergic satellite missions are able to provide the required products. Subsequently their tentative priority was assessed.

The first international SEN4SCI scientific workshop was organized on 22-24 March 2011 at ESA-ESRIN in Frascati (Italy). Topic of the workshop attracted more than 200 land, solid Earth, ocean, and cryosphere scientific experts, which discussed in several splinter sessions the prepared documents on scientific requirements and satellite product priorities. The workshop participants also agreed on several recommendations that would ensure a proper scientific exploitation of the Sentinel 1-2-3 missions.

The land and solid Earth document, up-dated by outcomes of the SEN4SCI workshop, was from July to September 2011 posted on a publicly accessible Internet forum facilitated by ESA. Several scientists took a chance to comment, discuss and improve the final version of this document. Afterwards, examples of three land and solid Earth scientific variables were selected for further development of their processing chains using the Sentinel 1-2-3 datasets and for outlining their potential validation scheme. Their selection was taking into account the following aspects: i) serving a wide scientific community, ii) possibility to develop innovative processing methods based on technical specifications of the Sentinel instruments, and iii) potential for the synergistic use of data provided by any or several Sentinel 1-2-3 and Earth Explorer instruments.

Table of Contents

1. Introduction

The European Space Agency (ESA) is leading a federation of 'Sentinel' Earth observation missions built within the Global Monitoring for Environmental Security (GMES) Space Component that has the objective to ensure comprehensive and sustainable supply of data from space-based observations in response to the GMES service needs. While the primary purpose of Sentinel missions is to support European operational and policy needs, their acquired data and products also have the potential to meet observation needs of research communities in advancing understanding of particular aspects of the Earth environment. To enable ESA to facilitate more complete exploitation of the scientific potential of Sentinel observations, the Sentinels for Science (SEN4SCI) project was released. SEN4SCI focuses on identifying and consolidating: i) land and solid Earth, ocean, and cryosphere science needs to which the Sentinel 1-2-3 data could usefully contribute, ii) required data and products that could enhance the scientific yield from the Sentinel 1-2-3 missions, and iii) inputs from the broader scientific community with respect to these needs and requirements.

This report provides the final results of literature review on scientific needs of the land and solid Earth Sentinel 1-2-3 products, which were reviewed by a broad scientific community. The science observational needs were extracted from publically available documents of research programs and projects and consolidated during the international SEN4SCI workshop (22-24 March 2011, ESA-ESRIN, Frascati, Italy). Land and solid Earth Sentinel 1-2-3 observational needs and requirements were published for revision at the SEN4SCI WiKi EO portal (http://wiki.services.eoportal.org/tiki-index.php?page=Sentinel%20Wiki) during August and September 2011. All posted comments and corrections of participating scientific experts were reviewed and consolidated in this final document.

2. Land & solid Earth science

2.1. Land and solid Earth essential climate variables (ECVs)

A basic document on observations of climate variables is the Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (United Nations Framework Convention on Climate Change) (GCOS, 2010). It was prepared under the guidance of the Global Climate Observing System (GCOS) steering committee, taking into account feedback from several hundred experts.

The report prepared a list of Essential Climate Variables (ECVs) that may slowly evolve as requirements change and as technological developments permit. Compared to the Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (IP-04), the updated list of ECVs includes soil moisture and soil carbon (GCOS, 2010). The report notes that although biodiversity and habitat properties are important to climate impact studies, they are currently impossible to define as ECVs, as only some aspects of these complex properties can be measured, and only at a limited number of sites.

The ECVs that are currently feasible for global implementation and have high impact on UNFCCC requirements are: *above ground biomass, albedo, fire disturbance, fraction of absorbed photosynthetically active radiation (FAPAR), groundwater (levels, use), lakes (levels, area), land cover (including vegetation type), leaf area index (LAI), river discharge, soil carbon, soil moisture, water use (area of irrigated land, amount of water used for irrigation)*. ECVs such as *snow cover, glaziers and ice caps, ice sheets and permafrost* can be found in section 3. Cryosphere science. No ECVs are identified by GCOS (2010) with respect to the solid Earth scientific domain.

2.2. Land variables required by research programs and projects

Land variables of high scientific value were extracted from documentation of various research programs and projects. Not all the examined programs and projects were directly concerned with satellite observations, however, some of them i) use or will use satellite observations for achieving their objectives, ii) are likely to use satellite data-based products to achieve their objectives, and iii) may, but are unlikely, to use information products derived from satellite observations. The following 48 programs and projects related to land research scientific domain were included: *ALMA, AMMA, BALTEX, CARBONES, CCAFS, CEOP, CLIVAR, COCOS, EURO4M, GCP, GCOS, GECAFS, GECHH, GEO-Biodiversity CoP, GEO-Carbon Cycle CoP, GEO-Forests CoP, Geohazards CoP, GOOS, GEWEX, GGOS, GLP, GWSP, GLACE2, GTOS, GOFC-GOLD, Global Agricultural Monitoring CoP, GLASS, GMES, GMES-FIELD AC, GMES-Geoland2, GMES-SubCoast, GPCP, ICOS, IGOS Themes*[1] *(Geohazards Theme, Land Theme, Water Cycle Theme), iLEAPS, Kyoto & Carbon, LandFLUX, LoCo, LUCID, LOICZ, LPB, MedCLIVAR, NEESPI, NACP, NASA – EOS, NOAA – NESDIS, PILPS, SRB, and Water Cycle CoP*.

Not all the abovementioned programs and projects explicitly define requirements of the specified products and/or variables. We have identified 30 land variables of scientific interest with particularly (numerically) expressed specific observational requirements. These variables are listed in Table 2.1 (their definitions are provided in Appendix 1 to this document). The following requirement criteria were extracted from available program's and project's documentation: i) spatial resolution, ii) temporal resolution (or repeat), and iii) accuracy. Table 2.1 provides for each of these criteria two

[1] The objectives and activities of the IGOS Theme teams are now being pursued within the framework of the Group on Earth Observations and the Communities of Practice.

indicators: i) the 'goal' value is an ideal requirement above which further improvements are not necessary, and ii) the 'threshold' value is the minimum requirement to be met to ensure that data are useful. The values in Table 2.1 show the minimum (Min) and the maximum (Max) requirements as found across all reviewed programs and projects. If the Min/Max requirements of two thematically related variables (e.g. land cover and land cover change) do not correspond, then the variables are required by different number of projects or programs establishing different (more contrasting) needs. Brief descriptions of the reviewed land research programs and projects that defined observational requirements in Table 2.1 are listed below.

Global Geodetic Observing System (GGOS) provides observations of the three fundamental geodetic observables and their variations: the Earth's shape, the Earth's gravity field and the Earth's rotational motion. It is designed to collect, archive and ensure the accessibility of geodetic observations, results and models covering: geometry and kinematics of the Earth's surface, Earth orientation and rotation, and the Earth's gravity field and its variability. GGOS integrates different geodetic techniques, models, and approaches to ensure a long-term monitoring of the geodetic observables in agreement with the Integrated Global Observing Strategy. Main reference: http://www.ggos.org/.

Global Monitoring for Environment and Security - Land Monitoring Service (GMES-Geoland2) objective is to monitor the state of the environment on land and to improve the security of the citizens in a world facing an increased risk of natural and other disasters. Within GMES the Geoland2 project aims to organise a qualified production network, to build, validate and demonstrate operational processing lines and to set-up a user driven product quality assurance process. Main references are: http://www.gmes-geoland.info and Lacaze et al. (2009) at http://www.gmes-geoland.info/project-documentation/user-requirements.html.

Global Terrestrial Observing System (GTOS) is a programme for observations, modelling, and analysis of terrestrial ecosystems to support sustainable development. It facilitates access to information on terrestrial ecosystems for researchers and policy makers, so that they can detect and manage global and regional environmental change. The Global Terrestrial Observing System fulfils its mission through a number of complementary activities. It facilitates communication and cooperation between existing initiatives and promotes the harmonization of measurement methods and data processing. The four main GTOS panels are the: Coastal GTOS (C-GTOS), the Terrestrial Observation Panel on Climate (TOPC), the Terrestrial Carbon Observation panel (TCO) and the Global Observation of Forest and Land Cover Dynamics panel (GOFC-GOLD). These expert groups are aimed at promoting regional and global datasets and facilitating the synthesis of globally consistent data. GTOS has two sister observing systems, the Global Climate Observing System (GCOS), and the Global Oceanic Observing System (GOOS). The Food and Agriculture Organization (FAO), the International Council for Science (ICSU), the United Nations Environment Programme (UNEP), the United Nations Educational, Scientific and Cultural Organization (UNESCO), and the World Meteorological Organization (WMO) sponsor GTOS activities. Main reference: http://www.fao.org/gtos/.

Global Observation of Forest and Land Cover Dynamics (GOFC-GOLD) is a coordinated international effort to ensure a continuous program of space-based and in situ forest and land cover observations to better understand global change, to support international assessments and environmental treaties and to contribute to natural resources management. The objectives are: i) to present and assess GOFC-GOLD progress in various areas and activities, ii) to review the overall GOFC-GOLD strategy and defined future priorities and areas of activity including interactions with political and policy processes, iii) to engage the global community of forest and land cover monitoring experts to develop technical consensus in critical areas such as: Reducing Emissions from

Deforestation and Degradation (REDD), boreal forest monitoring, development of standards and reporting guidelines, assessment and validation of forest and land cover change, linking global and regional land mapping monitoring initiatives, formulate action plan for the land cover team and its partners, and foster future joint activities. Main reference: http://www.gofc-gold.uni-jena.de/.

Global Climate Observing System (GCOS) is a joint undertaking of WMO, the Intergovernmental Oceanographic Commission (IOC) of UNESCO, UNEP and ICSU. Its goal is to provide comprehensive information on the total climate system, involving a multidisciplinary range of physical, chemical and biological properties, and atmospheric, oceanic, hydrological, cryospheric and terrestrial processes. It is designed to monitor, understand and predict weather and climate, describe and forecast the state of the ocean (including living resources), improve management of marine and coastal ecosystems and resources, mitigate damage from natural hazards and pollution, protect life and property on coasts and at sea, and enable scientific research. GCOS observation requirements were defined in detail through science panels: Atmospheric Observation Panel for Climate (AOPC), Ocean Observations Panel for Climate (OOPC), Terrestrial Observation Panel for Climate (TOPC), and complementary WCRP Observation and Assimilation Panel (WOAP). Main reference: http://www.wmo.int/pages/prog/gcos/. Observational requirements are communicated through: http://www.wmo.int/pages/prog/sat/Databases.html.

Integrated Global Observing Strategy (IGOS/GEO) published the Observation Land Theme report outlining observational requirements for a large range of uses including agriculture, forestry, land degradation, ecosystem goods and services, biodiversity and conservation, human health, water resource management, disasters, energy, urbanization and sustainable human settlement. It does not deal with other important aspects of land observations, such as those relating to climate change, which are dealt with in other IGOS-P reports. The Integrated Global Observations for Land (IGOL) report has tried to distinguish carefully between the needs for improved observations and the products and observations required to satisfy those needs. However, no detailed observation requirements were specified. Main references are: Townshend, J.R., Latham, J., Arino, O., et al. (2008), Integrated Global Observations of the Land: IGOS-P Theme, IGOL Report No. 8/ GTOS 54. Report is available at http://www.fao.org/gtos/igol/docs/IGOS-theme-report-final-draft.pdf (accessed 2009-10-22).

The *ALOS Kyoto & Carbon (K&C) Initiative* is an international collaborative project led by the JAXA Earth Observation Research Center (EORC). It forms the continuation of JAXA's JERS-1 SAR Global Rain Forest and Global Boreal Forest Mapping project (GRFM/GBFM) into the era of the Advanced Land Observation Satellite (ALOS). The objective of the ALOS K&C Initiative is to define, develop and validate thematic products derived primarily from ALOS PALSAR data that can be used to meet the specific information requirements relating to conventions on climate change. A key component of this work has been the development of a systematic data acquisition strategy for ALOS, comprising fixed, systematic global observation plans for PALSAR. The strategy is implemented as a top-level foreground mission with a priority level second only to that of emergency observations. With emphasis on acquiring repetitive and consistent data over continental scales, it ensures that adequate data will be collected to allow the development of the required thematic output products on a timely basis. Main reference: http://w ww.eorc.jaxa.jp/ALOS/en/kyoto/kyoto_index.htm.

Monitoring Atmospheric Composition & Climate (MACC & MACC-II) is the pre-operational GMES atmospheric service. MACC provides data records on atmospheric composition for recent years, data for monitoring present conditions, and forecasts of the distribution of key constituents a few days ahead. MACC combines atmospheric modelling with EO data to provide information services covering European Air Quality, Global Atmospheric Composition, Climate, UV, and Solar Energy.

Main reference: http://gmes-atmosphere.eu.

North American Carbon Programme (NACP), the central objective of the U.S. North American Carbon Program is to measure and understand the sources and sinks of Carbon Dioxide (CO_2), Methane (CH_4), and Carbon Monoxide (CO) in North America and in adjacent ocean regions. The programme has identified monitoring needs including satellite data products. These include classification of land cover changes with emphasis on changes due to land use, wetland mapping, snow depth mapping, fire disturbance and burn severity, crop types, continental scale land ECVs such as those produced from the MODIS sensors, freeze-thaw dates, and soil carbon information. Main reference: http://www.nacarbon.org.

National Oceanic and Atmospheric Administration - National Environmental Satellite, Data, and Information Service (NOAA-NESDIS), NOAA's next strategic plan identifies four strategic goals: Climate Adaptation and Mitigation: An informed society anticipating and responding to climate and its impacts, Weather-Ready Nation: Society is prepared for and responds to weather-related events, Healthy Oceans: Marine fisheries, habitats, and biodiversity are sustained within healthy and productive ecosystems, Resilient Coastal Communities and Economies: Coastal and Great Lakes communities are environmentally and economically sustainable. Using environmental satellites to observe the Earth from space is one of the key tools in forecasting weather, analysing climate, and monitoring hazards worldwide. In collaboration with other U.S. agencies, NOAA manages and operates fleets of weather and environmental monitoring satellites, and it produces and manages environmental information derived from these measurements. Main references are: http://www.nesdis.noaa.gov/ and http://www.noaa.gov/.

World Meteorological Organisation (WMO) is a specialized agency of the United Nations. The vision of WMO is to provide world leadership in expertise and international cooperation in weather, climate, hydrology, water resources and related environmental issues and thereby contribute to the safety and well being of people throughout the world and to the economic benefit of all nations. Several WMO application areas have specified various number of the Land observation requirements: Agricultural meteorology, Hydrology, High resolution and Global Numerical Weather Prediction (NWP), Nowcasting and Very Short Range Forecasting, Synoptic Meteorology (SynopMet), and Seasonal and Inter-annual Forecasting (S&IA). Main reference: http://www.wmo.int/pages/index_en.html. Observational requirements are available at http://www.wmo.int/pages/prog/sat/Databases.html.

World Climate Research Programme (WCRP) is sponsored by ICSU, WMO and UNESCO. The overarching objectives are to determine the predictability of climate and to determine the effect of human activities on climate. These two objectives underpin and directly address the needs of the UN Framework Convention on Climate Change (UNFCCC) and contribute to many other international policy instruments. The core projects and activities of WCRP defining the observational requirements are: Climate and Cryosphere (CLIC), Climate Variability and Predictability (CLIVAR), Global Energy and Water Cycle Experiment (GEWEX), Stratospheric Processes And their Role in Climate (SPARC), Surface Ocean-Lower Atmosphere Study (SOLAS), and the Working Group on Surface Fluxes (WGSF). Main references are: http://www.wmo.int/pages/prog/wcrp/About_Aims.html and http://www.wcrp-climate.org/.

Certain land observational requirements are also specified in the *Global Ocean Observing System* (GOOS) documents. GOOS programs are working on different but complementary aspects of establishing an operational ocean observation capability for all of the world's nations. It is a permanent global system for observations, modelling and analysis of marine and ocean variables to support operational ocean services worldwide. Main objectives are: i) to monitor, understand and predict weather and climate, ii) to describe and forecast the state of the ocean, including living resources, iii) to improve management of marine and coastal ecosystems and resources, iv) to mitigate damage from natural hazards and pollution, v) to protect life and property on coasts and at sea, and vi) to enable scientific research. Main reference is: http://www.ioc-goos.org/.

Table 2.1. Observational requirements, minimum and maximum values, for land research variables extracted from programs and projects reviewed within the Sentinels for Science project (for definitions see Appendix 1).

Nr	Variable	Spatial Resolution		Temporal Repeat		Accuracy		Project (application) /program /organization
		Goal	Thresh-old	Goal	Thresh-old	Goal	Thresh-old	
1	***Earth surface albedo***	1 - 10 km	10 - 20 km	1 h - 1 d	12 h -30 d	3 - 5 % (Max)	10 % (Max)	WMO (High resolution NWP), GCOS, NOAA-NESDIS, Geoland2
2	***Biomass***	0.01 - 0.1 km	1- 10 km	1 y	2 y	5 t/ha	10 t/ha	GCOS, NACP, GOFC-GOLD, GEO-Carbon COP, K&C
3	***Downwelling long-wave radiation at the Earth surface***	10 - 25 km	100 km	1 - 3 h	6 - 12 h	1 - 5 W/m^2	10 - 20 W/m^2	WMO (Global NWP), GCOS, Geoland2
4	***Downwelling short-wave radiation at the Earth surface***	5 - 25 km	100 km	1-24 h	12-120 h	1-5 W/m^2	10-20 W/m^2	WMO, GCOS, Geoland2
5	***Downwelling solar radiation at TOA***	25 - 100 km	100 -500 km	1 - 3 d	6 d	0.1 - 1 W/m^2	1 - 2 W/m^2	GCOS (AOPC), WCRP (Global Modelling)
6	***Active fire equivalent area (burnt area)***	0.01 - 5 km	10 - 250 km	0.25 - 1 d	1-12 d	5 % (Max)	10-20 % (Max)	GCOS, Geoland2, WMO (Agricutural Meteorology)
7	***Active fire equivalent temperature***	0.01 - 5 km	10 - 250 km	0.25 d	1 - 12 d	50 - 500 K	200-1000 K	WMO (High resolution NWP, Nowcasting)
8	***Fire Radiative Power (FRP)***	1km	10km	1h	3d	10%	30%	MACC, MACC-II
9	***Flood/Standing Water***	0.1 km	Unspec.	1 h	Unspec.	0.01 km	Unspec.	NOAA - NESDIS
10	***Fraction of Photosynthetically Active Radiation (FPAR)***	0.25-50 km	2-500 km	0.04-7 d	2-30 d	5 % (Max)	10-20%	WMO (High res NWP, Global NWP, Agricultural meteorology, S&IA), GCOS (TOPC), GOOS, Geoland2
11	***Geoid***	100-250 km	500 km	240 mo	360 mo	1-2 cm	5 cm	WMO (S&IA), GOOS
12	***Ground water***	1 km	10 km	30 d	360 d	5 % (Max)	10 % (Max)	GCOS (TOPC)
13	***Lake level***	4 km	40 km	30 d	90 d	10 cm	20 cm	GCOS (TOPC)
14	***Lake surface temperature***	1 km	10 km	1 d	10 d	0.2 K	0.4 K	GCOS (TOPC)
15	***Land cover***	0.01-1 km	1-250 km	0.02 - 1 y	1 - 5 y	10-50 classes	4-5 classes	GTOS, GOFC-GOLD, WMO(Agricultural meteorology, Hydrology), GCOS (TOPC), NOAA-NESDIS, Geoland2
16	***Land cover change***	1 km	Unspec.	1 y	Unspec.	Unspec.	Unspec.	GTOS, GOFC-GOLD, IGOS, GCP, Geoland2

17	***Land Surface Temperature (LST)***	0.01-50 km	10-500 km	0.25 h -1 d	1-10 d	0.3-1 K (<300 m Geoland2)	2-4 K	WMO (Agricultural meteorology, Global NWP, Hydrology, Nowcasting, High resolution NWP), GCOS (AOPC), NOAA-NESDIS, WCRP (GEWEX), Geoland2
18	***Land surface topography***	0.01-0.250 km	1-10 km	5-10 y	10-50 y	1 m (vert.)	5-10 m (vert)	WMO (Hydrology), GCOS (TOPC)
19	***Leaf Area Index (LAI)***	0.01-2 km	10-40 km	1-7 d	7- 30 d	3-5% (max)[*1]	10-20% (max)[*2]	GCOS (TOPC), Geoland2, WMO (Agricutural Meteorology, Global NWP, Hydrology, High resolution NWP)
20	***Normalized Differential Vegetation Index (NDVI)***	0.01-5 km	10-250 km	0.5 - 1 d	2 -30 d	1-5%[*3]	5-20%[*4]	GTOS, WMO (Agricutural Meteorology, Global NWP, Hydrology, High resolution NWP), Geoland2
21	***Outgoing long-wave radiation at TOA***	2-100 km	50-500 km	0.5-3 h	6-12 h	5-10 W/m^2	10-30 W/m^2	WMO (Global NWP, Hydrology, High resolution NWP), GCOS, WCRP
22	***Outgoing short-wave radiation at TOA***	0.1-100 km	50-500 km	0.5-3 h	6-12 h	5-10 W/m^2	5-10 W/m^2	GCOS (AOPC), NOAA - NESDIS, WCRP (SPARC), WMO (Global NWP, Hydrology, High resolution NWP)
23	***Precipitation index (daily cumulative)***	0.5-100 km	10-500 km	0.5-24 h	6-72 h	0.5-2 mm/d	2-10 mm/d	GCOS (AOPC), WCRP (GEWEX), WMO (Agricultural meteorology, Global NWP, High res NWP)
24	***Precipitation rate (liquid) at the surface***	0.5-100 km	10-500 km	0.08-3 h	1-12 h	0.1-1 mm/h	1-2 mm/h	GCOS (AOPC), NOAA - NESDIS, WMO (Global NWP, Nowcasting, Synoptic Meteorology, High resolution NWP)
25	***River discharge***	10 km	100 km	1 d	7 d	5 % (Max)	10 % (Max)	GCOS (TOPC)
26	***Soil moisture***	0.01-50 km	1-500 km	0.125-7 d	6 h - 30 d	5-10 g/kg (0.02 m^3/m^3 High res NWP)	10 - 50 g/kg (0.08 m^3/m^3 High res NWP)	BALTEX, GCOS, NOAA-NESDIS, WCRP (GEWEX), Geoland2, WMO (Global NWP, Hydrology, S&IA, Nowcasting, High resolution NWP)
27	***Soil type***	0.1 km	10 km	1 y	2 y	15 classes	5 classes	WMO (Agricultural meteorology)
28	***Vegetation type***	0.01-50 km	0.5 - 500 km	7-30 d	30-365 d	18-50 classes	5-9 classes	WMO (Agricultural meteorology, Global NWP, Hydrology, S&IA)
29	***Wind speed over land surface (horizontal)***	0.5-20 km	20-250 km	0.25-24 h	3-12 h	0.5-2 m/s	2-5 m/s	WMO (Global NWP, Synoptic high res NWP)
30	***Wind vector over land surface (horizontal)***	2 -20 km	40 - 250 km	0.25- 1 h	0.5 -12 h	0.5 - 2 m/s	1.077 - 5 m/s	WMO (Global NWP, Nowcasting, Synoptic high res NWP), GCOS, GOOS, NOAA-NESDIS

[*1] 5% (other sources)
[*2] 20% (other sources)
[*3] 5% as FAPAR (other sources)

*4 5% as FAPAR (other sources)

Acronyms:

AOPC	Atmospheric Observation Panel for Climate
BALTEX	Baltic Sea Experiment
GCOS	Global Climate Observing System
GCP	Global Carbon Project
GEO-COP	Group on Earth Observations – Community of Practice
GEWEX	Global Energy and Water Cycle Experiment
GNWP	Global Numerical Weather Prediction
GOFC-GOLD	Global Observation of Forest and Land Cover Dynamics
GOOS	Global Ocean Observing System
GTOS	Global Terrestrial Observing System
K&C	Kyoto and Carbon
NACP	North American Carbon Programme
NOAA-NESDIS	National Oceanic and Atmospheric Administration - National Environmental Satellite Data and Information Service
NWP	Numerical Weather Prediction
IGOS	Integrated Global Observing Strategy
S&IA	Seasonal and Inter-annual Forecasting
TOPC	Terrestrial Observation Panel for Climate
WMO	World Meteorological Organisation
WCRP	World Climate Research Programme

Several additional variables of higher processing level (e.g. land productivity, dynamics of surface water and energy fluxes, prediction of latent heat convection loop, global carbon dioxide flux fields, and global crop monitoring parameters) are of interest to the reviewed programs and projects. However, as they are being generated from the products of lower level (Table 2.1), no specific observational requirements regarding spatial resolution, temporal repeat, and accuracy are provided.

Finally, in comparison to optical reflectance and its derivative (e.g., surface albedo), radar backscatter *amplitude* values are more heavily distorted by terrain-effects (foreshortening, layover, occlusions) than passive optical measurements. Backscatter *phase* values are employed in SAR interferometry via phase differences to derive information about local terrain height or land cover (via interferometric *coherence*). Thus, radar backscatter amplitude, phase, and coherence, as the lower processing level products, are not listed in Table 2.1.

2.3. Solid Earth required variables

Gross et al. (2009) published scientific variables required by the solid Earth community in "*Global Geodetic Observing System: Meeting the requirement of a global society on a changing planet in 2020*" Additionally, some of the solid Earth variables are provided by IGOS-Geohazards Theme Report (2004). Table 2.2 presents 17 solid Earth variables of scientific interest (their definitions are provided in Appendix 2 to this document) with specific requirements regarding horizontal spatial resolution, temporal resolution (temporal repeat and observing cycle), vertical spatial resolution, and accuracy. Only one value is indicated for each of these criteria, since data sources do not specify what type of requirement they present ('goal' or 'threshold'). The variables shared with other scientific disciplines, i.e. land (geoid, hydrology, land cover/use, near surface Earth thermal infrared (TIR) emitted radiance, soil moisture, surface temperature, and vegetation types), cryosphere (snow/ice cover), and ocean (sea level, sea temperature), are not listed in Table 2.2. Also atmosphere related variables as clouds, ash cloud top height, ash column density, ash cover, SO_2 cloud tropospheric, and

SO_2 total columnar content are not included. No particular observational requirements were found in reviewed documents for the following solid Earth variables: clay mineralogy variables, Earth MIR-TIR emitted radiance (brightness and temperature), infrastructure and geotechnical parameters, lava flows, and seismo-acoustic emission.

Table 2.2. Observational requirements for reviewed solid Earth variables (for definitions see Appendix 2).

Nr	Variable (Application)	Horizontal Resolution	Vertical Reso-lution	Temporal Resolution	Accuracy	Sensor type	Programme/ Source
1	***3-D Displacements*** (Climate change, Hydrological cycle, Seasonal variations, Surface loading, Seismotectonic, Volcanoes, Earthquakes)	100 km (Climate change, Hydrological cycle, Seasonal variations); < 100 km (Surface loading, Seismotectonics) 1 to 100 km (Volcanoes); << 100 km (Earthquakes)	--	Months (Climate change, Hydrological cycle, Seasonal variations); < 1 d (Surface loading, Volcanoes); days (Seismotectonics) sec. to days (Earthquakes)	1 mm (Climate change, Seismotectonics, Volcanoes); < 1 mm (Hydrological cycle, Seasonal variations, Surface loading); 1 mm to 1 cm (Earthquakes)	SAR/ GNSS (Galileo)	Gross et al., 2009
2	***3-D Velocities*** (Mantle convection and plate tectonics, Climate change)	n/a (Mantle convection and plate tectonics); < 102 km (Climate change)	--	n/a	< 1 mm/yr	SAR/ GNSS (Galileo)	Gross et al., 2009
3	***Crustal plates positioning*** (Geohazards)	250 km	--	5 yr	1 cm	GNSS (Galileo)	IGOS-Geohazards
4	***Displacement rate***; ***Surface deformation*** (Geohazards)	5 km; 1 m	100 km; 5 m	--	0.1 cm/yr; 3 m/min	SAR/ GNSS (Galileo)	IGOS-Geohazards
5	***Earth rotation*** (Climate change, Seasonal variations)	--	--	--	0.1 mas/yr (Climate change); 1 mas (Seasonal variations)	GNSS (Galileo)/ DORIS/SLR	Gross et al., 2009
6	***Faults*** (Geohazards)	3 m	--	--	--	--	IGOS-Geohazards
7	***Fissures/ cracks/ faults opening*** (Geohazards)	10 m	--	continuous	1 m	SAR	IGOS-Geohazards
8	***Fissures/ cracks/ faults widening*** (Geohazards)	10 m	--	continuous	0.1 cm/day	SAR	IGOS-Geohazards
9	***Geological information*** [classification] (Geohazards)	10 m	--	1 month	--	--	IGOS-Geohazards
10	***Gravity*** (Geohazards, Volcanoes, Hydrological cycle, Seasonal variations)	1 km (Geohazards); 1- 100 km (Volcanoes); 100 km (Hydrological cycle, Seasonal variations)	--	1 hr (Geohazards; days (Volcanoes); months (Hydrological cycle, Seasonal variations)	10 mGal (Geohazards); 1 µGal (Volcanoes); $< 10^{-9}$ (Hydrological cycle, Seasonal variations)	Gravity gradiometry, or satellite to satellite tracking	IGOS-Geohazards; Gross et al., 2009

11	***Levelling*** [Geoid combined with geometric heights above ellipsoid] (Geohazards)	0.1 km	--	--	0.1 cm	SAR	IGOS-Geohazards
12	***Local gravity*** (Climate change, Seasonal variations, Surface loading, Earthquakes)	< 100 km (Climate change); n/a (Seasonal variations); << 100 km (Surface loading, Earthquakes)	--	n/a (Climate change); months (Seasonal variations); < 1 d (Surface loading); sec to days (Earthquakes)	< 0.3 µGal (Climate change); < 1 µGal (Seasonal variations); 0.1 µGal (Surface loading); 0.3 µGal (Earthquakes)	--	Gross et al., 2009
13	***Magnetic field*** (nT) (Geohazards)	1 km	--	continuous	0.001 MHz	--	IGOS-Geohazards
14	***Secular strain rate*** (Mantle convection and plate tectonics)	1000 km	--	n/a	10^{-19} s^{-1}	GNSS (Galileo)/ SAR	Gross et al., 2009
15	***Speed of crustal motion***, [ground displacements] (Geohazards)	250 km	500 km	5 yr	1 mm/yr	SAR/ GNSS (Galileo)	IGOS-Geohazards
16	***Strain and strain rate*** (Seismo-tectonics, Earthquakes)	Strain and Strain rate: ~ 10 km (Earthquakes); Strain rate: < 10 km (Seismo-tectonics)	--	Strain: offsets; Strain rate: Years to secular (Seismotectonics) ; < 1 y (Earthquakes)	Strain: 10^{-8} (Earthquakes); Strain rate: 10^{-19} s^{-1} (Seismotectonics) ; 10^{-15} s (Earthquakes)	SAR/ GNSS (Galileo)	Gross et al., 2009
17	***Total Electron Content*** (TEC units), (Geohazards)	10 km	--	2h	10 TECU	GNSS-networks (Galileo)	IGOS-Geohazards

Acronyms:

IGOS Integrated Global Observing Strategy

2.4. Present and future European satellite missions for land and solid Earth science

Detailed information on the performance of the European present (Earth Explorer and MetOp missions) and future (Sentinel 1-2-3) satellite instruments is for the reviewed land variables provided in Table 2.3 and for the solid Earth variables in Table 2.4.

Table 2.3. Observational capabilities of Sentinel 1-2-3, Earth Explorer and MetOp missions for land variables.

Nr	Variable	Sensor type*	Sentinel mission /sensor (spatial resolution)	Earth Explorer/ Sensor (spatial resolution)	Other ESA missions/ sensor (spatial resolution)	MetOp (SG) (spatial resolution)
1	***Earth surface albedo***	MROI, HROI	S-2/ MSI (10, 20, 60 m); S-3/OLCI & SLSTR (300 m & 0.5 km, 1 km)	--	Envisat/MERIS (300 m); Proba/CHRIS (18 m); Envisat/AATSR (1 km)	AVHRR (1.1 km)

2	***Biomass***	(C-, L-, and P- band) SAR, LIDAR	S-1/SAR (20 m)	Biomass (candidate: not operational)	Envisat/ASAR (20, 120 m & 1 km)	--
3	***Downwelling long-wave radiation at the Earth surface***	MWI, MWR	S-3/SLSTR (0.5 km, 1 km) & MWR	--	Envisat/MERIS (300 m)	AVHRR (1.1 km)
4	***Downwelling short-wave radiation at the Earth surface***	HROI, MROI, LROI	S-2/ MSI (10, 20, 60 m); S-3/OLCI (300 m)	--	Envisat/MERIS (300 m)	AVHRR (1.1 km)
5	***Downwelling solar radiation at TOA***	HROI, MROI, LROI	S-2/ MSI (10, 20, 60 m); S-3/OLCI & SLSTR (300 m & 0.5 km, 1 km)	--	Envisat/MERIS (300 m)	AVHRR (1.1 km)
6	***Active fire equivalent area (burnt area)***	HROI, MROI, SAR	S-1/SAR (20 m); S-2/ MSI (10, 20, 60 m); S-3/OLCI & SLSTR (300 m & 0.5 km, 1 km)	--	Envisat/ASAR (20, 120 m & 1 km); Envisat/MERIS (300 m); Envisat/AATSR (1 km); ERS/ATSR (1 km)	AVHRR (1.1 km)
7	***Active fire equivalent temperature***	HROI, MROI (SWIR, TIR)	S-3/ SLSTR (300 m & 0.5 km, 1 km)	--	ERS/ATSR (1 km)	AVHRR (1.1 km)
8	***Fire Radiative Power (FRP)***	HROI, MROI (SWIR, TIR)	S-3/ SLSTR (300 m & 0.5 km, 1 km)	--	ERS/ATSR (1 km)	AVHRR (1.1 km)
9	***Flood/Standing Water***	MROI, HROI, SAR	S-1/SAR (20 m); S-2/ MSI (10, 20, 60 m); S-3/OLCI & SLSTR (300 m & 0.5 km, 1 km)	--	Envisat/ASAR (20, 120 m & 1 km)	
10	***Fraction of Photosynthetically Active Radiation (FPAR)***	MROI, HROI	S-2/ MSI (10, 20, 60 m); S-3/OLCI (300 m & 0.5 km, 1 km)	--	Envisat/MERIS (300 m); Proba/CHRIS (18 m); Proba-V (not operational) (300 m)	AVHRR (1.1 km)
11	***Geoid***	Gradiometer, RA	S-3/SRAL (300 m)	GOCE (100 km)	--	--
12	***Ground water***	--	--	--	--	--
13	***Lake level***	RA, POD	S-3/SRAL (300 m) & POD	CryoSat2/DORIS-NG	Envisat/RA-2 & DORIS-NG; ERS-2/RA (footprint 16-20 km)	
14	***Lake surface temperature***	MROI, MWI	S-3/SLSTR (0.5, 1 km)	--	Envisat/AATSR (1 km)	IASI (30 km); AVHRR (1.1 km); HIRS (20.3 km)
15	***Land cover***	SAR, MROI, HROI	S-1/SAR (20 m); S-2/ MSI (10, 20, 60 m); S-3/OLCI & SLSTR (300 m & 0.5 km, 1 km)	--	Envisat/MERIS (300 m); Proba/CHRIS (18 m); Envisat/ASAR (20, 120 m & 1 km)	--
16	***Land cover change***	SAR, MROI, HROI	S-1/SAR (20 m); S-2/ MSI (10, 20, 60 m); S-3/OLCI & SLSTR (300 m & 0.5 km, 1 km)	--	Envisat/MERIS (300 m); Proba/CHRIS (18 m); Envisat/ASAR (20, 120 m & 1 km)	--

17	***Land Surface Temperature (LST)***	HROI, MROI (SWIR, TIR)	S-3/SLSTR (0.5, 1 km)	--	Envisat/AATSR (1 km)	--
18	***Land surface topography***	RA, HROI, SAR, LIDAR	S-1/SAR (20 m);	--	ERS/SAR (20 m); Envisat/ASAR (20, 120 m & 1 km)	--
19	***Leaf Area Index (LAI)***	MROI, HROI, SAR	S-2/ MSI (10, 20, 60 m); S-3/OLCI & SLSTR (300 m & 0.5 km, 1 km)	--	Envisat/MERIS (300 m); Proba/CHRIS (18 m)	--
20	***Normalized Differential Vegetation Index (NDVI)***	LROI, MROI, HROI	S-2/ MSI (10, 20, 60 m); S-3/OLCI (300 m)	--	Envisat/MERIS (300 m); Proba/CHRIS (18 m); Proba-V (not operational) (300 m)	AVHRR (1.1 km)
21	***Outgoing long-wave radiation at TOA***	MWI, MWR	S-3/SLSTR (0.5, 1 km) & MWR	EarthCare (not operational) (10 m)	--	GERB (44.6 x 39.3 km)
22	***Outgoing short-wave radiation at TOA***	LROI, MROI, HROI	S-2/ MSI (10, 20, 60 m); S-3/OLCI (300 m)	--	Envisat/MERIS (300 m); Proba/CHRIS (18 m)	AVHRR (1.1 km)
23	***Precipitation index (daily cumulative)***	--	--	--	--	--
24	***Precipitation rate (liquid) at the surface***	--	--	--	--	--
25	***River discharge***	RA, LIDAR	--	--	--	--
26	***Soil moisture***	SCAT, SAR, MROI (TIR), MWI, MWR	S-1/ SAR (potential utility) (20 m); S-3/MWR	SMOS (50 km)	ERS/SAR (20 m); Envisat/ASAR (20, 120 m & 1 km)	ASCAT (25-37 km); AVHRR (1.1 km); AMSU-A (48 km)
27	***Soil type***	MROI, HROI	S-2/ MSI (10, 20, 60 m); S-3/OLCI & SLSTR (300 m & 0.5 km, 1 km)	--	Envisat/MERIS (300 m); Proba/CHRIS (18 m)	--
28	***Vegetation type***	MROI, HROI, SAR	S-1/SAR (20 m); S-2/ MSI (10, 20, 60 m); S-3/OLCI & SLSTR (300 m & 0.5 km, 1 km)	--	Envisat/MERIS (300 m); Proba/CHRIS (18 m); ERS/SAR (20 m); Envisat/ASAR (20, 120 m & 1 km); Envisat/AATSR (1 km)	AVHRR (1.1 km)
29	***Wind speed over land surface (horizontal)***	Doppler Wind LIDAR	--	ADM-Aeolus/ALADIN (not operational)	--	--
30	***Wind vector over land surface (horizontal)***	Doppler Wind LIDAR	--	ADM-Aeolus/ALADIN (not operational)	--	--

* Sensor types:

HROI	High resolution multispectral optical imager
HRSOI	High resolution stereo optical imager
LA	Laser altimeter
LIDAR	Light detection and ranging sensor
LROI	Low resolution multispectral optical imager
MROI	Medium resolution multispectral optical imager

MWI	Imaging microwave radiometer
MWR	Microwave radiometer
POD	Precise orbit determination
RA	Radar altimeter
SAR	Synthetic aperture radar
SCAT	Scatterometer
SWIR	Short wave infrared
TIR	Thermal infrared radiometer

Table 2.3 shows that the optical instruments of both Sentinel-2 (S-2) and Sentinel-3 (S-3) will provide spectral information for the mapping of basic radiation variables (e.g., downwelling long-wave radiation at the Earth surface and at top of atmosphere (TOA), outgoing short & long-wave radiation at TOA, etc.), including the highly prioritized Earth surface albedo. Spectral images of Multi Spectral Instrument (MSI) and Ocean Land Colour Instrument (OLCI), supported by Sea Land Surface Temperature Radiometer (SLSTR), will be used to derive the highly prioritized time series of traditional vegetation variables, i.e. fraction of photosynthetically active radiation (FAPAR) with leaf area index (LAI), and, important for data continuity, normalized difference vegetation (NDVI). They can also provide various experimental variables of medium priority, e.g. fire disturbance (burnt areas) or vegetation and soil types. Synergistic use of S-2, -3 optical sensors and Sentinel-1 (S-1) Synthetic Aperture Radar (SAR) instruments will improve the quality of highly prioritized land cover and land cover change products, and also vegetation type maps of medium priority. Both enabling short revisits and synergistic use of optical/SAR data requires prior sensor-specific correction of terrain-induced distortions on both geometry & radiometry. The S-1 C-band SAR (dedicated all-weather, day-and-night radar imaging mission) will be able to contribute to the mapping of standing water (floods), specific land cover classes (e.g. snow and vegetation types), and soil moisture at the surface, benefiting from quicker revisit than previously available. S-1 will also contribute to estimating vegetation biomass (important for carbon cycle monitoring) and highly prioritized land surface topography (in arid regions where high coherence can be obtained, or more generally if flown in a possible tandem formation). Relatively low-resolution land surface topography will be measured along the satellite track by the S-3 Synthetic Aperture Radar Altimeter (SRAL). SRAL is also designed to monitor the level of lake water surfaces. Although the major role of S-3 SLSTR is to measure temperature and emissivity of water surfaces (lakes) and with high priority land surfaces (including fire events), its new combined spectral and angular sampling capability will improve observation quality and support retrieval of several land variables delivered primarily by the S-2 and S-3 imaging spectroradiometers (MSI, OLCI).

Table 2.4. Observational capabilities of Sentinel 1-2-3, Earth Explorer and other ESA missions for solid Earth research.

Nr	Variable	Sensor type*	Sentinel mission /Sensor (spatial resolution)	Earth Explorers	Other ESA missions/ Sensor (spatial resolution)
1	***3-D Displacements***	SAR/ GNSS (Galileo)	S-1/SAR (20 m)	BIOMASS (candidate; not operational), CoReH2O (not operational)	ERS/SAR (20 m); Envisat/ASAR (20, 120 m & 1 km)
2	***3-D Velocities***	SAR, PSI, POD/ GNSS (Galileo)	S-1/SAR (20 m); S-3/POD	CryoSat2/DORIS-NG	ERS/SAR (20 m); Envisat/ASAR (20, 120 m & 1 km) & DORIS-NG
3	***Crustal plates***	POD/GNSS	S-3/POD	CryoSat2/DORIS-NG	Envisat/ DORIS-NG

	positioning	(Galileo)			
4	***Displacement rate***; ***Surface deformation***	SAR, PSI, POD/ GNSS (Galileo)	S-1/SAR (20 m); S-3/POD	CryoSat2/DORIS-NG	ERS/SAR (20 m); Envisat/ASAR (20, 120 m & 1 km) & DORIS-NG
5	***Earth rotation***	GNSS (Galileo)	--	--	--
6	***Faults***	HROI	S-2/ MSI (10, 20m)	--	Chris/Proba (18 m)
7	***Fissures/ cracks/ faults opening***	SAR	S-1/SAR (20 m)	--	ERS/SAR (20 m); Envisat/ASAR (20, 120 m & 1 km)
8	***Fissures/ cracks/ faults widening***	SAR	S-1/SAR (20 m)	--	ERS/SAR (20 m); Envisat/ASAR (20, 120 m & 1 km)
9	***Geological information*** [classification]	HROI	S-2/ MSI (10, 20m)	--	Chris/Proba (18 m)
10	***Gravity***	Gradiometer, or satellite to satellite tracking	--	GOCE/ EGG	--
11	***Levelling***	SAR	S-1/SAR (20 m)	GOCE/EGG	ERS/SAR (20 m); Envisat/ASAR (20, 120 m & 1 km)
12	***Local gravity***	--	--	GOCE/EGG	--
13	***Magnetic field*** (nT)	--	--	SWARM/Vector Fluxgate Magnetometer (not operational)	--
14	***Secular strain rate***	GNSS (Galileo)	--	--	--
15	***Speed of crustal motion***	SAR, PSI/ GNSS (Galileo)	S-1/SAR (20 m)	--	ERS/SAR (20 m); Envisat/ASAR (20, 120 m & 1 km)
16	***Strain and strain rate***	GNSS (Galileo)	--	--	--
17	***Total Electron Content***	GNSS (Galileo)	--	SWARM/Electric Field Instrument (not operational)	--

* Sensor types:

GNSS Global navigation satellite system (e.g. European system Galileo)
HROI High resolution multispectral optical imager
POD Precise orbit determination
PSI Persistent scatterer interferometry
SAR Synthetic aperture radar

Table 2.4 illustrates that the S-1 C-band SAR sensor will enable retrievals of a wide variety of solid-earth parameters. Radar phase difference information retrieved via repeat-pass SAR interferometry requires at least two same-track acquisitions – when known elevation information is integrated, the effects of orbit baseline can be modelled and corrected, resulting in displacement estimates (Massonnet et al., 1993). Given a stack of observations, distortions caused by dynamic atmosphere can be modelled and corrected using the technique of persistent scatterer interferometry (Ferretti et al., 2001), enabling point-wise velocity estimates. S-1 is well suited for measurements of the Earth surface motions (3-D displacements and velocities, displacement rate, speed of crustal motion, tectonics, etc.) and also for levelling monitoring. S-3 Precise Orbit Determination (POD) can provide supporting information in some cases. The high spatial and spectral resolution of MSI images will enable S-2 to detect faults and also to map spatially heterogeneous geological information.

2.5. Proposed priorities for satellite products on land and solid Earth variables

A priority assessment for land and solid Earth variables was proposed based on observational requirements, capabilities of the first three Sentinels, and availability of related auxiliary data. Proposed priorities, presented in Table 2.5 and Table 2.6, were discussed and consolidated during the international SEN4SCI workshop (22-24 March 2011, ESA-ESRIN, Frascati, Italy).

ESA currently supports several scientific projects defining requirements and developing the processing algorithms of several land and solid Earth products. The following ESA programmes initiate and maintain the scientific development: i) ESA Data User Element (DUE, 2011; http://due.esrin.esa.int/), ii) ESA Support to Science Element (STSE, 2011; http://wfaa-dat.esrin.esa.int/stse/), and iii) ESA Climate Change Initiative (CCI). For defining priorities of the future Sentinel scientific products, the liaison with these programmes is important. Therefore, ESA DUE, STSE, CCI projects and other associated activities dealing with the required land and solid Earth variables are also stated in Table 2.5 and Table 2.6, in the column 'Heritage activity'. Information on heritage of the products, referring to retrieval algorithm development, product generation, and application demonstration is also provided.

The priority ranking took into account the following aspects of the variables:

- Scientific importance, i.e. variables should match the requirements for ECVs (specified by GCOS - GTOS) and meet the scientific challenges of ESAs Living Planet Programme (ESA, 2006).
- Exploitation of the potential synergies of the Sentinel missions (complemented by other ESA missions and third party missions.)
- Feasibility and maturity of the processing algorithm to generate homogeneous, accurate and thoroughly validated geophysical products matching the requirements of the scientific community in terms of accuracy and data continuity.

Considering these criteria, the priority indication of the land and solid Earth products, consolidated during the SEN4SCI workshop, was split into two classes:

- *High priority* (H): product of high importance for scientific applications generated with a mature/validated retrieval algorithm.
- *Medium priority* (M): product important for scientific applications, however, being produced on demand usually at regional scale possibly with relatively immature retrieval algorithm.

Missing prioritization of some solid Earth variables was not discussed during the SEN4SCI workshop.

Table 2.5. Preliminary priority assessment of potential products on land variables from Sentinel 1-2-3, missions, auxiliary data required, and heritage ESA projects (priority rating: H ~ High priority, M ~ Medium priority; NR ~ Not Rated; ECV ~ Essential Climate Variable).

Nr	Variable	Sentinel mission /sensor	Auxiliary data	Heritage project (activity)	Priority
1	***Earth surface albedo***	S-2/ MSI; S-3/OLCI (SLSTR)	Skylight diffusion coefficients	GlobAlbedo	H (ECV)
2	***Biomass***	S-1/SAR		Kyoto & Carbon, BioSAR, TropiSAR, BIOMASAR	M (ECV)

3	***Downwelling long-wave radiation at the Earth surface***	S-3/SLSTR & MWR			H
4	***Downwelling short-wave radiation at the Earth surface***	S-2/MSI; S-3/OLCI			H
5	***Downwelling solar radiation at TOA***	S-2/MSI; S-3/OLCI & SLSTR			M
6	***Active fire equivalent area (burnt area)***	S-2/MSI; S-3/OLCI & SLSTR		GlobScar; Innovators II-nea-Forest; ITALSCAR	H (ECV)
7	***Active fire equivalent temperature***	S-3/ SLSTR			NR
8	***Fire Radiative Power (FRP)***	S-3/ SLSTR			NR
9	***Flood/Standing Water***	S-1/SAR; S-2/MSI; S-3/OLCI & SLSTR	Land-Water mask	FAIRE, G-POD RESPOND	H-M
10	***Fraction of Photosynthetically Active Radiation (FPAR)***	S-2/ MSI; S-3/OLCI		GlobCarbon	H (ECV)
11	***Geoid***	S-3/SRAL			H
13	***Lake level***	S-3/SRAL (300 m) & POD		CECINA, TIGER	M
14	***Lake surface temperature***	S-3/SLSTR (1 km)			M
15	***Land cover***	S-1/SAR; S-2/MSI; S-3/OLCI & SLSTR		AgriSAR, Tropical Mapping; Forest Mapping; GlobCORINE; GlobCover; GOFC-GOLD-LC-PO; IMCASSAR; Innovators I-CARTO-CHANGE	H (ECV)
16	***Land cover change***	S-1/SAR; S-2/ MSI; S-3/OLCI & SLSTR		AgriSAR, Tropical Mapping; Forest Mapping; GlobCORINE; GOFC-GOLD-LC-PO; IMCASSAR; Innovators I-CARTO-CHANGE	H (in areas experiencing rapid change), M (elsewhere)
17	***Land Surface Temperature (LST)***	S-3/SLSTR			H
18	***Land surface topography***	S-1/SAR			H
19	***Leaf Area Index (LAI)***	S-2/ MSI; S-3/OLCI (SLSTR)		GlobCarbon	H (ECV)
20	***Normalized Differential Vegetation Index (NDVI)***	S-2/MSI; S-3/OLCI			H (for data continuity)
21	***Outgoing long-wave radiation at TOA***	S-3/SLSTR & MWR			M
22	***Outgoing short-wave radiation at TOA***	S-2/ MSI; S-3/OLCI			M
26	***Soil moisture***	S-1/ SAR (potential utility)		CLIMSCAT, TIGER, SHARE	H
27	***Soil type***	S-2/ MSI; S-3/OLCI & SLSTR		AgriSAR	M
28	***Vegetation type***	S-1/SAR; S-2/ MSI; S-3/OLCI & SLSTR			M

Table 2.6. Priority assessment of potential Sentinel 1-2-3 solid Earth products with required auxiliary data (priority rating: H ~ High priority, M ~ Medium priority, NR ~ Not Rated).

Nr	Variable	Sentinel mission /sensor type	Auxiliary data	Priority
1	***3-D Displacements***	S-1/SAR	Temporal gravity field variations; GNSS (Galileo)	H-M
2	***3-D Velocities***	S-1/SAR, S-3/POD	GNSS (Galileo)	M
3	***Crustal plates positioning***	S-3/POD	GNSS (Galileo)	M
4	***Displacement rate***; ***Surface deformation***	S-1/SAR, S-3/POD	GNSS (Galileo)	M
6	***Faults***	S-2/MSI		NR
7	***Fissures/ cracks/ faults opening***	S-1/SAR		NR
8	***Fissures/ cracks/ faults widening***	S-1/SAR		NR
9	***Geological information*** [classification]	S-2/MSI		NR
11	***Leveling***	S-1/SAR/20 m	GNSS (Galileo)	H
15	***Speed of crustal motion***	S-1/SAR/20 m		H-M (ground displacement)

2.6. Recommendations of the land and solid Earth scientific experts during SEN4SCI workshop

The discussion of the land experts at the SEN4SCI workshop addressed the following land thematic groups: i) mapping of land cover (land use), ii) retrieval of biophysical (biochemical and structural) parameters of vegetation, iii) monitoring of global cycle variables, and iv) detection of rapid natural hydrological events. In addition to discussed scientific user requirements and land product scientific priorities, the land splinter group at the SEN4SCI workshop agreed on the following science-related *recommendations*:

- A new state-of-the-art land cover product, derived from Sentinel observations, should include information on land cover change, land use, and land management. Such a regularly produced single-epoch land cover map can be used to perform fine spatial-temporal resolution change detection, while integrating also other available supporting information sources. Inclusion of spatial-temporal aggregation schemes will allow integrating various spatial and temporal scales of different data sources, however, the legend of the land cover (land use) maps must be harmonized beforehand.
- Large-area time series processing, required to characterize drivers of land cover change (abiotic, biotic, and anthropogenic), will significantly benefit from synergetic use of S-2 and S-3 sensors.
- The bio-physical/-chemical variables of vegetation such as FAPAR and LAI, vegetation canopy cover, leaf chlorophyll/water/dry matter content, and other characteristics describing the canopy structure (e.g., foliage clumping and leaf angle distribution function) should be retrieved jointly using the physically based inversion routines whenever feasible. An evolutionary prototyping approach should be included in their operational retrieval.
- Calibration/validation (CAL/VAL) and quantification of per-pixel measurement accuracy and uncertainty is very important for science applications. Both on-board and external calibration is required throughout full mission lifetime. CAL/VAL of Sentinel observations and products should be performed using the standardized protocols and the dedicated sites within a fully funded operational context.
- The use of both continuous fields and discrete classification approach will promote the interoperability of Sentinel global land products with the existing scientific models and decision support systems.

- Sentinel optical and radar data should be fused and complemented by regional estimates of the ESA Earth Explorers (e.g., SMOS or BIOMASS) to produce systematic and accurate maps of variables important for modelling the global cycles (e.g., map of soil moisture for water cycle or vegetation biomass for carbon cycle).
- Coupling the processes of carbon, water, and atmosphere cycles within the multi-process modelling environments requires consistent and thematically detailed description of vegetation, but also information about surface moisture and soil conditions. Frequent and regular Sentinel observations are capable of establishing standardised episodic remote sensing observations and sparse in-situ sampling of these parameters.
- The S-1 C-band SAR in a constellation with other radar missions can be used for rapid mapping of unexpected flood events. It will also be able to facilitate long-term monitoring studies of inland water bodies, but only processed systematically with previous heritage SAR datasets.
- Mapping soil properties using the Sentinels active and passive instruments need to be further investigated.

Also the solid Earth expert group at the SEN4SCI workshop raised the following specific *recommendations* about the scientific exploitation of the first three Sentinels in solid Earth research:

- The S-1 C-band SAR is particularly suited for surface motion measurements. The value of the mission is increased by the use of one consistent main mode: Interferometric Wide Swath (IWS) that reduces mode-conflicts over a given site.
- The S-1 SAR will be able to meet a strain mapping requirement of very long time series However, to reach this goal the S-1 observations need: i) to acquire data during both Ascending and Descending orbits (as long as mission capabilities allows), ii) to improve revisit time for many areas, and iii) to be complemented by the verification of calibration stability over time using corner reflector networks.
- The repeat cycle of 12 days for one S-1 satellite may not be sufficient for capturing very dynamic Earth processes (e.g. landslides or earthquakes). Specific approaches would be required to include scientific investigations of these phenomenona into the SAR tasking plan (e.g. to invoke a strip mapping mode).
- The representatives of the solid Earth community prefer to be provided with raw data and tools for Sentinel data processing rather than products. Fast, open (free) and prioritized access to the data archives of lower processing levels (priority in downlink of L0 data) and availability of standardized toolboxes allows versioning control and fast reprocessing of historical data at local nodes.

Finally, the SEN4SCI workshop land and solid Earth scientist community jointly agreed on the following *technical requirements* regarding the future Sentinel 1-2-3 missions:

- Ground segment should support mechanisms allowing systematic processing of data in a fast and robust fashion (local L0/L1 data processing in a distributed system). On the other hand, the ground segment may consider supporting advanced data processing such as access to direct radiance assimilation, ensemble modelling and direct inversion approaches.
- Data access needs to support large data volume across sensors access by science users. It should allow bidirectional interoperability in data manipulation between the ground segment and users whenever possible.

- Mechanisms should be in place to incorporate updated algorithms within core data processing, allowing version controlling, and product reproducibility and traceability.

2.7. Selection of land and solid Earth variables as Sentinel product examples

In total thirteen land variables and three solid Earth variables were ranked as of high scientific priority in Table 2.5 and Table 2.6. The research community at the SEN4SCI Workshop expressed the importance of all these variables to obtain comprehensive information on land and solid Earth processes. Need to limit the number of variables resulted in only three variables that were selected as examples for further development of their processing chains using the Sentinel 1-2-3 observations as the inputs, and for outlining their potential validation schemes. The main criterions applied for selecting these variables as the important Sentinel scientific products were: i) serving a wide scientific community, ii) possibility to develop an innovative processing method based on technical specifications of the Sentinel 1-2-3 instruments, and iii) a potential synergistic use of the data provided by any or several Sentinel 1-2-3 and Earth Explorer instruments. The following two land and one solid Earth variables were chosen based on these criterions:

I. *LAI/FPAR and Land cover/Land cover change*: both variables are of high importance mainly for various scientific modelling purposes. Although both variables will be provided by the GMES services (e.g. Geoland-2), an advanced scientific processing/validation scheme, which would take into account full exploitation of synergies between the Sentinel 1-2-3 sensors, is still missing.

II. *3-D Displacement*: one of the most important solid Earth variables that finds its use in several scientific disciplines as: seismotectonic, volcanology, research on earthquake and tsunami, surface loading, Earth tides, and many others.

These three variables are of high importance, but can obviously serve only part of the scientific community. It should be noted that also other variables listed as the ECVs, e.g. *Earth surface albedo*, *biomass*, or *active fire equivalent area*, are equally important for research and modelling of various climate-land interactions and dynamic processes.

3. Summary

The first phase of the SEN4SCI project resulted in a document draft stating scientific needs and requirements of 30 land and 17 solid Earth variables, which are observable from space. This document was based on review of 70 research international programs and projects that are reflecting the science objectives of ESA's Living Planet Programme outlined in the The Changing Earth study (ESA, 2006). The extensive review of observational requirements was followed up by the gap analysis identifying 24 land and 10 solid Earth scientific variables that can be delivered by the Sentinel 1-2-3 sensors alone or in a synergistic cooperation with other European satellite missions (i.e. Earth Explorers and MetOp missions). The public open Internet peer-review, conducted after interactive discussions of SEN4SCI workshop participating scientists, assessed 13 land and 3 solid Earth potential Sentinel products as of high priority and 9 land and 3 solid Earth products as of medium priority (6 land and solid Earth variables were not rated).

Besides discussing the domain-specific scientific issues, the experts participating at the SEN4SCI workshop postulated the following general conclusions and recommendations for a future scientific exploitation of Sentinel observations:

- Comprehensive spatial and temporal coverage, long-term overall duration, new technical capabilities of the Sentinel 1-2-3 instruments, and also potential synergistic use of Sentinel data jointly with observations of other related missions offer a unique opportunity for development of new scientific products and applications.
- Global science requires data records (satellite time series) that are of global nature, long-term (multi-decadal), and accurate (i.e., undergoing the inter-calibration and stability monitoring during the entire life of the space borne mission constellation).
- Both on-board and external calibration/validation and quantification of per-pixel measurement accuracy and uncertainty should be performed using the standardized protocols and the dedicated sites within a fully funded operational context.
- Scientific input into the development of new products, applications, and calibration/validation protocols is essential for success of all Sentinel missions, both prior to and after their launch.

The following three land and solid Earth representative variables were selected from all the reviewed requirements to demonstrate ability of Sentinel 1-2-3 to generate important science products: *leaf area index and fraction of absorbed photosynthetically active radiation, land cover and land cover change,* and *3-D (Earth) displacement*. Three external scientific experts were asked to prepare a more detailed study proposing processing chain and potential validation scheme of these satellite products, while paying a special attention to the innovative contribution and synergistic use of the Sentinel 1-2-3 missions. It is important to mention, that the selected variables are not indicating the most required satellite products by scientific community, but should be considered just as demonstrators providing the concrete examples how the GMES Sentinel 1-2-3 missions can contribute to advance the state-of-the-art Earth system science.

4. References

CEOS 2004. The Geohazards IGOS Theme: Space Component Requirements. An analysis for discussion at CEOS SIT-13.

CEOS EO Handbook, 2010. http://database.eohandbook.com/, last access: Feb. 21, 2011.

CEOS Systems Database, 2011. http://ceos-sysdb.com/CEOS/, last access: Feb. 21, 2011.

ESA, 2006. The Changing Earth – New Scientific Challenges for ESA's Living Planet Programme, European Space Agency, SP-1304, pp. 1-83.

ESA, 1999. Gravity Field and Steady-State Ocean Circulation Mission, Reports for mission selection, SP-1233(1), pp. 199-201.

GCOS, 2010. Implementation plan for the global observing system for climate in support of the UNFCCC. GCOS-138 (GOOS-184, GTOS-76, WMO-TD/No. 1523). http://www.wmo.int/pages /prog/gcos/Publications/gcos-138.pdf

GEO Geohazard Supersites Consortium, "White Paper and Implementation Plan", Draft Version 3.2, 9 April 2011.

Gross, R., Beutler, G., Plag, H-P., 2009. Integrated scientific and societal user requirements and functional specifications for the GGOS. In Global Geodetic Observing System, Meeting the requirement of a global society on a changing planet in 2020. H.-P. Plag, M. Pearlman (eds.), Global Geodetic Observing System, Springer-Verlag Berlin Heidelberg 2009. DOI: 10.1007/978-3-642-02687-4_7.

Lacaze, R., Atzberger, C., Bartholomé, E., Combal, B., Calvet, J.C., Lefèvre, V., Olsson, B., Biopar Teams, 2009. Towards an Operational GMES Land Monitoring Core Service. BioPar User Requirements. Geoland2. BP-RP-BP01, Issue 1.00, HYGEOS.

Massonnet, D., Rossi, M., Carmona, C., Adragna, F., Peltzer, G., Feigl, K., Rabaute, T., 1993. The displacement field of the Landers earthquake mapped by radar interferometry. Nature 364, pp. 138-142. DOI:10.1038/364138a0.

Small, D., 2011. Flattening Gamma: Radiometric Terrain Correction for SAR Imagery, IEEE Trans. on Geoscience and Remote Sensing, Aug. 2011, 49(8), pp. 3081-3093. DOI: 10.1109/TGRS.2011.2120616.

5. Appendices

Appendix 1: Definitions of reviewed land variables.

Variable	Definition
Earth surface albedo	Fraction of the irradiance reflected by the surface of the Earth in the range of 0.4-0.7 µm (or other specific short-wave ranges). Physical unit: [%]. The directional (black-sky) albedo (directional-hemispherical reflectance) integrates the bi-directional reflectance over viewing hemisphere assuming that all radiation is coming directly from sun. The hemispherical (white-sky) albedo (bi-hemispherical reflectance) integrates the directional reflectance over all illumination directions assuming that all radiation comes in equal amounts from the entire hemisphere.
Biomass	Total amount of vegetation in a reference area. Physical unit: m^3/ha.
Downwelling long-wave radiation at the Earth surface	Flux of long-wave (4-200 µm) thermal radiation from sun, atmosphere and clouds to the Earth's surface. Physical unit: [W/m^2].
Downwelling short-wave radiation at the Earth surface	Flux of short-wave (0.2-4 µm) radiation from sun, atmosphere and clouds to the Earth's surface. Physical unit: [W/m^2].
Downwelling solar radiation at TOA	Flux density of the solar radiation at the top of the atmosphere. Physical unit: [W/m^2].
Active fire equivalent area (burnt area)	Observed area disturbed by fire in [ha].
Active fire equivalent temperature	Observed temperature of the occurring fire. Physical unit: [K].
Fire Radiative Power (FRP)	Observed power of the occurring fire. Physical unit: [W].
Flood/Standing Water	Area of standing water created by flood in [ha].
Fraction of Photosynthetically Active Radiation (FPAR)	Fraction of incoming photosynthetically active radiation absorbed by chlorophyll of green vegetation. Physical unit: [%].
Geoid	Equipotential surface, which would coincide exactly with the mean ocean surface of the Earth, if the oceans were in equilibrium, at rest, and extended through the continents (such as with very narrow channels).
Ground water	Amount of water present beneath the ground surface per unit area.
Lake level	Map of the height of the lake surface in [cm].
Lake surface temperature	Temperature of the apparent lake surface (water surface). Physical unit: [K].
Land cover	Classification of land surface imagery by assigning identified cluster(s) within a given area to the specific classes of land surfaces.
Land cover change	Difference between land cover maps produced from land surface images of two time successive acquisitions.

Land Surface Temperature (LST)	Temperature of the apparent land surface (bare soil or vegetation or snow), as measured in the direction of the remote sensor and taking the emissivity of the surface (e.g. soil vs. foliage) into account. Physical unit: [K].
Land surface topography	Map of land surface heights. Physical unit: [m].
Leaf Area Index (LAI)	One half of the total projected green leaf fractional area in the plant canopy within a given area. Physical unit: [%].
Normalized Differential Vegetation Index (NDVI)	Difference between reflectance in near infrared and red wavelengths, normalised to their summation. Physical unit: [%].
Outgoing long-wave radiation at TOA	Flux of the terrestrial radiation in the range 4-200 µm (thermal emission) moving to Space through the top of the atmosphere. Physical unit: [W/m^2].
Outgoing short-wave radiation at TOA	Flux of the terrestrial radiation in the range 0.2-4 µm (reflected solar radiation) moving to Space through the top of the atmosphere. Physical unit: [W/m^2].
Precipitation index (daily cumulative)	Integration of precipitation rate reaching the ground over several time intervals. The reference requirement refers to integration time of 24 h.
Precipitation rate (liquid) at the surface	Rate of precipitation reaching the ground. Since accuracy changes with rate, it is necessary to specify a reference rate. Assumed rate: 5 mm/h.
River discharge	Volume of water flowing through a river per unit of time.
Soil moisture	Fractional content of water in a volume of wet soil surface layer (upper few centimetres). Physical unit: [%].
Soil type	Result of the classification of different types of soil within an area.
Vegetation type	Result of the classification of different types of vegetation within a vegetated area.
Wind speed over land surface (horizontal)	Magnitude of the horizontal component of the 3-D wind vector.
Wind vector over land surface (horizontal)	Horizontal vector component (2-D) of the 3-D wind vector, conventionally measured at 10 m height. The accuracy is meant as vector error, i.e. the magnitude of the vector difference between the observed vector and the true vector.

Appendix 2: Definitions of reviewed solid Earth variables.

Variable	**Definition**
3-D Displacements	Tectonic displacements due to the Earth's surface motion in three-dimensional space. Physical unit: [mm].
3-D Velocities	Velocity of tectonic displacements due to the Earth's surface motion in three-dimensional space. Physical unit: [mm/yr].
Crustal plates positioning	Basic for monitoring the evolution of the lithosphere dynamics. Physical unit: [cm].
Displacement rate; *Surface deformation*	Distance of the Earth's surface deformation in a given time interval. Physical unit: [cm/yr].
Earth rotation	Rotation of the solid Earth around its own axis. Physical unit: [mas/yr]. Earth's rotation period relative to the Sun is its true solar day. The average of the true solar day over an entire year is the mean solar day.

Faults	Fault is a planar fracture or discontinuity in the Earth's crust created by the tectonic forces, across which there has been significant displacement.
Fissures/ cracks/ faults opening	Horizontal distance measured across the fissures/cracks/faults opening. Physical unit: [m].
Fissures/ cracks/ faults widening	Speed with which the opening of the fissures/cracks/faults is increasing. Physical unit: [cm/day].
Geological information [classification]	Geological thematic map of the Earth surface obtained from interpretation (classification) of the remotely sensed image data.
Gravity	The natural force of attraction exerted by a celestial body, such as Earth, upon objects at or near its surface, tending to draw them toward the centre of the body. Gravity of Earth refers to the acceleration that the Earth imparts to objects on or near its surface. Physical unit: [Gal].
Levelling	Measurement of a geodetic height providing the elevation of a given point at the Earth surface with respect to the predefined Datum. Physical unit: [cm].
Local gravity	Gravity at a particular point on the surface of the Earth. Physical unit: [Gal].
Magnetic field	Field produced by moving electric charges, by electric fields that vary in time, and by the 'intrinsic' magnetic field of elementary particles associated with the spin of the particle. Earth's magnetic field is approximately a magnetic dipole, with the magnetic field South pole near the Earth's geographic north pole and the other magnetic field N pole near the Earth's geographic south pole.
Secular strain rate	Long-term (centuries) earth-strain (deformation) detected per year.
Speed of crustal motion	Speed (distance per time) of the position and height changes of the Earth's plates. Indicates the lithosphere dynamics, i.e. important for the earthquake predictions. Physical unit: [mm/yr].
Strain and strain rate	Geometrical measure of deformation representing the relative displacement between particles in a material body, i.e. a measure of how much a given displacement differs locally from a rigid-body displacement, per year in case of rate.
Total Electron Content	An important descriptive quantity for the ionosphere of the Earth describing the total number of electrons present along a path between two points, with units of electrons per square meter, where 10^{16} electrons/m² = 1 TEC unit (TECU).

6. List of Abbreviations

2-D	Two Dimensional
3-D	Three Dimensional
AATSR	Advanced Along-Track Scanning Radiometer
ADM	Atmospheric Dynamics Mission
ALADIN	Atmospheric LAser Doppler INstrument
ALOS	Advanced land observing Satellite
AMI	Active Microwave Instrument
AMMA	African Monsoon Multidisciplinary Analyses
AMSR	Advanced Microwave Scanning Radiometer
AMSU	Advanced Microwave Sounding Unit
AOPC	Atmospheric Observation Panel for Climate
AOT	Aerosol Optical Thickness
ASAR	Advanced Synthetic Aperture Radar
ASCAT	Advanced Scatterometer
ATSR	Along Track Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
BALTEX	Baltic Sea Experiment
CAL/VAL	Calibration/Validation
CCI	Climate Change Initiative
CEOS	Committee on Earth Observation Satellites
CHRIS	Compact High Resolution Imaging Spectrometer
CIRES	Cooperative Institute for Research in Environmental Sciences
CLIC	Climate and Cryosphere
CLIVAR	Climate Variability and Predictability
CoP	Community of Practice
DAAC	Distributed Active Archive Center
DEM	Digital Model of Elevation
Dev	Deliverable
DiNSAR	Differential SAR Interferometry
DMSP	Defense Meteorological Satellite Program
DORIS	Doppler Orbitography and Radio-positioning Integrated by Satellite
DUE	Data User Element
DWSS	Defense Weather Satellite System
ECVs	Essential Climate Variables
EE	Earth Explorer
EGG	European GOCE Gravity
ENV-CAN	Environment Canada
EO	Earth Observational
EORC	Earth Observation Research Center
EPS	EUMETSAT Polar System
ERS	European Remote Sensing
ESA	European Space Agency
EXP	EXPerimental product
FAIRE	Fast Access to Imagery for Rapid Exploitation

FAO	Food and Agriculture Organization
FAPAR	Fraction of Absorbed Photosynthetically Active Radiation
FRP	Fire Radiative Power
G	Goal
G-POD	Grid Processing On Demand
GCOS	Global Climate Observing System
GCP	Global Carbon Project
GEO	Group on Earth Observations
GERB	Geostationary Earth Radiation Budget
GEWEX	Global Energy and Water Cycle Experiment
GGOS	Global Geodetic Observing System
GMES	Global Monitoring for Environmental Security
GMES-Geoland2	GMES Land Monitoring Service
GNSS	Global Navigation Satellite System
GNWP	Global Numerical Weather Prediction
GOCE	Gravity field and steady-state Ocean Circulation Explorer
GOFC-GOLD	Global Observation of Forest and Land Cover Dynamics
GOOS	Global Oceanic Observing System
GRFM/GBFM	Global Rain Forest and Global Boreal Forest Mapping
GTOS	Global Terrestrial Observing System
H	High priority
HIRS	High Resolution Infrared Radiation Sounder
HR	High Resolution
HROI	High Resolution multispectral Optical Imager
HRSOI	High Resolution Stereo Optical Imager
IASI	Infrared Atmospheric Sounding Interferometer
ICSU	International Council of Scientific Unions
IGOL	Integrated Global Observations for Land
IGOS	Integrated Global Observing Strategy
InSAR	Interferometric Synthetic Aperture Radar
IOP	Inherent Optical Properties
IPCC	Intergovernmental Panel on Climate Change
IR	Infrared
IS	Infrared sounder
IWS	Interferometric Wide Swath
JAXA	Japan Aerospace Exploration Agency
JERS	Japan Earth Resources Satellite
JPSS	Joint Polar Satellite System
K&C	Kyoto & Carbon
LA	Laser Altimeter
LAI	Leaf Area Index
LIDAR	LIght Detection And Ranging
LRM	Low-Rate Mode
LROI	Low Resolution multispectral Optical Imager
LST	Land Surface Temperature
M	Medium priority
MACC	Monitoring Atmospheric Composition & Climate

Max	Maximum
MERIS	MEdium Resolution Imaging Spectrometer
Min	Minimum
MIR	Middle Infrared
MIRAS	Microwave Imaging Radiometer using Aperture Synthesis
Mod	Modus
MODIS	Moderate Resolution Imaging Spectroradiometer
MROI	Medium Resolution multispectral Optical Imager
MSI	Multi-Spectral Instrument
MWI	Imaging Microwave Radiometer
MWR	Microwave Radiometer
NA	Not Available
NACP	North American Carbon Programme
NASA	National Aeronautics and Space Administration
NDVI	Normalized Differential Vegetation Index
NESDIS	National Environmental Satellite, Data, and Information Service
NMA	No Mature algorithm or sensor Available
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NR	Not Rated
NWC-VSRF	Nowcasting and Very Short Range Forecasting
NWP	Numerical Weather Prediction
OD	Produced On Demand
OLCI	Ocean and Land Colour Imager
OOPC	Ocean Observations Panel for Climate
OP	Operational Product
PALSAR	Phased Array type L-band Synthetic Aperture Radar
PAR	Photosynthetically Active Radiation
POD	Precise Orbit Determination
PR	PRoduct generation for project
PSD	Particle Size Distribution
PSI	Persistent Scatterer Interferometry
RA	Radar Altimeter
REDD	Reducing Emissions from Deforestation and Degradation
RS	Remote Sensing
RSL	Remote Sensing Laboratories
S-1	Sentinel 1
S-2	Sentinel 2
S-3	Sentinel 3
S&IA	Seasonal and Inter-annual Forecasting
SAR	Synthetic Aperture Radar
SCAT	Scatterometer
SEN4SCI	Sentinels for Science
SG	Second Generation

SIRAL	SAR Interferometric Radar Altimeter
SLSTR	Sea and Land Surface Temperature Radiometer
SMOS	Soil Moisture and Ocean Salinity
SOLAS	Surface Ocean-Lower Atmosphere Study
SPARC	Stratospheric Processes And their Role in Climate
SRAL	SAR Radar Altimeter
SSE	Support to Science Element
SSM/I	Special Sensor Microwave Imager
SWIR	Shortwave Infrared
SynopMet	Synoptic Meteorology
T	Threshold
TACE	Tropical Atlantic Climate Experiment
TCO	Terrestrial Carbon Observation
TEC	Total Electron Content
TIR	Thermal Infrared
TOA	Top Of Atmosphere
TOPC	Terrestrial Observation Panel on Climate
TPM	Third Party Missions
UN	United Nations
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
URD	User Requirements Document
UTAS	University of Tasmania
UV	Ultraviolet
UZH	University of Zurich
VIS	Visible
WCRP	World Climate Research Programme
WGMS	World Glacier Monitoring Service
WGSF	Working Group on Surface Fluxes
WMO	World Meteorological Organization
WOAP	WCRP Observation and Assimilation Panel
WS	Wide Swath

SEN4SCI (Sentinels for Science) – Assessing Product Requirements for the Scientific Exploitation of the Sentinel Missions

Project final document:

'The science needs for cryosphere Sentinel 1-2-3 products'

For the European Space Agency edited by:
Zbyněk Malenovský (RSL-UZH/UTAS).
Approved and released by:
Michael Schaepman (RSL-UZH).
Contribution:
Helmut Rott (ENVEO), Thomas Nagler (ENVEO) and Zbyněk Malenovský (RSL-UZH/UTAS).

Abstract

The main objective of the SEN4SCI European Space Agency (ESA) project is an assessment of product requirements for the scientific exploitation of the Global Monitoring for Environmental Security (GMES) Sentinel 1-2-3 missions. The following tree complementary approaches were used to identify the Sentinel-based products that are needed to support current activities in land, solid Earth, ocean, and cryosphere research: i) an Internet search for relevant research programs and projects and their documentation review, ii) an international SEN4SCI scientific workshop devoted to the scientific potential of Sentinel 1-2-3, and iii) a public Internet discussion forum for scientific experts.

In the first approach, the intensive documentation search and literature review was carried out to find out the important cryosphere research programs and projects and to synthetize their requirements on data, products or other information obtained through satellite observations. Documentation review of several research programs and projects all over the World resulted in a document listing goal and threshold observational requirements of 45 cryospheric scientific variables deliverable from space. The following up gap analysis pointed out, which sensor aboard of the Sentinel 1-2-3 missions and other synergic satellite missions are able to provide the required products. Subsequently their tentative priority was assessed.

The first international SEN4SCI scientific workshop was organized on 22-24 March 2011 at ESA-ESRIN in Frascati (Italy). Topic of the workshop attracted more than 200 land, solid Earth, ocean, and cryosphere scientific experts, which discussed in several splinter sessions the prepared documents on scientific requirements and satellite product priorities. The workshop participants also agreed on several recommendations that would ensure a proper scientific exploitation of the Sentinel 1-2-3 missions.

The cryosphere document, up-dated by outcomes of the SEN4SCI workshop, was from July to September 2011 posted on a publicly accessible Internet forum facilitated by ESA. Several scientists took a chance to comment, discuss and improve the final version of this document. Afterwards, examples of two cryosphere scientific variables were selected for further development of their processing chains using the Sentinel 1-2-3 datasets and for outlining their potential validation scheme. Their selection was taking into account the following aspects: i) serving a wide scientific community, ii) possibility to develop innovative processing methods based on technical specifications of the Sentinel instruments, and iii) potential for the synergistic use of data provided by any or several Sentinel 1-2-3 and Earth Explorer instruments.

Table of Contents

1. Introduction

The European Space Agency (ESA) is leading a federation of 'Sentinel' Earth observation missions built within the Global Monitoring for Environmental Security (GMES) Space Component that has the objective to ensure comprehensive and sustainable supply of data from space-based observations in response to the GMES service needs. While the primary purpose of Sentinel missions is to support European operational and policy needs, their acquired data and products also have the potential to meet observation needs of research communities in advancing understanding of particular aspects of the Earth environment. To enable ESA to facilitate more complete exploitation of the scientific potential of Sentinel observations, the Sentinels for Science (SEN4SCI) project was released. SEN4SCI focuses on identifying and consolidating: i) land and solid Earth, ocean, and cryosphere science needs to which the Sentinel 1-2-3 data could usefully contribute, ii) required data and products that could enhance the scientific yield from the Sentinel 1-2-3 missions, and iii) inputs from the broader scientific community with respect to these needs and requirements.

This report provides the final results of literature review on scientific needs of the cryosphere Sentinel 1-2-3 products, which were reviewed by a broad scientific community. The science observational needs were extracted from publically available documents of research programs and projects and consolidated during the international SEN4SCI workshop (22-24 March 2011, ESA-ESRIN, Frascati, Italy). Cryosphere Sentinel 1-2-3 observational requirements were published for revision at the SEN4SCI WiKi EO portal (http://wiki.services.eoportal.org/tiki-index.php?page=Sentinel%20Wiki) during August and September 2011. All posted comments and corrections of participating scientific experts were reviewed and consolidated in this final document.

2. Cryosphere science

2.1. Main cryosphere scientific challenges

The global snow and ice masses (the cryosphere) comprise the following elements: seasonal snow cover, river and lake ice, sea ice, glaciers and ice caps, ice sheets, permafrost and seasonally frozen ground (Lemke et al., 2007). In terms of area extent and temporal variability the seasonal snow cover on land and seasonally frozen ground dominate, followed by sea ice (Table 2.1). The main ice masses are stored in the big ice sheets of Antarctica and Greenland. Most of the snow and ice masses accumulating in Antarctica are transported to floating ice shelves and finally discharged to the ocean in the form of icebergs. In Greenland mass loss due to surface melt is of the same order of magnitude as iceberg calving.

Table 2.1. Area, volume and sea level equivalent (SLE) of components of the cryosphere. For snow, sea ice and seasonally frozen ground the annual minimum and maximum are specified (Lemke et al., 2007).

Cryospheric Component	Area (10^6 km^2)	Ice Volume (10^6 km^3)	Potential Sea Level Rise (SLE) (m)[g]
Snow on land (NH)	1.9–45.2	0.0005–0.005	0.001–0.01
Sea ice	19–27	0.019–0.025	~0
Glaciers and ice caps			
Smallest estimate[a]	0.51	0.05	0.15
Largest estimate[b]	0.54	0.13	0.37
Ice shelves[c]	1.5	0.7	~0
Ice sheets	14.0	27.6	63.9
Greenland[d]	1.7	2.9	7.3
Antarctica[c]	12.3	24.7	56.6
Seasonally frozen ground (NH)[e]	5.9–48.1	0.006–0.065	~0
Permafrost (NH)[f]	22.8	0.011–0.037	0.03–0.10

Scientific challenges, pointing out the importance of satellite observation for cryosphere monitoring and research are documented in the report "The Changing Earth" on the science objectives of ESA's Living Planet Programme (ESA, 2006). The report highlights the following main challenges for cryosphere research:

- Quantify the distribution of sea-ice mass and freshwater equivalent, asses the sensitivity of sea ice to climate change, and understand thermodynamic and dynamic feedbacks to the ocean and atmosphere.
- Quantify the mass balance of grounded ice sheets, ice caps and glaciers, partition their relative contributions to global eustatic sea-level change, and understand their future sensitivity to climate change through dynamic processes.
- Understand the role of snow and glaciers in influencing the global water cycle and regional water resources, identify links to the atmosphere, and assess likely future trends.
- Quantify the influence of ice-shelves, high-latitude river run-off and land ice melt on global thermohaline circulation, and understand the sensitivity of each of these fresh-water resources to future climate change.

- Quantify current changes taking place in permafrost and frozen-ground regimes, understand their feedback to other components of the climate system, and evaluate the sensitivity to future climate forcing.

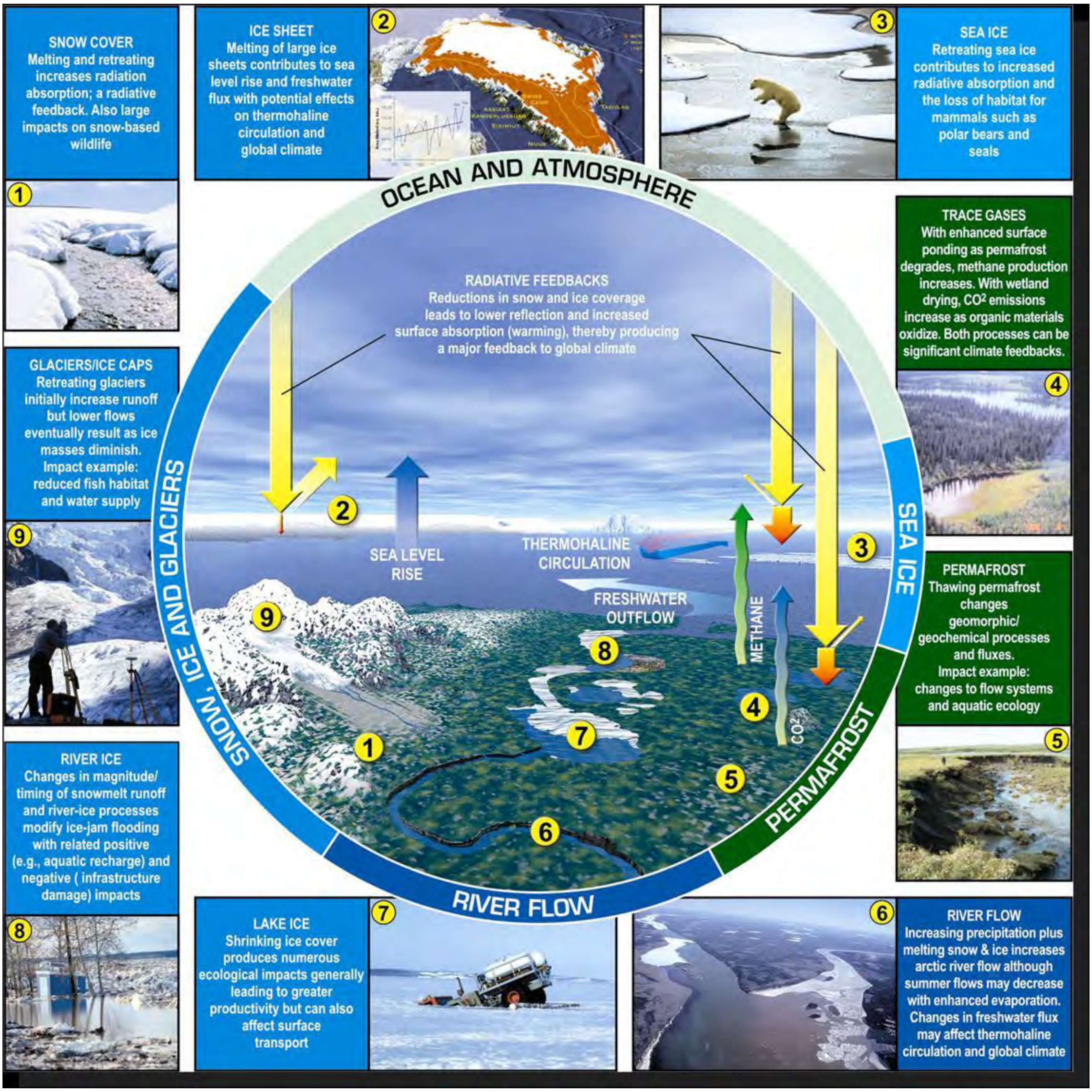

Figure 2.1. Key elements and processes of the cryosphere affected by climate change (from K. Steffen, 2010).

The importance of improved snow and ice observations for climate research and modelling, for numerical weather prediction, for water management and ecology, and for supporting the adaptation to climate change is also stressed in the IPCC Report on Climate Change (Lemke et al., 2007), in the UNEP Outlook for Global Ice and Snow (UNEP, 2007), the Arctic Climate Impact Assessment report (ACIA, 2004) and in several other reports on issues of climate and environment. These initiatives clearly point out present deficits in observations of snow and ice and the need to improve integrated observing systems based on in situ, airborne and satellite-borne observations.

An important new initiative is the Global Cryosphere Watch (GCW), aimed at serving societal needs for weather, climate and water and at supplying related environmental information and services. GCW has been proposed as a program within the World Meteorological Organization (WMO), and was approved at the World Meteorological Congress session in May 2011.

An important initiative for cryosphere research is the Climate and Cryosphere (CliC) Project. The CliC Project was established in March 2000 by the World Climate Research Programme (WCRP) to stimulate, support, and coordinate research into the processes by which the cryosphere interacts with the rest of the climate system. The Scientific Committee on Antarctic Research (SCAR) and the International Arctic Science Committee (IASC) are co-sponsors of CliC. Elements of the cryosphere and key processes that are affected by climate change are illustrated in Figure 2.1.

2.2. Cryosphere observational requirements

A basic document on observations of climate variables is the Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (United Nations Framework Convention on Climate Change) (GCOS, 2010). The most recent version is the 2010 update of this report, published in August 2010. The report was prepared under the guidance of the Global Climate Observing System (GCOS) Steering Committee, taking into account feedback from several hundred experts.

GCOS-2010 lists the following elements of the cryosphere as Essential Climate Variables (ECVs):

- *Oceanic:* sea ice.
- *Terrestrial:* snow cover, glaciers and ice caps, ice sheets, permafrost.

These variables, with exception of permafrost, are listed in Table 5 of GCOS-2010 as ECVs for which satellite observations make a significant contribution. It is stated that a detailed global climate record for the future critically depends upon an observing system involving a major satellite component. For ECV *sea ice* it is explained that the parameters sea-ice extent, concentration, thickness and drift should be measured by satellites, but without further specifications. For ECV *snow cover* the parameters area extent, snow water equivalent (SWE) and snow depth are addressed. For the ECV *glaciers* the application of satellite measurements for glacier inventories (total glacier area and outlines of individual glaciers) and surface topography are put forward, and for in situ measurements the glacier mass balance. For ECV *ice sheets* the importance of altimetry to determine the mass balance, of microwave sensors to map melt areas and of imaging radars to monitor ice velocities are mentioned as priority applications of satellites. However, the document lacks the detailed specification of observational requirements that would be needed to quantify the requirements for satellite-derived geophysical products (Level-2, Level-3).

A main international initiative for worldwide observation of glaciers is the *Global Land Ice Measurement from Space* (GLIMS) project (Bishop et al., 2004; Raup et al., 2007). GLIMS is a cooperative effort of over sixty institutions worldwide with the goal of inventorying a majority of the world's estimated >160000 glaciers. The GLIMS Glacier Database is accessible on the World Wide Web at http://nsidc.org/glims/. GLIMS lists basic glacier parameters such as glacier outlines, centrelines, snowlines, etc., to be derived from the satellite data, but does not define a quantitative list of requirements.

There are four ESA DUE (Data User Element) projects dealing with the development and delivery of data sets of satellite-derived products on the cryosphere: DUE GlobGlacier, DUE GlobSnow, DUE

GlobICE, DUE Permafrost. These projects address needs of the scientific community in cryospheric research. During the first phase of these projects requirements and specification of products were defined, based on the needs of end-users. These requirements of the scientific community, specified for these projects, are also of relevance for defining Sentinel products for science.

DUE GlobGlacier delivers the following products for selected glacier regions of the world:

(1) glacier outlines (area), (2) terminus position, (3) late summer snow / ice area and snowline, (4) surface topography, (5) surface elevation change, (6) surface velocity.

The DUE GlobGlacier project has been completed recently, and is followed up by the ESA CCI (Climate Change Initiative) Glacier project, coordinated by department of Geography, University of Zürich. Some guidelines on product requirements are provided based on input of the user groups. The processing lines and validation of products are described in detail in separate project reports.

DUE GlobSnow delivers two products on the global snow cover:

(1) snow extent, (2) snow water equivalent (SWE).

The SWE product is of very low spatial resolution (25 km) based on microwave radiometer measurements blended with in situ snow data. In the baseline requirements document (Project Deliverable 1.4) product requirements are specified which are based on the IGOS Cryosphere Theme Report (IGOS, 2007).

DUE GlobICE has the objective to define, implement and validate a sea ice information system to support the Climate and Cryosphere (CliC) project of the World Climate Research Programme (WCRP). The main production line focuses at validated products of sea ice motion, deformation and flux. These are generated using SAR data of the ESA archives, provided on a 5km grid for a 3-day averaged period and on a 50 km grid for a monthly averaged period. In addition, it is planned to deliver a combined ice deformation, thickness and open water fraction product using Envisat ASAR and radar altimeter data. In terms of sea ice products and requirements, DUE GlobICE satisfies a subset of variables specified in IGOS (2007) and listed in Table 2.2.

DUE Permafrost has the objective to define and establish a monitoring system in support of permafrost research based on satellite data. Because permafrost is a subsurface phenomenon it cannot be observed directly with satellite data. Satellite observations can supply permafrost indicators and provide input to permafrost models. In the project thermokarst lake dynamics and surface elevation changes were identified as indicators, to be observed on local scale. Regional to circumpolar monitoring requires the use of permafrost models, where relevant satellite observed parameters are land surface temperature (LST), snow extent, snow water equivalent (SWE), vegetation, and soil moisture.

The *Global Inter-agency IPY Polar Snapshot Year* (GIIPSY) *Strategy Document* addresses science objectives and requirements for polar observations (ice sheets, glaciers, sea ice) by means of satellites (GIIPSY, 2006). This document is based on input from the international scientific community focussing at needs of research projects performed in the international polar year. The document discusses the requirements to obtain spaceborne snapshots of the Polar Regions and key high latitude processes. Its main objective has been planning for satellite data acquisition and data processing in the international polar year (IPY 2007-08). Detailed technical and scientific requirements for cryosphere variables are not specified in this document.

In the *IGOS Water Cycle Report* (for which only a draft version is available) only numbers for snow cover extent (1-10 km spatial resolution, 1-3 day repeat) and SWE (10 km spatial resolution, 1-3 day repeat) are listed (IGOS-Water, 2003).

Within the *Global Terrestrial Network for Glaciers* (GNT-G), jointly run by WGMS, NSIDC, and GLIMS, in-situ and remote sensing observations of glaciers and ice caps are compiled and disseminated in standardized formats. Overviews on available standards are given in IGOS (2007) and GTOS (2009).

The only document providing detailed specifications on the observational requirements for al elements of the global cryosphere, based on broad consultation of the scientific community, is the *Cryosphere Theme Report of the Integrated Global Observing Strategy* (IGOS 2007). The document was worked out by an international team of scientists during working sessions held between 2004 and 2007 under the umbrella of WCRP, CliC, SCAR and ICSU (International Council for Science). This is a most comprehensive document on cryosphere observation requirements and systems, and consequently used as main information source for the specification of observational requirements in this section. In the IGOS Water Cycle (for which only a draft version is available) only numbers for snow cover extent (1-10 km spatial resolution, a -3 day repeat) and SWE (10 km spatial resolution, 1-3 day repeat) are listed (IGOS-Water, 2003).

The WMO Programme on cryosphere observations, the *Global Cryosphere Watch* (GCW) will be a major customer of satellite-based snow and ice products. The programme has been approved at the World Meteorological Congress in May 2011. GCW will serve societal needs for weather, climate and water and related environmental information and services.

Table 2.2. Observational requirements for cryosphere research. (For references see programmes and projects described above). (G) ~ 'Goal' value is an ideal requirement above which further improvement is not necessary (except possibly for special tasks), (T) ~ 'Threshold' value is the minimum requirement to be met to ensure that data are useful. (For definitions of listed variables see Appendix 1).

Nr	*Variable*	*Spatial Resolution*	*Temporal Repeat*	*Accuracy*	*Sensor types**	*Maturity of Satellite Technique*
Snow cover, global (climate research)						
1	Snow Cover Area	5 km(T), 1 km(G)	7 d(T), 1 d(G)	10%(T), 5%(G)	MROI	H
2	Snow water equivalent	25 km	1 d	10% (T), 7% (G)	MWI	H
3	Snow depth	25 km	1 d	10% (T), 6% (G)	MWI	H
4	Surface albedo	8 km(T), 5 km(G)	1 d	3% (T), 1% (G)	MROI	H
5	Snow melt area	5 km(T), 1 km(G)	1 d	10%(T), 5%(G)	WS-SAR, SCAT	H
Snow cover regional (water balance, hydrology)						
6	Snow cover area	1 km(T), 0.5km(G)	3 d(T), 1 d(G)	10%(T), 5%(G)	MROI, WS-SAR	H
7	Snow water equivalent	1 km(T), 0.2km(G)	7 d(T), 1 d(G)	10% (T), 7% (G)	SAR (Ku + X-band)	M
8	Snow depth	1 km(T), 0.5km(G)	3 d(T), 1 d(G)	10% (T),6% (G)	SAR (Ku + X-band)	M
9	Surface albedo	1 km(T), 0.5km(G)	3 d(T), 1 d(G)	5% (T), 2% (G)	MROI	H
10	Grain size	1 km(T), 0.5km(G)	7 d(T), 1 d(G)	0.2 m(T), 01. mm(G)	MROI	M
11	Snow liquid water content	1 km(T), 0.5 km(G)	3 d(T), 1 d(G)	2 Vol%(T), 1 Vol%(G)	SAR	M
Lake and river Ice						
12	Ice area	100 m(T), 30m(G)	3 d(T), 1 d(G)	10% (T), 5% (G)	SAR, HROI, MROI	H
13	Concentration	100 m(T), 30m(G)	3 d(T), 1 d(G)	10% (T), 5% (G)	SAR, HROI	H
14	Ice thickness	100 m(T), 30m(G)	7 d(T), 1 d(G)	5 cm(T), 2 cm(G)	in situ	NA
Permafrost and frozen ground						
15	Spatial distribution	1 km(T), 50m(G)	1 yr	2%(T), 1%(G)	in situ (&SAR + HROI)	NA (indirect

						info by satellites)
16	Active layer depth	1 km(T), 50m(G)	7 d	1 cm	in situ	NA
17	Soil freezing area	1 km(T), 0.5km(G)	7d (T), 1d (G)	2%(T), 1%(G)	SAR, SCAT	M
18	Surface temperature	1 km(T), 0.1 km (G)	1d (T), 0.5d (G)	1 K	MROI	H
Sea ice						
19	Ice extent, ice edge	10 km(T), 1 km(G)	1 d	5 km(T), 0.5 km(G)	SAR, SCAT, MWI	H
20	Ice concentration	10 km(T), 5 km(G)	7 d(T), 1 d(G)	10%(T), 5%(G)	SAR, SCAT, MWI	H
21	Ice type	15 km(T), 5 km(G)	7 d(T), 1 d(G)	10%(T), 5%(G)	SAR, MWI	M
22	Leads, polynyas	1 km2(T), 0.1 km2(G)	7 d(T), 1 d(G)	5% of lead area	SAR	H
23	Ice thickness	25 km(T), 0.5 km(G)	1 m(T), 1d(G)	0.5 m(T), 0.1 m(G)	RA, LA	H
24	Snow depth on sea ice	25 km(T), 5 km(G)	7 d(T), 1d(G)	5 km(T), 0.5 km(G)	MWI	L
25	Ice drift	25 km(T), 1 km(G)	3 d(T), 1d(G)	3 km/d(T), 1 km/d(G)	SAR	H
Mountain glaciers and ice caps						
26	Glacier area	50 m(T), 15 m(G)	5 yr(T), 1 yr(G)	3%(T), 1%(G)	HROI	H
27	Surface topography	100 m(T), 30 m(G)	5 yr(T), 1 yr(G)	5 m(T), 0.5m(G) (in z)	InSAR, HRSOI	H
28	Facies, snowline	100 m(T), 50 m(G)	1 mo(T), 10 d(G)	200 m(T), 50 m(G)	SAR, HROI	H
29	Glacier dammed lakes	50 m(T), 15 m(G)	1 mo(T), 5 d(G)	50 m(T), 15 m(G)	SAR, HROI	H
30	Ice velocity	100 m(T), 50 m(G)	1 yr(T), 6 mo(G)	5%(T), 1%(G)	InSAR & image correlation	H
31	Surface accumulation	500 m(T), 100 m(G)	1 yr(T), 1 mo(G)	10%(T), 5%(G) of annual	SAR (Ku + X-band)	M
32	Ice thickness	200 m(T), 100 m(G)	10 yr	20 m (in z)	In situ, airborne	NA
Ice sheets						
33	Ice margin	1 km (T), 25 m(G)	1 yr(T), 1 m(G)	1 km (T), 25 m(G)	WS-SAR, MROI, HROI	H
34	Grounding line	500 m (T), 100 m(G)	5 yr(T), 1 yr(G)	500 m (T), 100 m(G)	InSAR	H
35	Surface topography	1 km(T), 0.1 km(G)	1 yr	5 m (T), 1 m(G)	InSAR, RA, LA	H
36	Surface elevation change	5 km(T), 1 km(G)	5 yr(T), 1 yr(G)	10 cm/yr(T), 5 cm/yr(G)	RA, LA	H
37	Surface velocity	1 km(T), 0.1km(G)	1 yr(T), 6 m(G)	5%(T), 1%(G)	InSAR & image correlation	H
38	Snow accumulation	25 km(T), 1km(G)	1 yr(T), 6 m(G)	5% of annual(T), 1cm/yr(G)	MWI, SCAT	M
39	Surface melt extent	25 km(T), 1km(G)	1 d	1%(T) of area, 0.5%(G)	MWI, SCAT	H
40	Ice thickness	10 km(T), 1km(G)	10 yr	20 m (in z)	SAR (P-band)	M
41	Internal layer depth	10 km(T), 1km(G)	10 yr	20 m (in z)	SAR (P-band)	M
Icebergs						
42	Iceberg size	100 m(T), 10 m(G)	7 d(T), 1d(G)	30%	SAR, HROI	M
43	Iceberg position	1 km	1 d(T), 2hr(G)	1km (absolute)	SAR, HROI	H
44	Iceberg draft	100 m(T), 1 m(G)	7 d(T), 1d(G)	10 m(T), 1 m(G) (in z)	SAR, LA (large icebergs)	M
45	Iceberg drift velocity	1 km/d(T), 0.5 km/d(G)	1 d(T), 2hr(G)	10%	WS-SAR	H

	***Sensor types**
HROI	High resolution multispectral optical imager
HRSOI	High resolution optical stereo imager
InSAR	Interferometric SAR
LA	Laser altimeter
MROI	Medium resolution multispectral optical imager
MWI	Multispectral imaging microwave radiometer
RA	Radar altimeter
SAR	Synthetic aperture radar
SCAT	Scatterometer
WS-SAR	Wide swath SAR

	Maturity of RS technique and retrieval algorithm
H	Sensor and tested and retrieval algorithm available
M	Sensor planned or proposed, (preliminary) retrieval algorithm available
L	At present no suitable sensor or retrieval algorithm available
NA	At present no suitable satellite-based RS technique available

Main snow and ice variables for the various elements of the cryosphere are listed in Table 2.2. Table also specifies requirements for spatial resolution, temporal repeat interval and measurement accuracy. In addition, sensors used or potentially useful for observation of these parameters and the maturity of the remote sensing technique (in terms of sensor availability and retrieval method) is specified.

In Table 2.2 the *snow cover* requirements are separated into two classes:

- Snow cover monitoring for climate research at continental to global scale.
- Snow cover monitoring at regional scale with emphasis at applications in snow hydrology, snow process modelling and climate impact studies.

Basic *snow cover variables* for climate studies are: (1) snow cover area, (2) snow water equivalent, (3) snow depth, (4) surface albedo, (5) snow melt area. For snow process modelling grain size is also important, and for snow hydrology quantitative information on the liquid water content of melting snow. Snow area mapping using optical sensors is well established. Snow depth is closely related to SWE (snow depth x density = SWE). C-band SAR (e.g. Envisat ASAR, Radarsat) and C-band scatterometers are only sensitive to wet snow and are applied for snow mapping during the melting season, complementary to optical sensors (Nagler and Rott, 2000). The mass of snow over ground (the snow water equivalent, SWE) is an important parameter for climate research and hydrology. It can be measured at very low spatial resolution using satellite-borne microwave radiometry. The spatial resolution of presently available SWE products, such as the SWE product delivered by the ESA-DUE project GlobSnow, is 25 km. For SWE mapping at medium to high spatial resolution active sensors operating at short radar wavelengths are needed. For this purpose a Ku- and X-band SAR has been proposed for the Earth Explorer Programme of ESA (the CoReH2O mission), but this mission is still in feasibility study (Phase-A) (Rott et al, 2010). SAR backscatter in the C-band to Ku-band range is sensitive to the liquid water content in snow, but in order to quantify the wetness signal it has to be separated from other effects (surface roughness, grain size), so that dual frequency and/or fully polarimetric measurements would be needed.

Lake and river ice are important climate indicators and river ice monitoring is also important for flood hazard assessment (Brown and Duguay, 2010; Prowse et al., 2007). Ice area, concentration and thickness are main parameters, where ice thickness cannot be observed by present satellite-borne remote sensing techniques. Laser altimetry might offer a possibility in the future, but large spacing between tracks would still be a significant constraint. Optical imaging sensors and SAR are suitable for mapping ice extent and concentration. For river ice high spatial resolution sensors are required, whereas for large lakes medium resolution sensors are also suitable. In IGOS (2007) the spatial requirements for both river ice and lake ice (defined jointly) are rather demanding, whereas for large lakes the usefulness of low resolution sensors has been confirmed (Howell et al., 2009).

Permafrost refers to the layer of soil or rock at some depth beneath the surface, in which the temperature has been continuously below 0 °C for at least several years. It exists where summer warming does not reach the base of the layer of frozen ground. Decadal changes in permafrost temperatures and depth of seasonal freezing/thawing are indicators of climate change. Warming may result in an increase of active layer thickness (melting in summer) and subsequent reduction in permafrost thickness and extent. Permafrost and seasonally frozen ground also influence surface and subsurface hydrology. The main tools for permafrost monitoring and research rely at standardized in situ measurements (Smith and Brown, 2009). Long-term monitoring sites are contributing to the Global Terrestrial Network for Permafrost (GTN-P). Satellite sensors observe the immediate surface (optical sensors) or are able to penetrate only through a shallow top layer of soil if frozen (SAR). Therefore, satellite sensors deliver only data that can be used as indicators of permafrost supporting the mapping of permafrost extent or used as input to models of permafrost processes. Relevant observables are surface temperature, land cover type, snow cover properties and time series, soil moisture, soil freezing and melting state, surface water area, spatially detailed surface topography, and surface erosion. The mapping of permafrost extent benefits from the availability of such parameters, but requires also in situ observations. Active layer depth, a main permafrost parameter, can only be determined in situ. The freezing state of soil can be mapped by means of change detection applying active microwave techniques, where SAR provides high spatial resolution. Microwave radiometer and scatterometer measurements are also sensitive to the freezing state of soil, but the low spatial resolution is significant drawback for permafrost applications requiring spatially detailed information.

Sea ice is a component of the cryosphere, which is subject to rapid temporal and spatial variations due to continuous exchange with the ocean and the atmosphere. For large-scale studies of sea ice dynamics and thermodynamics at basin-scale medium to low spatial resolution on ice extent, ice type, concentration, thickness, motion and surface melt are important. Satellite observations at medium to low spatial resolution are applied to obtain complete coverage at short repeat intervals (Sandven and Johannessen, 2006). For ice thickness estimates satellite altimeters are used, measuring the freeboard of ice floes (Giles at al., 2008, Alexandrow et al., 2010). For regional and local studies of sea ice formation, energy budgets and ice/ocean/atmosphere interactions high resolution sensors (in particular SAR) are needed to resolve size and properties of polynyas and leads.

The observations for *glaciers and ice caps* listed in Table 2.2 include the variables delivered as GlobGlacier products, namely: glacier outlines (area), late summer snow / ice area and snowline (which are interrelated), surface topography (including its temporal change), surface velocity. Glacier terminus position (treated as separate parameter in GlobGlacier) is a subset of glacier outlines, although it might be of interest to map the glacier terminus for certain glacier types (e.g. calving glaciers) more frequently than glacier inventories. High resolution optical satellite sensors are the main tool for mapping glacier outlines over large regions world-wide, whereas SAR is preferably used for mapping the front of calving glacier because of frequent repeat observations.

Surface elevation change is a separate product of GlobGlacier. In Table 2.2 (in accordance with IGOS,

2007) it is not separated from surface topography. A main objective for measuring surface elevation change is the measurement of glacier mass balance (mass changes) using the geodetic technique. High accuracy in measurements of elevation change (0.5 m to 1 m) in annual or multi-annual intervals is required for this purpose. The threshold requirement for vertical accuracy refers to base maps, as for example employed in models of glacier mass balance and dynamics. High resolution optical satellite sensors are the main tool for mapping glacier outlines over large regions world-wide. For mapping glacier surface topography from space, high resolution optical sensors and SAR interferometry (InSAR) are applied, supported by laser altimetry over the ground tracks of this sensor. Another important parameter for studies of glacier mass balance and surface/atmosphere exchange processes is the extent of the diagenetic glacier facies (glacier ice, wet snow, percolation, and dry snow zone), where SAR is the optimum data source.

For ice motion mapping repeat pass InSAR offers excellent capabilities if the repeat observation interval is short enough to preserve coherence. As an alternative, correlation of incoherent amplitude images can be applied if distinct surface features are available (Rott, 2010). For mapping surface accumulation on glaciers, a main parameter for modelling glacier/climate interactions, the feasibility of a similar technique as for mapping SWE on ice-free land surfaces is presently studied in Phase-A of the CoReH2O mission. Ice thickness measurements require a ground penetrating radar operating at P-band or lower frequencies. The feasibility of a satellite ice-sounding radar system on mountain glaciers is questionable because the signals reflected from the bedrock may be disturbed by returns from slopes and the signal penetration is reduced in ice near the melting point.

The term *ice sheets* refers to the two continental-scale ice bodies of body of ice Greenland and Antarctica. Smaller ice bodies with multiple outlet glaciers are called ice caps and are grouped in Table 2.2. in one category with glaciers (following IGOS, 2007). The snow and ice masses, accumulating in the central parts of the ice sheets, are transported from the inland ice to coast via fast flowing ice streams and outlet glaciers. In Antarctica the main part of mass transport from grounded inland ice to the coast is routed through floating ice shelves which can be up to 1000 m thick. At the front of the ice shelves the ice masses are discharged to the ocean through the process of iceberg calving (Figure 1). In Greenland most of the large glaciers and ice streams are calving directly into the ocean. Whereas surface plays only a small role in the mass balance of Antarctica, the mass deficit due to surface melt is in Greenland of similar magnitude as the mass export through calving (Bougamont and Bamber, 2005).

Satellite observations are the main information source for several basic ice sheet parameters. The ice margins are surveyed by various types of imaging sensors. As for glaciers, measurements of surface topography are serving two different objectives: (i) base maps for various modelling purposes, (ii) mass balance measurements. For the second task very precise measurements of elevation change are required, as delivered by satellite altimetry (Wingham et al., 2006).

2.3. Present and future European satellite missions for cryosphere science

In this section the potential of the following European satellite missions for observation of cryosphere variable is reviewed: the Sentinel missions, Earth Explorer missions, MetOp (present and upcoming MetOp Second Generation, SG). The Sentinel missions provide the basis for the GMES programme and are very interesting for climate research applications, which require long-term continuity of observations. The Earth Explorers are Earth-science missions, focusing at specific scientific problems driven by need of the scientific community. As Earth Explorers are single missions, synergy and integration of these measurements with long-term data sets provided by satellite series such as the Sentinels, MetOp and Meteosat are important for climate research applications.

Sentinel-1 is a C-band imaging radar mission consisting of two satellites after full deployment, providing consistent reliable operations and quick data delivery with global coverage (Attema et al., 2007). The first Sentinel-1 satellite is scheduled for launch in late 2013. Services based on Sentinel-1 within GMES will include the monitoring of Arctic sea-ice extent and concentration, surveillance of the marine environment including oil-spill monitoring, ship detection for maritime security, and various land applications.

The Sentinel-2 polar-orbiting satellites will provide systematic global acquisitions of high-resolution multi-spectral imagery with a high revisit frequency (Martimort et al., 2007). This mission is tailored towards the needs of operational land monitoring and emergency services, but has also excellent capabilities for mapping and monitoring snow and ice at regional scale.

Sentinel-3 is a mission addressing primarily services related to the marine environment, but has also significant capabilities for land-, atmosphere- and cryosphere-related applications (Aguirre et al. 2007). After full deployment the two operational Sentinel-3 satellites, the mission will provide global coverage in 2 days from a high-inclination sun-synchronous polar orbit. Sentinel-3 will carry an altimetry system, an ocean and land colour instrument (OLCI, MERIS follow-on) and a VIS-NIR-thermal IR dual view sensor (SLSTR, AATSR follow-on).

MetOp Second Generation (MetOp-SG) is a program addressing the need to continue EPS in the areas of operational meteorology, climate monitoring and detection of global climatic changes. Post-EPS will provide space observations at global scale and at medium to high spatial resolution starting in 2018 and for at least 15 years. High level objectives of the Post-EPS program:

1. To support operational meteorology, continuing and enhancing the core relevant services provided by EPS, focusing on advanced sounding capability in the mid-morning orbit in accordance with user needs and priorities, taking into account WMO requirements.
2. To provide operational services in support of climate monitoring and detection of global climate change in the frame of relevant international initiatives, through cooperation and partnership.
3. To develop new environmental services covering the oceans, atmosphere, land and biosphere, and natural disasters to the extent that they are driven by meteorology and climate.

Taking into account point 2 of the high level objectives of the EPS programme, the capabilities of the MetOp satellites are also taken into account in this section of the report, complementary to the Sentinels and Earth Explorer missions.

In Table 2.3 the principal feasibility for a given sensor and mission to observe a certain snow and ice variable is indicated. The sensor may not be able to fully serve the observational requirements (e.g. in temporal or spatial resolution), because the sensors have not necessarily been optimized for cryosphere observations. The assessment of the capabilities of these satellite missions and sensors is to a large part based on development of processing techniques and scientific applications for previous and current ESA missions (in particular ERS-1, ERS-2, Envisat), as well as on experience with third party missions.

Sensors suitable for observations of snow and ice variables will be on board of Sentinel-1 (S-1), Sentinel-2 (S-2) and Sentinel-3 (S-3). There is one Earth Explorer mission in operation (CryoSat-2), which is dedicated to observation of the cryosphere with the SAR/Interferometric Radar Altimeter (SIRAL) as primary payload (Francis, 2010). SIRAL has extended capabilities to meet the measurement requirements for ice-sheet elevation and sea-ice freeboard. For CryoSat-2 the scheduled minimum mission duration is 3 years. As climate research requires observations over longer periods, the Sentinel-3 Ku/C Radar Altimeter (SRAL) is an excellent candidate for carrying on the measurements over ice sheets and sea ice. CoReH2O is another Earth Explorer mission dedicated to snow and ice observations, with the main objective of spatially detailed measurements of snow accumulation using a dual frequency SAR (Rott et al., 2010). CoReH2O is presently Phase-A, together with two other candidate Earth Explorer missions. One of the three missions will be selected for implementation after completion of Phase-A in 2012.

With the present MetOp system the imaging radiometer AVHRR and the C-band Scatterometer ASCAT are of interest for snow and ice observations. AVHRR would address similar snow and ice variables as SLSTR and OLCI on S-3, but the spectral capabilities and spatial resolution of the SLSTR- OLCI combination (or SLSTR as single sensor) should be more interesting. The microwave imaging radiometer on the upcoming MetOp-SG satellites will be very interesting for daily observations of seasonal snow, sea ice and land ice at low spatial resolution.

Table 2.3. Observational capabilities of Sentinel, Earth Explorer and MetOp satellite missions for cryosphere research.

Nr	*Variable*	*Sensor types**	*Sentinel mission / sensor*	*Earth Explorer*	*MetOp (SG)*
Snow cover, global (climate research)					
1	Snow cover area	MROI	S-3 SLSTR, OLCI		AVHRR
2	Snow water equivalent	MWI	NS		SG-MWI
3	Snow depth	MWI	NS		SG-MWI
4	Surface albedo	MROI	S-3 SLSTR, OLCI		AVHRR
5	Snow melt area	WS-SAR, SCAT	S-1 SAR		ASCAT
Snow cover regional (water balance, hydrology)					
6	Snow cover area	MROI	S-3 SLSTR, OLCI		AVHRR
7	Snow water equivalent	SAR (Ku + X-band)		CoReH2O (Phase-A)	
8	Snow depth	SAR (Ku + X-band)		CoReH2O (Phase-A)	
9	Surface albedo	MROI	S-3 SLSTR, OLCI		AVHRR
10	Grain size	MROI	S-3 SLSTR, OLCI		AVHRR
11	Snow melt area	SAR	S-1 SAR		
Lake and river ice					
12	Ice area	SAR, HROI, MROI	S-1 SAR, S-2 MSI, S3-OLCI, SLSTR		
13	Concentration	SAR, HROI	S-1 SAR, S-2 MSI		
14	Ice thickness	in situ	NA		
Permafrost and frozen ground					
15	Spatial distribution	in situ (&SAR + HROI)	(S-1 SAR, S-2 MSI)		
16	Active layer depth	in situ	NA		
17	Soil freezing area	SAR, SCAT	S-1 SAR		ASCAT
18	Surface temperature	MROI	S-3 SLSTR		
Sea ice					
19	Ice extent, ice edge	SAR, SCAT, MWI	S-1 SAR		ASCAT, SG-MWI
20	Ice concentration	SAR, SCAT, MWI	S-1 SAR		ASCAT, SG-MWI
21	Ice type	SAR, MWI	S-1 SAR		SG-MWI
22	Leads, polynyas	SAR	S-1 SAR		
23	Ice thickness	RA, LA	S-3 SRAL	CryoSat SIRAL	
24	Snow depth on sea ice	MWI	NS		SG-MWI
25	Ice drift	SAR	S-1 SAR		
Mountain glaciers and ice caps					
26	Glacier area	HROI	S-2 MSI		

27	Surface topography	InSAR, HRSOI	S-1 SAR, (S-3 SRAL)	(CryoSat SIRAL)	
28	Facies, snowline	SAR, HROI	S-1 SAR, S-2 MSI		
29	Glacier dammed lakes	SAR, HROI	S-1 SAR, S-2 MSI		
30	Ice velocity	SAR, InSAR	S-1 SAR		
31	Surface accumulation	SAR (Ku + X-band)		CoReH2O (Phase-A)	
32	Ice thickness	In situ, airborne	NA		
Ice sheets					
33	Ice margin	WS-SAR, MROI, HROI	S-1 SAR, S-3 OLCI, SLSTR		AVHRR
34	Grounding line	InSAR	S-1 SAR		
35	Surface topography	InSAR, RA, LA	S-3 SRAL, S-1 SAR	CryoSat SIRAL	
36	Surface elevation change	RA, LA	S-3 SRAL	CryoSat SIRAL	
37	Surface velocity	SAR, InSAR	S-1 SAR		
38	Snow accumulation	MWI, SCAT	NS		ASCAT, SG-MWI
39	Surface melt extent	MWI, SCAT, WS-SAR	S-1 SAR		ASCAT, SG-MWI
40	Ice thickness	SAR (P-band ice sounder)	NS		
41	Internal layer depth	SAR (P-band ice sounder)	NS		
42	Mass change at low spatial resolution	gravimetry		GOCE+GRACE	
Icebergs					
43	Iceberg size	SAR, HROI	S-1 SAR, S-2 MSI		
44	Iceberg position	SAR, HROI	S-1 SAR, S-2 MSI		
45	Iceberg draft	SAR, LA (large icebergs)	S-1 SAR, S-3 SRAL	CryoSat SIRAL	
46	Iceberg drift velocity	WS-SAR	S-1 SAR		

	***Sensor types**
HROI	High resolution multispectral optical imager
HRSOI	High resolution optical stereo imager
InSAR	Interferometric SAR
LA	Laser altimeter
MROI	Medium resolution multispectral optical imager
MWI	Multispectral imaging microwave radiometer
RA	Radar altimeter
SAR	Synthetic aperture radar
SCAT	Scatterometer
WS-SAR	Wide swath SAR
SG-MWI	MWI planned for EPS second generation
NS	No sensor on Sentinel
NA	At present no suitable satellite-based RS technique available

Further background information on the observational capabilities of the sensors listed in Table 2.3 is presented below.

Snow cover: Multi-spectral capabilities, including visible, short-wave IR (1.6 μm) and thermal IR (TIR) is required for snow/cloud discrimination. SLSTR operates at these wavelengths, and therefore should be the main sensor for snow mapping. OLCI offers somewhat higher spatial resolution, but does not have the spectral capability for snow/cloud discrimination. Therefore OLCI would be of interest in combination with SLSTR for the snow mapping application where higher spatial resolution is needed. Both sensors, SLSTR and OLCI, are also of interest for retrieving surface albedo and snow grain size. S-1 C-band SAR, being not sensitive to dry snow, will be used for mapping melting snow areas. The combination of SLSTR with S-1 SAR is of particular interest in boundary zones of snow areas, as S-1 SAR enables updating of SLSTR snow maps during cloudy periods. The microwave imaging radiometer on MetOp SG will enable the mapping of snow water equivalent and snow depth at low spatial resolution. There is no Sentinel sensor available for these observations.

Lake and river ice: The required spatial resolution, related to the size of a lake or river, is relevant for the choice of sensors. S-1 SAR, offering high spatial resolution and regular repeat observation capability, would be the primary sensor for mapping ice area and concentration. S-2 MSI may be used as complementary sensor where high spatial resolution is required, and S-3 SLSTR and OLCI for large lakes.

Permafrost and frozen ground: As mentioned above, satellite sensors do not enable direct observation of permafrost. Geo-morphological and land cover information, mapped by S-1 SAR and S-2 MSI can support the delineation of permafrost areas. Interferometric analysis of surface deformation and erosion by S-1 SAR is also of interest. Additional information of importance for permafrost and land surface processes is the surface temperature (delivered by S-3 SLSTR), soil moisture and the freezing state of soil, delivered by S-1 SAR at high spatial resolution and Metop ASCAT at low spatial resolution and frequent repeat interval.

Sea ice: S-1 SAR is a key sensor for sea ice observations, mapping ice extent, concentration, ice type, leads and polynyas at high spatial resolution. Scatterometers (MetOp ASCAT) and microwave radiometers (MetOp SG MWI) can be used for mapping sea ice extent, concentration and type at low spatial resolution. Measuring sea ice drift requires high spatial resolution and frequent repeat observation, which will be provided by S-1 SAR, in particular after full deployment with two satellites. CryoSat SIRAL offers an operation mode optimized for measuring sea ice freeboard. S3-SRAL will enable to extend the time series of these measurements. Satellite techniques for measuring snow depth on sea ice are still rather experimental. Multi-spectral microwave radiometers (MetOp SG MWI) show sensitivity to this parameter.

Mountain glaciers and ice caps: For observation of mountain glaciers and small ice caps high resolution sensors are required. Glacier boundaries and area are mapped with high resolution imaging sensors. S-2 MSI has excellent capabilities for this application, with VIS, NIR and SWIR spectral channels and up to 10 m spatial resolution. This sensor, as well as S-1 SAR, is very useful for monitoring snow and ice areas (and snowline) on glaciers, and mapping glacier lakes. For surface topography InSAR (S-1 SAR) can be applied, although the temporal decorrelation may cause problems. CryoSat SIRAL and S-3 SRAL do not provide the required spatial density of measurements, but should be of interest for validating and improving InSAR elevation products.

Ice sheets: For ice sheet observations several of the Sentinel sensors are very useful. For mapping the ice margin S-1SAR and S-3 OLCI or SLSTR would be the primary sensors. CryoSat SIRAL and S-3 SRAL provide excellent vertical accuracy for measuring surface elevation and elevation change. In boundary zone of ice sheets and mountain ranges inland higher spatial resolution is required for topographic measurement, as provided by S-1 InSAR. For measuring surface velocity, S-3 SAR repeat pass images can be employed either in interferometric mode, or on fast-flowing ice streams using template matching in incoherent amplitude images. The position of the grounding line can be well detected by S-1 InSAR. For mapping snow accumulation and the extent of surface melt areas, low resolution active and passive microwave sensors (MetOp ASCAT and SG MWI) show good capabilities, where single sensor or dual sensor (active/passive) retrieval methods can be applied. S-1 SAR can also be applied for mapping melt extent, but for most applications frequent repeat observation is more important than high spatial resolution. For ice thickness sounding a special P-band sounder is required to penetrate ice up to 4800 m thickness and to achieve the required vertical resolutions (different technical requirements than for a biomass P-band SAR).

Icebergs: For detecting and mapping small to medium sized icebergs high resolution sensors (S-1 SAR, S-2 MSI) are required. With these sensors accurate detection of the position is also possible, and measurement of iceberg drift if time sequences are available. Iceberg draft can be estimated from high resolution SAR data (S-1 SAR) if steep boundaries are available. For large (tabular) icebergs CryoSat SIRAL and S-3 SRAL can be applied.

2.4. Capabilities and cryosphere products of selected third party satellite missions

In this section snow and ice delivered by selected third party missions are summarized (Table 2.4). The focus is at systems and products that are widely used by the international scientific community. The focus is on current sensors. In addition, one important sensor that recently failed (QuikScat) and one future sensor (ICESat-2) due to be launched in 2015 are included. The concept for a QuikScat follow on mission is still under investigation. The current Indian Oceansat-2 has a Ku-Band-Scatterometer of similar type as QuikScat on board, but with lower spatial resolution.

Previously, it was planned to replace some of the current sensors, (MODIS and SSM/I) widely used for cyrospheric research, by similar sensors on the U.S. National Polar-orbiting Operational Environmental Satellite System (NPOESS) program. NPOESS was cancelled in February 2010, split into two separate lines of polar-orbiting satellites, JPSS (Joint Polar Satellite System) of NOAA and NASA, and the Defense Weather Satellite System (DWSS). A microwave radiometer similar to SSM/I will probably be accommodated on DWSS.

A major player in producing global snow and ice data sets from satellite observations and performing cryospheric research is the National Snow and Ice Data Center (NSIDC), being part of the Cooperative Institute for Research in Environmental Sciences (CIRES) at the University of Colorado at Boulder. NASA supports the NSIDC Distributed Active Archive Center (DAAC) and funds the production and distribution of remote-sensing data sets. Also NOAA supports the management of cryospheric data at NSIDC. There are as well institutions in various other countries active in processing and distributing snow and ice data sets for research and applications, but most of this work is done at project level without guarantee for long-term continuity.

Table 2.4. Cryosphere products delivered by selected current and future Third Party Missions (TPM).

Nr	*Variable*	*Mission / sensor*	*Product*	*Supplier*	*Product status*
Snow cover, global (climate research)					
1	Snow Cover Area	NOAA AVHRR, Terra-MODIS	Snow map, global	NOAA, NSIDC	OP
2	Snow water equivalent	DMSP-SSM/I, Aqua-AMSR	SWE map, global	NSIDC, GlobSnow	OP, PR
3	Snow depth	DMSP-SSM/I, Aqua-AMSR	global	NSIDC	OP
4	Surface albedo	Terra-MODIS	Global surface albedo map	NASA	PR
5	Snow melt area	DMSP-SSM/I, Aqua-AMSR, Q-Scat	Maps of snowmelt area	science projects	PR

Snow cover regional (water balance, hydrology, etc.)					
6	Snow cover area	Terra-MODIS	Snow map	various	OP
7	Snow water equivalent	DMSP-SSM/I, Aqua-AMSR	SWE map, regional	ENV-CAN, and others	OP
8	Snow depth	DMSP-SSM/I, Aqua-AMSR	regional	ENV-CAN, and others	OP
9	Surface albedo	Terra-MODIS	TOA albedo standard, surface albedo exper.	science projects	PR
10	Grain size	Terra-MODIS	Maps of grain size	science projects	PR
11	Snow liquid water content	Radarsat		science projects	EXP
Lake and river Ice					
12	Ice area	Radarsat, TerraSAR-X, COSMO		science and application projects	OD
13	Concentration	Radarsat, TerraSAR-X, COSMO		science projects	PR
Permafrost and frozen ground					
15	Spatial distribution	Radarsat, TerraSAR-X		science projects	NMA
17	Soil freezing area	DMSP-SSM/I, Aqua-AMSR		science projects	EXP
18	Surface temperature	MODIS	Land surface T	NASA	OP
Sea ice					
19	Ice extent, ice edge	SSM/I, MODIS	Weekly, daily	NSIDC	OP
20A	Ice concentration	SSM/I, AMSR	Sea ice concentration	NSIDC	OP
20B	Ice concentration	SSM/I, AMSR	Sea ice concentration	Univ. Bremen	PR
21	Ice type	ALOS PALSAR	Map of ice type	science projects	EXP
22	Leads, polynyas	Radarsat	Maps of polynyas	science projects	PR
23	Ice thickness	ICESat-2	Freeboard	NASA	Launch 2015
24	Snow depth on sea ice	AMSR-E	Feasibility study	science project	EXP
25	Ice drift	SSM/I, AVHRR,	daily motion vectors	NSIDC, GlobICE	PR
Mountain glaciers and ice caps					
26	Glacier area, outline	HROI (Landsat, ASTER, etc.)	Maps of glacier area	GLIMS, GlobGlacie, CCI-glaciersr	PR
27	Surface topography	HRSOI (Pleiades), SPOT-5, TanDEM-X, COSMO-SkyMed	Maps of surface topography	science projects	PR
28	Facies, snowline	HROI (Landsat, ASTER, etc.); Radarsat	Maps of facies extent	science projects	PR
29	Glacier dammed lakes	Radarsat, TerraSAR-X, COSMO-SkyMed	Map of lakes	science projects	PR
30	Ice velocity	Radarsat-2, TerraSAR-X, HROI, COSMO-SkyMed	Maps of glacier velocity	science projects, GlobGlacier, CCI-glaciers	PR
Ice sheets					
33	Ice margin	MODIS	Image map of ice sheets	NSIDC	PR
34	Grounding line	RadarSat-2	Regional maps of grounding line	science projects	PR
35	Surface topography	ICESat-2		NASA	launch

					2015
36	Surface elevation change	ICESat-2		NASA	launch 2015
37	Surface velocity	RadarSat-2, TerraSAR-X, COSMO-SkyMed	Regional maps of surface velocity	science projects	PR
38	Snow accumulation	SSM/I, AMSR & follow-on	Map of surface accumulation	science projects	EXP
39	Surface melt extent	SSM/I, AMSR, QuikScat follow-on	Extent of melt areas	NSIDC	OP
Icebergs					
42	Iceberg size	RadarSat-2, MODIS	Case studies	science projects	PR
43	Iceberg position	RadarSat-2	Case studies	science projects	PR
44	Iceberg draft	ICESat	Case studies	science projects	EXP
45	Iceberg drift velocity	RadarSat-2; QuikScat	Case studies	science projects	PR

	Supplier
ENV-CAN	Environment Canada
NOAA	National Oceanic and Atmospheric Administration
NSIDC	National Snow and Ice Data Center, Boulder, Colorado

	Product status
NMA	No mature algorithm or sensor available
OD	Produced on demand of customers
OP	Operational product
EXP	Experimental product
PR	Product generation for project (e.g. DUE, etc.)
NA	At present no suitable satellite-based RS technique available

2.5. Proposed priorities for satellite products on cryospheric variables

A list of products on cryospheric variables to be derived from Sentinels and associated satellite missions has been worked out at the SEN4SCI scientific workshop, based on the presentations and discussions in the splinter meeting on cryosphere. The list of products, presented in Table 2.5 is identical to the list presented in the final plenary session of the SEN4SCI scientific workshop.

The discussion and definition of the products at the workshop started from a preliminary list of potential products on cryospheric variables, to be derived from Sentinels and associated satellite missions, which was elaborated in preparation for the workshop. These preparatory activities took into account the following aspects, which were also relevant for the workshop:

- Scientific importance: to match the requirements for ECVs and other key variables (specified by WCRP and IGOS) and to meet the scientific challenges of ESAs Living Planet Programme (ESA, 2006).
- Exploit the potential of the Sentinel missions, complemented by other ESA missions and third party missions.
- Feasibility and maturity to generate homogeneous, accurate and thoroughly validated geophysical (Level-2, Level-3) products matching the requirements of the scientific community in terms of accuracy and data continuity.

The list of products on cryospheric variables in Table 2.5, to be derived from Sentinels and associated missions, takes into account the priorities of the scientific community represented at the workshop. The following priority rating was proposed for applications cryospheric science. *H-1, H-2*: two levels of top priority with slightly different weight; *M* – medium priority. Most of the products are also of interest for environmental monitoring and management, so that the product would serve dual needs.

Table 2.5. List of potential products on cryospheric variables from Sentinels, Earth Explorers and MetOp missions, auxiliary data required, based on input and discussion from the SEN4SCI scientific workshop. '*Global*' refers to all regions of snow and ice cover, varying with the season. Priority rating for applications cryospheric science: *H-1, H-2*: two levels of top priority; *M* – medium priority.

Nr	*Variable*	*Product specs (for specified sensor)*	*Mission/Sensor*	*Auxiliary data / Synergy*	*Priority*
Cryosphere Element: All					
A-1	Spectral surface albedo	Global, 0.5 -1 km, daily, weekly	S-3 SLSTR, OLCI	Atmospheric correction, Land cover	H-1
A-2	Surface temperature	Global, 0.5 -1 km, daily, weekly	S-3 SLSTR	Atmospheric correction, Land cover	H-1
Comments from SEN4SCI scientific workshop: • Establish/ maintain dedicated CAL/VAL sites for measurements of physical snow parameters • Short repeat (daily product) required for process studies. • Joint product with Land & Ocean Themes					
Cryosphere Element: Snow Cover					
SN-1	Snow Cover Area, including fractional	Global, 1 km daily, weekly	S-3 SLSTR, OLCI	Land cover	H-1
SN-2	Snow Cover Area Regional	Regional, 0.1– 0.5 km daily, weekly	S-3 SLSTR, OLCI	Land cover	H-1
SN-3	Snow water equivalent (SWE)	Global, daily, 10-25 km grid	MetOp SG MWI	Land cover, in situ snow data	H-1
SN-4	Snowmelt area	Regional, 100 m, 1 to 5 days	S-1 SAR	Land cover, DEM	H-1
SN-5	Snowmelt liquid water content	Regional, 100 m, 1 to 5 days	S-1 SAR dual pol.	Land cover, DEM	H-2 experim.
SN-6	Snow grain size	Global, regional, 0.1-1 km, weekly	S-3 SLSTR, OLCI, S-2	Atmospheric correction, Land cover	M
SN-7	Snow pollution content	Global, regional, 0.1-1 km, weekly	S-3 SLSTR, OLCI, S-2	Atmospheric correction, in situ cal/val	M experim.
Comments from SEN4SCI scientific workshop: • Establish/ maintain dedicated CAL/VAL sites for measurements of physical snow parameters • Synergy of optical (S-3)/SAR (S-1) particularly important for snowmelt period • High resolution SWE products important for snow hydrology, snow processes study. Presently there is now sensor available. This gaps is addressed by CoReH2O (Candidate Earth Explorer mission).					

• S-1 Combination of ascending and descending SAR images required in mountain areas					
Cryosphere Element: Lake and River Ice					
LR-1	Lake ice area and ice concentration	Global, 0.1 - 1 km daily, weekly	S-1 SAR, (S-3 SLSTR, OLCI)	Water bodies	H-1
LR-2	Snow on lake ice	Global, 0.1 - 1 km daily, weekly	S-1 SAR & SRAL	Algorithm tbd	M experimental
Cryosphere Element: Permafrost and Frozen Soil					
PF-1	Frozen soil area (incl. freeze/thaw)	N-hemisphere	MetOp-ASCAT S-1 SAR, MWI	Land cover	H-2
PF-2	Snow and soil surface temperature	Global, 1km, weekly	S-3 SLSTR, MetOp AVHRR	Atmospheric correction	H-1
PF-3	Lake extent	≤ 50 m, daily to weekly	S-1 SAR, S-2	High spatial res. needed	H-1
PF-4	Surface deformation	InSAR repeat pass, 6-12 d, seasonal	S-1 SAR	Synergy with L-band SAR	H-2 experim.
Comments from SEN4SCI scientific workshop: • Combination with in situ data important; regular long-term repeat needed • Additional satellite products for permafrost models: Snow (depth, snow water equivalent), vegetation type and biomass, surface albedo, soil parameters (type, moisture, etc.)					
Cryosphere Element: Sea Ice					
SI-1	Sea ice extent	Arctic, Antarctic, 1 km, 1-3d	S-1 WS-SAR, MetOp-ASCAT		H-1
SI-2	Sea ice concentration	Arctic, Antarctic, 10 km raster, 1-5 d	S-1 WS-SAR, MetOp-ASCAT		H-1
SI-3	Sea ice type	Arctic, 1-10 km raster, 5-10d	S-1 WS-SAR, MetOp-ASCAT	Synergy with L-band SAR	H-2
SI-4	Leads, polynyas	Arctic, Antarctic; key regions, 1-3d	S-1 SAR, S-2		H-2
SI-5	Sea ice thickness	Arctic, Antarctic, 1mo	S-3 SRAL, CryoSat, ICESat-2	Snow depth on sea ice, synergy with L-band radiometry (experim.)	H-2
SI-6	Sea ice drift	Arctic, Antarctic; key regions, 1-3d	S-1 extended WS-SAR	Utilize also operational sea ice products	H-1
SI-7	Melting state	Arctic, Antarctic; key regions, 1-3d	S1-SAR, S-3 SLSTR, OLCI; MWI	Synergy SAR-optical	H-2
Comments from SEN4SCI scientific workshop: • Synergy MW radiometry/SAR to be developed for downscaling/improving sea ice types and concentration • High noise floor of S-1 cross-pol is problem for ice type classification • Trade off Extended WS. vs. Interferometric WS needed for coastal areas					

Cryosphere Element: Glaciers and Ice Caps					
G-1	Glacier area	Global glaciers, 1-5 yr	S-2 MSI	Inventory meta data / synergy with S-1	H-1
G-2	Glacier surface topography	Global glaciers, 1-5 yr	S-1 InSAR	Glacier outlines; single-pass InSAR, TanDEM-X	H-1
G-3	Glacier LSSIA, snowline	Global glaciers, 1mo (in summer)	S-2 MSI	Glacier surface topography	H-2
G-4	Glacier dammed lakes	Hazarduous glaciers, 7d-1mo	S-1 SAR, S-2 MSI	Glacier outlines	H-1
G-5	Glacier surface velocity	Representative glaciers, 1mo - 1yr	S-1 SAR/ InSAR, (S2)	Glacier surface topography	M

Comments from SEN4SCI scientific workshop:

- Sentinel-2 is important for glacier mapping (repeat coverage) – key sensor
- Glacier volume change is important parameter, requires precise high resolution DEM (annual, multi-annual repeat; single-pass InSAR TanDEM-X type mission)
- S-1 repeat pass DiNSAR may have coherence problems due to temporal decorrelation; incoherent amplitude matching is option for ice motion (for areas of conservative surface features)
- Acquisition in certain seasons needed (glacier area and LSSIA – late summer)

Cryosphere Element: Ice Sheets					
IS-1	Ice sheet margin	Ice sheets, 1mo – 1 yr	S-1 InSAR S-3SLSTR, OLCI		H-2
IS-2	Ice sheet surface topography	Ice sheets, 3 yr-5yr	S-3 SRAL, CryoSat, S-1 InSAR		H-2
IS-3	Ice sheet surface elevation change	Ice sheets, 1 yr	S-3 SRAL, CryoSat, ICESat-2		H-1
IS-4	Ice sheet/ice stream surface velocity	Outlet glaciers, 1mo -1yr	S-1 SAR/InSAR	Surface topography	H-1
IS-5	Ice sheet surface melt area	Ice sheets, 1d – 3d	MetOp-ASCAT, MWI		H-2
IS-6	Iceberg calving flux (frontal ice motion)	Outlet glaciers, 1d – 5 d	S-1 SAR/WS-SAR	Ice thickness	H-1
IS-7	Iceberg detection and drift	High latitude oceans, 1d	S-1 SAR/WS-SAR	Operational products available	M; H in some reg.

Comments from SEN4SCI scientific workshop:

- High resolution repeat pass SAR (S-1 Image Mode) required for ice motion at narrow fast ice streams (incoherent image correlation)
- Synergy of altimetry, InSAR (resp. image correlation), gravimetry for ice sheet mass balance of interest
- Surface ablation needed for mass balance modelling

Many of the products on cryospheric variables can build on previous activities, including projects for algorithm development, application demonstration and science support sponsored by ESA, as well as on scientific projects sponsored by other agencies. The listing of missions and sensors in the table focuses at the Sentinels and CryoSat. For a few variables MetOp ASCAT or MetOp-SG MWI would be the primary sensor. Spectral surface albedo and surface temperature are basic variables for all elements of the cryosphere, as well as essential for modelling and monitoring Earth surface/atmosphere interaction in general.

For *snow cover* key parameters for climate monitoring and research are the area extent, water equivalent and extent of melt areas. The ESA DUE project GlobSnow delivers these products at global coverage for the scientific community, based on AATSR data for snow area and AMSR data for SWE. The adaptation of the retrieval methods to SLSTR and SG-MWI should be well feasible. Monitoring snowmelt area with C-band SAR (e.g. ASAR) has found wide application in snow hydrology research and water management, based on services of value added industry and scientific institutions. The retrieval technique is mature. The transition to an operational product for the global (or at least continental) snow melt area would require an appropriate acquisition schedule for S-1 SAR. It is expected that the product will be of high priority for operational applications, to be produced by GMES service providers. Snow grain size is a useful product for snow process modelling and hydrology, although optical sensors deliver only the grain size at the snow surface The need for precise corrections for atmospheric propagation, topography and directional reflectance behaviour results in complex processing line requiring various auxiliary data not available globally at the same quality. A major gap in present observation capabilities is the lack of a sensor for delivering high resolution SWE products which are important for snow hydrology and snow processes studies. This gap is addressed by the Earth Explorer Candidate mission CoReH2O.

Lake and river ice area is a high priority product which can be well retrieved from SAR data. Dates of freezing and break-up are important climate indicators. During those periods frequent repeat observations are needed. Optical imagery is also suitable for lake ice observations, but often suffers from impact of cloudiness and poor illumination during the critical periods. Snow cover on lake is important for thermodynamic ice models, but work on deriving this product by means of remote sensing is still experimental.

Key parameters for *permafrost* and *frozen soil* are the frozen soil area (freeze/thaw) and surface temperature. Medium to low resolution sensors are available to deliver these products. An important observable is also the extent of thaw lakes in permafrost areas, for which high resolution sensor data (SAR and optical) are needed. Surface deformation in permafrost areas can be monitored by means of repeat-pass InSAR, but temporal decorrelation may cause major limitations. Additional satellite products in support of permafrost studies and modelling are snow parameters, vegetation parameters, surface albedo, and soil parameters.

Sea ice extent and ice concentration are basic climate variables (high priority), to be derived by S-1 SAR (preferably Extended Wide-swath mode) and MetOp ASCAT. If the S-1 duty cycle would not allow for complete coverage of the sea ice areas, filling up gaps by means of ASCAT would be a viable option to obtain good repeat coverage. For sea ice type low to medium resolution sensors are presently employed. Classification of sea ice type can be significantly improved by adding a second frequency, where the combination of C- and L-band SAR is particularly interesting for regional studies. Sea ice thickness is another high priority sea ice parameter for which sensors (CryoSat SIRAL, S3-SRAL) and consolidated retrieval techniques are available. Other important sea ice variables for climate research and ice/ocean/atmosphere interactions are sea ice type, and the extent and temporal dynamics of polynyas and leads. S-1 SAR would be the primary sensor. For sea ice drift the Extended Wide Swath is the preferred operation mode for S-1.

For satellite products of *glaciers* and *small ice caps* consolidated retrieval techniques are available.

For glacier area mapping the methods are semi-automated (at least for the first processing run). Contextual information in various formats is needed, e.g. to separate boundaries of individual glaciers at ice fields, link the products with the (national) hydrological database, etc. The basic – high priority – variables as glacier area (outline) and surface topography do not need frequent repeat (1-5 years), except for special studies. S-2 MSI will be a perfect sensor for mapping glacier area and the extent of snow and ice areas. The late summer snow and ice area (LSSIA) is an important parameter for glacier mass balance modelling. Glacier surface topography can be mapped by means of InSAR. S-1 repeat pass InSAR can be used, applying differential retrieval techniques. The accuracy of the topographic product will be suitable for supplying base maps, as required for modelling glacier dynamics, correcting topographic effects for retrieval of LSSIA, etc. However, the accuracy of the S-1 topography products may not be sufficient to derive annual changes in glacier volume, at least for glaciers with small changes in surface topography. A main driver for monitoring glacier-dammed lakes is hazard assessment and mitigation (GMES service), but it is also of importance for scientific studies. Complementary to work in individual research projects, regular monitoring of glacier surface velocity for selected glaciers around the world is of interest, to support long-term studies of glacier dynamics and glacier/climate interaction.

For *ice sheet* research, including the links to ocean and atmosphere, satellite observations have become the main data source. For the variables specified in Table 2.5 mature retrieval techniques are available. Some of these variables are produced routinely within NASA sponsored programmes. In Europe the generation of geophysical products for ice sheet research so far has been funded by individual projects. For ice sheet research the upcoming data set of CryoSat, and its future extension by S-3 SRAL, is of high priority. Other basic ice sheet parameters, which can be routinely produced, are outlines of the ice sheet margins and maps of surface melt areas. The ice sheet margins (including the grounding line) can be mapped using S-1 SAR images, and during the daylight season also by means of medium resolution optical sensors. Along stable boundaries annual repeat surveys are sufficient, whereas for fronts of outlet glaciers and ice shelves monthly repeat surveys are desirable. Monitoring of ice sheet surface melt areas requires frequent repeat observations, but low spatial resolution is sufficient, so that MetOp ASCAT and SG-MWI would deliver a good database for this task. The surface velocity of outlet glaciers is of top priority for assessing ice sheet mass balance. Also for this variable the retrieval techniques are mature, employing repeat pass SAR images with InSAR or incoherent amplitude correlation technique.

A main scientific motivation for *iceberg* monitoring is to determine the calving flux. This can in principle be done by near continuous monitoring of iceberg calving and estimating the iceberg volume. High resolution observations with short repeat interval are be needed for this task. Another, more practicable option to estimate the calving flux is the monitoring of ice flow through gates close to the calving front. On the applied side, monitoring of icebergs is important to reduced risks for ship navigation in high latitudes.

2.6. Recommendations of the cryosphere scientific experts during SEN4SCI workshop

In addition to identifying scientific user requirements, the cryosphere splinter group at the SEN4SCI workshop worked out the following *recommendations*:

- The technical capabilities and continuity of the Sentinel missions will offer unique capabilities for long-term observations of all elements of the cryosphere. This potential should be exploited as far as possible for advancing research on cryosphere processes and climate/cryosphere interactions.
- Guaranteed free and open access to all Sentinel data is of highest priority for advancement of research in cryosphere & climate, including the use of these data for predictions of future scenarios

as addressed by WCRP CliC and other research programs.

- Long-term continuity of observations is important, performing measurements with same instrument type and operation mode for dedicated regions over many years, as well as performing inter-calibration between different sensors to extend the time series.
- Mature retrieval algorithms are available for retrieving cryosphere parameters from satellite measurements for many snow and ice parameters, but should be adapted and validated for Sentinels.
- Cal/Val and quantification of measurement accuracy and uncertainty is very important for science applications. Both on-board and external calibration (through dedicated cal/val sites) is required throughout mission life-time.
- Synergy of Sentinels with other missions is important for cryosphere research.

Apart of the recommendations the following important *data acquisition* related issues were pointed out:

- Priorities for acquisition and instrument setting for certain scientific tasks and key regions should be defined, taking into account the annual cycle of snow and ice.
- Cryosphere applications require trade off for SAR Stripmap Mode vs. Interferometric WS mode along ice sheet margins (ice stream motion with SAR amplitude correlation vs. sea ice and polynya mapping with WS). Extended WS vs. Interferometric WS needs to be traded-off for different sea ice applications.
- Both ascending and descending S-1 SAR swathes should be acquired for ice sheet and glacier motion (to reduce ambiguity in motion analysis) and for mountain regions (to reduce impact of fore-shortening and layover).

2.7. Selection of cryospheric variables as Sentinel product examples

Most of the identified cryosphere scientific variables were assessed as of high priority. The cryosphere community, present at the SEN4SCI Workshop, stressed the importance of these different variables in order to obtain comprehensive information on cryosphere processes and cryosphere/climate interactions. Necessity to limit the number of variables resulted in only two variables, *snow cover area* and *ice sheet surface elevation change*, that were selected as examples for further development of their processing chains using the Sentinel 1-2-3 observations as the inputs, and for outlining their potential validation schemes. The main criterions applied for selecting these variables as the important Sentinel scientific products were the same as in case of the land, solid Earth, and ocean variables, i.e.: i) serving a wide scientific community, ii) possibility to develop innovative processing methods based on technical specifications of the Sentinel instruments, and iii) potential for the synergistic use of data provided by any or several Sentinel 1-2-3 and Earth Explorer instruments.

Both selected variables are of great importance for climate research (i.e. ECVs), the production of which is not yet taken into account by any GMES service. Sentinel 1 and 3 missions will offer excellent datasets for deriving both of them.

I. *Snow cover area:* is one of the basic parameters for Earth/surface atmosphere heat exchange and water balance investigations that can be derived using the synergy of the optical sensors SLSTR (VIS, NIR, TIR) and OLCI (VIS, NIR). During the snow melt period, synergy of the optical snow product with SAR-derived snow maps of Sentinel-1 should be considered, in order to obtain a time sequence during snow depletion that is not affected by clouds.

II. *Ice sheet surface elevation change:* is a basic parameter for determining the mass balance of ice sheets and the contribution to sea level rise, which can be derived from Sentinel 3 SRAL altimeter data. Regarding the potential synergies, C-band SAR of Sentinel 1 will provide spatially detailed measurements of ice sheet surface topography and its rapid dynamic changes in the boundary zones of ice sheets. Sentinel 3 SRAL will extend the time series of the Earth Explorer CryoSat-2 with some overlapping period. In addition, CryoSat-2 will provide complementary observations reaching even higher polar latitudes.

Although being important, it is obvious that two selected variables are serving only part of the cryosphere scientific community. It is, therefore, necessary to mention that contribution of Sentinel 1-2-3 missions to other essential climate variables, as for instance *sea ice*, *lake and river ice*, *glaciers*, and *permafrost*, is also crucial for climate research.

3. Summary

The first phase of the SEN4SCI project resulted a document draft stating scientific needs and requirements of 45 cryospheric variables that are observable from space. This document was based on review of several research international programs and projects that are reflecting the science objectives of ESA's Living Planet Programme outlined in the The Changing Earth study (ESA, 2006). The extensive review of observational requirements was followed up by the gap analysis identifying 33 cryosphere scientific variables that can be delivered by the Sentinel 1-2-3 sensors alone or in a synergistic cooperation with other European satellite missions (i.e. Earth Explorers and MetOp missions). The public open Internet peer-review, conducted after interactive discussions of SEN4SCI workshop participating scientists, assessed 28 cryosphere potential Sentinel products as of high priority (level 1 or 2 with two different weights) and 5 cryosphere products as of medium priority.

Besides discussing the domain-specific scientific issues, the experts participating at the SEN4SCI workshop postulated the following general conclusions and recommendations for a future scientific exploitation of Sentinel observations:

- Comprehensive spatial and temporal coverage, long-term overall duration, new technical capabilities of the Sentinel 1-2-3 instruments, and also potential synergistic use of Sentinel data jointly with observations of other related missions offer a unique opportunity for development of new scientific products and applications.
- Global science requires data records (satellite time series) that are of global nature, long-term (multi-decadal), and accurate (i.e., undergoing the inter-calibration and stability monitoring during the entire life of the space borne mission constellation).
- Both on-board and external calibration/validation and quantification of per-pixel measurement accuracy and uncertainty should be performed using the standardized protocols and the dedicated sites within a fully funded operational context.
- Scientific input into the development of new products, applications, and calibration/validation protocols is essential for success of all Sentinel missions, both prior to and after their launch.

The following two cryosphere representative variables were selected from all the reviewed requirements to demonstrate ability of Sentinel 1-2-3 to generate important science products: *snow cover area* and *ice sheet surface elevation change*. Two external scientific experts were asked to prepare a more detailed study proposing processing chain and potential validation scheme of these satellite products, while paying a special attention to the innovative contribution and synergistic use of the Sentinel 1-2-3 missions. It is important to mention, that the selected variables are not indicating the most required satellite products by scientific community, but should be considered just as demonstrators providing the concrete examples how the GMES Sentinel 1-2-3 missions can contribute to advance the state-of-the-art Earth system science.

4. References

ACIA, 2004: Impacts of a warming Arctic: Arctic Climate Impact Assessment. Cambridge University Press. http://www.acia.uaf.edu.

Aguirre, M., Berruti. B., Bezy, J.-L-, Drinkwater, M., Heliere, F., Klein, U., Mavrocordatos, C., Silvestrin, P., Greco, B. and Benviste, J. 2007. Sentinel-3. The ocean and medium-resolution land mission for GMES operational services. ESA Bulletin, 131, 24-29.

Attema, E., Bargellini, P., Edwards, P., Levrini, G., Lokas, S., Moeller, L., Rosich-Tell, B., Secchi, P., Torres, R., Davidson M., and Snoeij, P. 2007. Sentinel 1. The radar mission for GMES operational land and sea services. ESA Bulletin, 131, 10-17.

Alexandrov, V., Sandven, S., Wahlin, J. and Johannessen, O.M. 2010. The relation between sea ice thickness and freeboard in the Arctic. The Cryosphere, 4, 373-380.

Bishop, M.P., Olsenholler, J.A., Shroder, J.F., Barry, R.G., Raup, B.H., Bush, A.B.G., Copland, L., Dwyer, J.L., Fountain, A.G., Haeberli, W., Kääb, A., Paul, F., Hall, D.K., Kargel, J.S., Molnia, B.F.,Trabant, D.C., Wessels, R. 2004. Global Land Ice Measurements from Space (GLIMS): remote sensing and GIS investigations of the Earth's cryosphere. Geocarto International, 19 (12), 57–84.

Brown, L.C. and Duguay, C.R. 2010. The response and role of ice cover in lake-climate interactions. Progress in Physical Geography, 34, doi: 10.1177/0309133310375653.

Bougamont. M. amd Bamber, J.L. 2005. A surface mass balance model for the Greenland ice sheet. J. Geophys. Res., 110 (F4), Article Nr. F04018.

ESA, 2006. The Changing Earth – New Scientific Challenges for ESA's Living Planet Programme, European Space Agency, SP-1304, pp. 1-83.

Francis, C.R. 2010. CryoSat: more important than ever. ESA Bulletin, 141, 10-18.

GCOS, 2010. Implementation plan for the global observing system for climate in support of the UNFCCC. GCOS-138 (GOOS-184, GTOS-76, WMO-TD/No. 1523). http://www.wmo.int/pages /prog/gcos/Publications/gcos-138.pdf

GIIPSY, 2006. Global Inter-agency IPY Polar Snapshot Year (GIIPSY) Strategy Document, Prepared by the International Cryospheric Research Community. November 2006. http://bprc.osu.edu/rsl/GIIPSY/documents/GIIPSY_Science_Sum_Nov_3.doc.

Giles, K. A., Laxon, S. W., and Ridout, A. L. 2008. Circumpolar thinning of Arctic sea ice following the 2007 record ice extent minimum, Geophys. Res. Lett., 35, L22502, doi: 10.1029/2008GL035710.

GTOS (2009): Assessment of the status of the development of standards for the terrestrial Essential Climate Variables: T06 - Glaciers and Ice Caps. Zemp, M., Gärtner-Roer, I., Haeberli, W., Hoelzle, M., Paul, F., Armstrong, R., Barry, R., Cihlar, J., Kääb, A., Kargel, J., Khalsa, S.J., Monteduro, M., Raup, B., Seiz, G. and Sessa, R. (eds.), Global Terrestrial Observing System, 61: 17 pp.

IGOS-Cryosphere, 2007. "Integrated Global Observing Strategy (IGOS) Cryosphere Theme Report"August 2007, WMO/TD-No. 1405. http://igos-cryosphere.org/.

IGOS-Water, 2003. "A Global Water Cycle Theme for the IGOS partnership", November 2003. http://www.igospartners.org/Water.htm.

Howell, S.E.L., Brown, L. C., Kang, K.-K. and Duguay, C.R. 2009. Variability in ice phenology on Great Bear Lake and Great Slave Lake, Northwest Territories, Canada, from SeaWinds/ QuikSCAT: 2000-2006. Remote Sensing of Environment, 113: 816-834.

Lemke, P., Ren, J., Alley, R., Allison, I., Carrasco, J., Flato, G., Fujii, Y., Kaser, G., Mote, P., Thomas, R. and Zhang, T., 2007. Observations: Changes in Snow, Ice and Frozen Ground. In:

Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Chang. Cambridge Univ. Press, Cambridge, UK and New York, NY, USA.

Martimort, P., Berger, M., Carnicero, B., Del Bello, U., Fernandez, V., Gascon, F., Silvestrin, P., Spoto, F., Sy O., Arino, O., Biasutti R. and Greco, B. 2007. Sentinel-2. The optical high-resolution mission for GMES operational services. ESA Bulletin, 131, 18-23.

Nagler, T. and Rott, H. 2000. Retrieval of wet snow by means of multitemporal SAR data. IEEE Trans. Geosc. Rem. Sens., 38, 754-765.

Prowse, T.D., Bonsal, B.R., Duguay, C.R., Hessen, D.O. and Vuglinsky, V. 2007. River and lake ice. Chapter 8 in Global Outlook for Ice and Snow, United Nations Environment Programme (UNEP), 201-213.

Raup, B., Racoviteanu, A., Khalsa S.J.S., Helm, C., Armstrong, R. and Arnaud, Y. 2007. The GLIMS geospatial glacier database: A new tool for studying glacier change. Global and Planetary Change, 56, 101– 110.

Rott, H. 2010. Advances in interferometric synthetic aperture radar (InSAR) in earth system science. Progress in Physical Geography. Vol 33(6), 769-791. doi:10.1177/0309133309350263.

Rott, H., Yueh, S.H., Cline, D.W, C. Duguay, R. Essery, C. Haas, F. Hélière, M. Kern, G. Macelloni, E. Malnes, T. Nagler, J. Pulliainen, H. Rebhan, A. Thompson. 2010. Cold Regions Hydrology High-resolution Observatory for Snow and Cold Land Processes. Proceeding of the IEEE, 98(5), 752 - 765. 10.1109/JPROC.2009.2038947.

Sandven, S. and Johannessen, O.M. 2006. Sea ice monitoring by remote sensing. In: Remote Sensing of the Marine Environment (ed. J. Gower), Manual of Remote Sensing, Third Edition, chapter 8, American Society for Photogrammetry and Remote Sensing, Vol. 6, pp. 241-283.

Smith, S. and Brown, J., et al. 2009. Assessment of the status of the development of the standards for the Terrestrial Essential Climate Variables - T7 - Permafrost and seasonnally frozen ground. GTOS-T07. http://archive.arcticportal.org/668/

Steffen, K. 2010. CliC – Climate and Cryosphere Project. Presentation at the “International Glaciological Conference Ice and Climate Change, View from the South" (VICC 2010) Valdivia, Chile, 1-3 February 2010.

UNEP, 2007: Global Outlook for Ice and Snow. Editor: J. Eamer, UNEP/GRID-Arendal, Norway. ISBN: 978-92-807-2799-9.

Wingham, D. J., Shepherd, A., Muir, A., Marshall, G. J. 2006. Mass balance of the Antarctic ice sheet. Phil Trans. Royal Soc. A – Math. Phys. Eng. Sciences, 3634 (1844), 1627-1635.

5. Appendices

Appendix 1: Definitions of reviewed cryosphere variables.

Variable	**Definition**
Cryosphere Element: All	
Earth surface albedo	Fraction of the irradiance reflected by the surface of the Earth in the range of 0.4-0.7 µm (or other specific short-wave ranges). Physical unit: [%].
Surface temperature	Temperature of the apparent surface of land (bare soil or vegetation or snow). Physical unit: [K].
Cryosphere Element: Snow Cover	
Snow Cover Area Global	Extent of snow cover area in [km_2] on land surfaces for climate monitoring.
Snow Cover Area Regional	Extent of snow cover area at high to medium spatial resolution. (~ 50 m to 300 m)
Snowmelt area	Extent of snow cover with liquid water in the snow pack.
Snowmelt liquid water content	Amount of liquid water in the snow pack (% by volume).
Snow grain size	Average diameter of ice particles (grains) in a snow pack in [mm].
Snow pollution content	Amount of organic and inorganic material (ice excluded) in a snow pack [g/m_3].
Cryosphere Element: Lake and River Ice	
Lake ice area and ice concentration	Extent of lake ice area in [km_2] and percentage of lake ice area within a defined lake surface area (e.g. % per km_2).
Snow on lake ice	Refers to snow cover on lake ice (in the context of thermodynamic ice models, depth of the snow cover is required). Area and/or snow mass.
Cryosphere Element: Permafrost and Frozen Soil	
Snow and soil surface temperature	Thermodynamic temperature (°C) of snow or soil, measured at a defined depth.
Thaw lake extent	Extent of open water (small lakes) during summer in regions where lower soil layers stay frozen all year round. [km_2]
Surface deformation	Small-scale change in surface topography (micro-topography) due to permafrost or melt/freeze activities [mm per time interval].
Cryosphere Element: Sea Ice	
Sea ice extent	Extent of sea ice area in [km_2].
Sea ice concentration	Percentage of sea ice area within a defined sea surface area (e.g. % per km_2).
Sea ice type	Type of sea ice according to morphological and structural properties.

Leads, polynyas	Stretches of open water between ice floes or along coast.
Sea ice thickness	Thickness of ice floe in [m].
Sea ice drift	Motion of ice flow (magnitude and direction) in [m/s].
Melt	Surface condition of sea ice surface (melting, frozen).
Cryosphere Element: Glaciers and Ice Caps	
Glacier area	Total extent of surface of a glacier in [km2].
Glacier surface topography	Geodetic elevation of glacier surface in [m], (map or digital elevation model).
Glacier LSSIA; snowline	LSSIA (late summer snow and ice area): extent of snow and ice area on a glacier (km2 or % of total glacier area) at the end of the ablation season (late summer); snow line: boundary of snow and ice area on a glacier.
Glacier dammed lakes	Extent [km2] and position of lake dammed by a glacier (e.g. lateral lake).
Glacier surface velocity	Motion of ice surface (magnitude and direction) in [m/day].
Cryosphere Element: Ice Sheets	
Ice sheet margin	Geodetic position of boundary between ice sheet and ocean or ice-free land.
Ice sheet surface topography	Geodetic elevation of ice sheet surface in [m].
Ice sheet surface elevation change	Temporal change in geodetic elevation of ice sheet surface in [m/year].
Ice sheet/ice stream surface velocity	Motion of ice surface (magnitude and direction) in [m/day].
Iceberg calving flux	Calving flux: Ice export in [kg/day] to the ocean across the ice front of a glacier or ice stream.
Iceberg detection and drift	Geodetic position and motion (magnitude and direction) of iceberg in [m/day].

6. List of Abbreviations

2-D	Two Dimensional
3-D	Three Dimensional
AATSR	Advanced Along-Track Scanning Radiometer
ACIA	Arctic Climate Impact Assessment
ADM	Atmospheric Dynamics Mission
ALADIN	Atmospheric LAser Doppler INstrument
ALOS	Advanced land observing Satellite
AMI	Active Microwave Instrument
AMSR	Advanced Microwave Scanning Radiometer
AMSU	Advanced Microwave Sounding Unit
AOPC	Atmospheric Observation Panel for Climate
AOT	Aerosol Optical Thickness
ASAR	Advanced Synthetic Aperture Radar
ASCAT	Advanced Scatterometer
ATSR	Along Track Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
C-GTOS	Coastal Global Terrestrial Observing System
CAL/VAL	Calibration/Validation
CCI	Climate Change Initiative
CEOS	Committee on Earth Observation Satellites
CHRIS	Compact High Resolution Imaging Spectrometer
CIRES	Cooperative Institute for Research in Environmental Sciences
CLIC	Climate and Cryosphere
CLIVAR	Climate Variability and Predictability
CoP	Community of Practice
DAAC	Distributed Active Archive Center
DEM	Digital Model of Elevation
Dev	Deliverable
DiNSAR	Differential SAR Interferometry
DMSP	Defense Meteorological Satellite Program
DORIS	Doppler Orbitography and Radio-positioning Integrated by Satellite
DUE	Data User Element
DWSS	Defense Weather Satellite System
ECVs	Essential Climate Variables
EE	Earth Explorer
EGG	European GOCE Gravity
ENV-CAN	Environment Canada
EO	Earth Observational
EORC	Earth Observation Research Center
EPS	EUMETSAT Polar System
ERS	European Remote Sensing
ESA	European Space Agency
EXP	EXPerimental product
FAIRE	Fast Access to Imagery for Rapid Exploitation

G	Goal
G-POD	Grid Processing On Demand
GCOS	Global Climate Observing System
GCW	Global Cryosphere Watch
GEO	Group on Earth Observations
GERB	Geostationary Earth Radiation Budget
GEWEX	Global Energy and Water Cycle Experiment
GGOS	Global Geodetic Observing System
GIIPSY	Global Inter-agency IPY Polar Snapshot Year
GLIMS	Global Land Ice Measurement from Space
GMES	Global Monitoring for Environmental Security
GNSS	Global Navigation Satellite System
GNT-G	Global Terrestrial Network for Glaciers
GNWP	Global Numerical Weather Prediction
GOCE	Gravity field and steady-state Ocean Circulation Explorer
GTN-P	Global Terrestrial Network for Permafrost
GTOS	Global Terrestrial Observing System
H	High priority
HIRS	High Resolution Infrared Radiation Sounder
HR	High Resolution
HROI	High Resolution multispectral Optical Imager
HRSOI	High Resolution Stereo Optical Imager
IASI	Infrared Atmospheric Sounding Interferometer
ICSU	International Council of Scientific Unions
IGOS	Integrated Global Observing Strategy
InSAR	Interferometric Synthetic Aperture Radar
IPCC	Intergovernmental Panel on Climate Change
IR	Infrared
IS	Infrared sounder
IWS	Interferometric Wide Swath
JAXA	Japan Aerospace Exploration Agency
JERS	Japan Earth Resources Satellite
JPSS	Joint Polar Satellite System
LA	Laser Altimeter
LAI	Leaf Area Index
LIDAR	LIght Detection And Ranging
LRM	Low-Rate Mode
LROI	Low Resolution multispectral Optical Imager
LSSIA	Late Summer Snow and Ice Area
LSSL	Late Summer Snow Line
M	Medium priority
MACC	Monitoring Atmospheric Composition & Climate
Max	Maximum
MERIS	MEdium Resolution Imaging Spectrometer
Min	Minimum
MIR	Middle Infrared
MIRAS	Microwave Imaging Radiometer using Aperture Synthesis

Mod	Modus
MODIS	Moderate Resolution Imaging Spectroradiometer
MROI	Medium Resolution multispectral Optical Imager
MSI	Multi-Spectral Instrument
MWI	Imaging Microwave Radiometer
MWR	Microwave Radiometer
NA	Not Available
NACP	North American Carbon Programme
NASA	National Aeronautics and Space Administration
NESDIS	National Environmental Satellite, Data, and Information Service
NMA	No Mature algorithm or sensor Available
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NR	Not Rated
NSIDC	National Snow and Ice Data Center
NWC-VSRF	Nowcasting and Very Short Range Forecasting
NWP	Numerical Weather Prediction
OD	Produced On Demand
OLCI	Ocean and Land Colour Imager
OOPC	Ocean Observations Panel for Climate
OP	Operational Product
PALSAR	Phased Array type L-band Synthetic Aperture Radar
POD	Precise Orbit Determination
PR	PRoduct generation for project
PSI	Persistent Scatterer Interferometry
RA	Radar Altimeter
RS	Remote Sensing
RSL	Remote Sensing Laboratories
S-1	Sentinel 1
S-2	Sentinel 2
S-3	Sentinel 3
SAR	Synthetic Aperture Radar
SCAR	Scientific Committee on Antarctic Research
SCAT	Scatterometer
SEN4SCI	Sentinels for Science
SG	Second Generation
SIRAL	SAR Interferometric Radar Altimeter
SLE	Sea Level Equivalent
SLSTR	Sea and Land Surface Temperature Radiometer
SMOS	Soil Moisture and Ocean Salinity
SOLAS	Surface Ocean-Lower Atmosphere Study
SPARC	Stratospheric Processes And their Role in Climate
SRAL	SAR Radar Altimeter
SSE	Support to Science Element

SSM/I	Special Sensor Microwave Imager
SWE	Snow Water Equivalent
SWIR	Shortwave Infrared
T	Threshold
TIR	Thermal Infrared
TOA	Top Of Atmosphere
TOPC	Terrestrial Observation Panel on Climate
TPM	Third Party Missions
UN	United Nations
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
URD	User Requirements Document
UTAS	University of Tasmania
UV	Ultraviolet
UZH	University of Zurich
VIS	Visible
WCRP	World Climate Research Programme
WGMS	World Glacier Monitoring Service
WGSF	Working Group on Surface Fluxes
WMO	World Meteorological Organization
WOAP	WCRP Observation and Assimilation Panel
WS	Wide Swath

SEN4SCI (Sentinels for Science) – Assessing Product Requirements for the Scientific Exploitation of the Sentinel Missions

Project final document:

'The science needs for ocean Sentinel 1-2-3 products'

For the European Space Agency edited by:
Zbyněk Malenovský (RSL-UZH/UTAS).
Approved and released by:
Michael Schaepman (RSL-UZH).
Contribution:
Zbyněk Malenovský (RSL-UZH/UTAS), Josef Cihlar (ZEMKON), and Michael Schaepman (RSL-UZH).

Abstract

The main objective of the SEN4SCI European Space Agency (ESA) project is an assessment of product requirements for the scientific exploitation of the Global Monitoring for Environmental Security (GMES) Sentinel 1-2-3 missions. The following tree complementary approaches were used to identify the Sentinel-based products that are needed to support current activities in ocean research: i) an Internet search for relevant research programs and projects and their documentation review, ii) an international SEN4SCI scientific workshop devoted to the scientific potential of Sentinel 1-2-3, and iii) a public Internet discussion forum for scientific experts.

In the first approach, the intensive Internet documentation search and literature review was carried out to find out the important ocean research programs and projects and to synthetize their requirements on data, products or other information obtained through satellite observations. Documentation review of about 70 research programs and projects all over the World resulted in a document listing goal and threshold observational requirements of 20 ocean scientific variables deliverable from space. The following up gap analysis pointed out, which sensor aboard of the Sentinel 1-2-3 missions and other synergic satellite missions are able to provide the required products. Subsequently their tentative priority was assessed.

The first international SEN4SCI scientific workshop was organized on 22-24 March 2011 at ESA-ESRIN in Frascati (Italy). Topic of the workshop attracted more than 200 land, solid Earth, ocean, and cryosphere scientific experts, which discussed in several splinter sessions the prepared documents on scientific requirements and satellite product priorities. The workshop participants also agreed on several recommendations that would ensure a proper scientific exploitation of the Sentinel 1-2-3 missions.

The ocean document, up-dated by outcomes of the SEN4SCI workshop, was from July to September 2011 posted on a publicly accessible Internet forum facilitated by ESA. Several scientists took a chance to comment, discuss and improve the final version of this document. Afterwards, examples of two ocean scientific variables were selected for further development of their processing chains using the Sentinel 1-2-3 datasets and for outlining their potential validation scheme. Their selection was taking into account the following aspects: i) serving a wide scientific community, ii) possibility to develop innovative processing methods based on technical specifications of the Sentinel instruments, and iii) potential for the synergistic use of data provided by any or several Sentinel 1-2-3 and Earth Explorer instruments.

Table of Contents

1. Introduction

The European Space Agency (ESA) is leading a federation of 'Sentinel' Earth observation missions built within the Global Monitoring for Environmental Security (GMES) Space Component that has the objective to ensure comprehensive and sustainable supply of data from space-based observations in response to the GMES service needs. While the primary purpose of Sentinel missions is to support European operational and policy needs, their acquired data and products also have the potential to meet observation needs of research communities in advancing understanding of particular aspects of the Earth environment. To enable ESA to facilitate more complete exploitation of the scientific potential of Sentinel observations, the Sentinels for Science (SEN4SCI) project was released. SEN4SCI focuses on identifying and consolidating: i) land and solid Earth, ocean, and cryosphere science needs to which the Sentinel 1-2-3 data could usefully contribute, ii) required data and products that could enhance the scientific yield from the Sentinel 1-2-3 missions, and iii) inputs from the broader scientific community with respect to these needs and requirements.

This report provides the final results of literature review on scientific needs of the ocean Sentinel 1-2-3 products, which were reviewed by a broad scientific community. The science observational needs were extracted from publically available documents of research programs and projects and consolidated during the international SEN4SCI workshop (22-24 March 2011, ESA-ESRIN, Frascati, Italy). Ocean Sentinel 1-2-3 observational needs and requirements were published for revision at the SEN4SCI WiKi EO portal (http://wiki.services.eoportal.org/tiki-index.php?page=Sentinel%20Wiki) during August and September 2011. All posted comments and corrections of participating scientific experts were reviewed and consolidated in this final document.

2. Ocean science

2.1. Ocean variables required by research programs and projects

The Changing Earth (ESA, 2006), a report outlining the science objectives of ESA's Living Planet Programme, defined six specific scientific challenges of the ocean research:

1. Quantify the interaction between variability in ocean dynamics, thermohaline circulation, sea level, and climate.
2. Understand physical and bio-chemical air/sea interaction processes.
3. Understand internal waves and the mesoscale in the ocean, its relevance for heat and energy transport and its influence on primary productivity.
4. Quantify marine-ecosystem variability, and its natural and anthropogenic physical, biological and geochemical forcing.
5. Understand land/ocean interactions in terms of natural and anthropogenic forcing.
6. Provide reliable model- and data-based assessment and predictions of the past, present and future state of the ocean.

In total 70 research programs and projects were reviewed during the SEN4SCI project, out of which 43 are dealing with the oceans, and 11 science projects were directly addressing the above-specified six ESA Living Planet challenges. Documentation of all 43 oceans addressing programs and projects was reviewed to search for the specific technical requirements of the ocean satellite products. Only 8 below-stated projects were providing specifications of the ocean variable requirements, out of which only 5 were proposing the threshold and/or goal technical specifications (in some cases not for all variables):

African Monsoon Multidisciplinary Analyses (AMMA, https://www.amma-eu.org/) aims to provide the African decision makers with improved assessments of similar rainfall changes, which are likely to occur during the 21st century due to natural fluctuations and as a result of anticipated global climate change. Only names of 5 required ocean variables were found.

The Baltic Sea Experiment (BALTEX, http://www.baltex-research.eu/) encompasses direct observations and primary data acquisition. Although, no overall satellite observation requirements have been described, very sparse technical specifications of 19 ocean products were found.

Climate Variability and Predictability (CLIVAR, http://www.clivar.org/) is an international project of the World Climate Research Programme (WCRP) with a particular focus on the role of ocean-atmosphere interactions in climate. Threshold requirements for spatial resolution, temporal sampling, and variable accuracy of 7 specific ocean products were found.

Global Carbon Project (GCP, http://www.globalcarbonproject.org/) aims to develop a complete picture of the global carbon cycle, including both its biophysical and human dimensions together with the interactions and feedbacks between them. Only names of 5 required ocean variables without any technical specifications were found.

Global Climate Observing System (GCOS, http://www.wmo.int/gcos/) addresses the total climate system including physical, chemical and biological properties, and atmospheric, oceanic, terrestrial, hydrologic, and cryospheric components. GCOS provides detailed observational requirement specifications for 12 ocean products.

Global Ocean Observing System (GOOS, http://www.ioc-goos.org/) is a permanent global system for observations, modelling and analysis of marine and ocean variables to support operational ocean services worldwide. As ocean is the main objective of GOOS, detailed requirements of 25 satellite observation products were provided.

Tropical Atlantic Climate Experiment (http://www.clivar.org/organization/atlantic/TACE/tace.php, TACE) aims, as a part of the CLIVAR project, to advance the understanding of coupled ocean-atmosphere processes and to improve climate prediction for the Tropical Atlantic region. TACE documentation states need for 5 ocean observation products, however, no technical requirements are mentioned.

World Climate Research Programme (WCRP, http://www.wcrp-climate.org/) has a major objective to determine the predictability of climate and the effect of human activities on climate. WCRP documents provided detailed technical specifications of 12 reviewed ocean variables.

In addition to these 8 programs and projects, the *Integrated Global Observing Strategy* (IGOS) *Themes* (http://www.igospartners.org/) were reviewed. Tracing back the IGOS documentation, specifications of several ocean products required by the Carbon (IGOS-Carbon, 2003), Coastal Zone (IGOS-Coastal Zone, 2006), and mostly Coral Reef (IGOS-Coral Reef, 2003) Observation Themes were revealed. No consistent scientific user requirements were found in the Final Report from the Ocean Theme Team (IGOS-Ocean, 2001). The *Communities of Practice* (CoP) pursue nowadays the objectives and original activities of the IGOS Themes within the framework of the *Group on Earth Observations* (GEO, http://www.earthobservations.org/cop.shtml). Nevertheless, no requirements on ocean observations were found in documentation of the Biodiversity, Carbon Cycle, Geohazards, and Water Cycle CoP.

The *Database of Observational Requirements* of the *World Meteorological Organization* (WMO) was included as an additional source specifying the ocean observational requirements independent of any particular measurement technique or instrument (WMO, 2011; http://www.wmo.int/pages/prog/sat/Databases.html#User). This database is a component of the Rolling Requirements Review process, which collects requirements of the several WMO application areas and co-sponsored programmes (GCOS, GOOS, and World Climate Research Programme – WCRP). Five out of nine WMO application areas have specified various number of the ocean observation requirements: 6 for the Global Numerical Weather Prediction (GNWP), 6 for the High-Resolution Numerical Weather Prediction (HR NWP), 4 for the Nowcasting and Very Short Range Forecasting (NWC-VSRF), 5 for the Synoptic Meteorology (SynopMet), and 6 for the Seasonal and Inter-annual Forecasting (S&IA).
Since the WMO requirements are related to nowcasting and short range forecasting, they differ significantly from the scientific needs of the global change projects focusing on a long term forecasting. Therefore, the global change 'climate research' needs, required specifications of 'IGOS Themes', and WMO requirements for 'operational products for meteorology' are presented in this document separately.

Draft of *User Requirements Document* (URD, 2011), formed during phase one of the *Ocean Colour Climate Change Initiative* (OC-CCI) was obtained after the SEN4SCI workshop. URD reports on user needs of several ocean-colour variables in climate research coming out of the consultation meeting and the analysis of user survey. Although it provides precisely specified requirements, it was still a document under revision, which means that stated values were still subjects of possible change.

2.2. Observational requirements of ocean variables

Many reviewed programs and projects expressed interest in ocean-related Earth observational (EO) products, but specific (numerical) requirements (i.e. spatial resolution, temporal sampling, and accuracy) of only 20 ocean variables were retrieved from their documentation. Following variables with non-defined or sparsely technically defined observational requirements were noted (in alphabetical order): *Bathymetry, Chlorophyll fluorescence, Nutrient concentrations, Potential primary productivity, Pollutant concentrations, Occurrence of filamentous cyanobacteria, Ocean/Sea chemistry,* O_2 *and* pCO_2*, Phytoplankton concentration (biomass), Reef maps, Shoreline position, Slicks, spills, films (sun glint), and Swell (sea state).*

Ocean scientific experts invited to the SEN4SCI workshop identified several additional important EO ocean parameters and products of various development stages (in alphabetical order): *Aerosol optical thickness (AOT), Aerosol angstrom exponent and dust AOT, Carbon-to-chlorophyll ratio, Divergence/convergence, Eddies, Euphotic depth, depth of heated layer, Floating vegetation and surface bloom slicks, Fluorescence line height (physiology), Fronts, Internal waves, Langmuir circulation, Mean dynamic topography, Particulate backscattering, Particulate organic carbon, Particulate inorganic carbon, Phytoplankton (growth rate, loss rate, carbon, etc.), Precipitation rate, Rossby waves, Spring bloom (initiation, amplitude, duration, total production, etc.), Total suspended matter, Upwelling zones, Wave-current interaction, and Waveforms.*

It is necessary to mention that the reviewed ocean surface variables do not include the Sea-Ice parameters (ice thickness, ice coverage/concentration, ice type/form, ice movement, etc.) as these are being analysed in the cryosphere science section of this document. The programs and projects observational variables with defined requirements were for easier comprehension grouped into two thematic categories: i) *physical oceanography*, and ii) *biological and biogeochemical oceanography*. The threshold and goal observational requirements regarding spatial resolution, temporal sampling, and accuracy for variables of both categories are specified in Table 2.1 (their definitions are provided in Appendix 1 to this document). The '*threshold*' value is the minimum requirement to be met to ensure that data are useful, while the '*goal*' value is an ideal requirement above which further improvement is not necessary. To synthesize and present properly the required goal and threshold values of all the programs and projects, Table 2.1 was divided into the '*climate research*', '*operational meteorology*', and '*IGOS Theme*' requirements (obtained from IGOS Carbon, 2003; IGOS Costal Zone, 2006; and IGOS Corral Reef, 2003). The objective of Table 2.1 is not to provide just one representative value, but rather to illustrate the range of goal and threshold requirements as defined by all the reviewed programs and projects. Therefore, the most demanding (minimum: *Min*), the most frequent (modus: *Mod*) and the most relaxed (maximum: *Max*) requirement values are stated whenever possible. In case of only two available values both are stated as *Min* & *Max* and finally a single value is stated in case of only one available requirement. Because many reviewed programs and projects do not make clear distinction between the open ocean and the coastal water requirements, numbers in Table 2.1 represent integrated values of both cases (except the marine biodiversity and habitat properties, which are related only to the coastal waters). The next two columns present number and names of programs and projects stating the particular ocean variable. Finally, the confidence level of the product is estimated in a scale of four grades: i) *firm* (very high confidence), ii) *reasonable* (acceptable confidence), iii) *speculative* (low confidence), and iv) *unspecified* (unknown confidence).

Specific observing requirements of the following physical oceanography variables are listed in the first part of Table 2.1:

Ocean circulation (Surface currents) is large-scale horizontal flow of ocean water in [m/s] that is persistent and driven by atmospheric circulation. Spatial changes in water mass density properties also trigger ocean motion along the density front. Observations of the ocean currents are required to advance the understanding of ocean dynamics, to estimate volume and heat transport, and to provide reliable surface drift estimates (e.g. oil spill drift) for marine services applications, and also for testing and validation of the ocean models. Large-scale surface geostrophic currents (order of 100 km) are mapped very well with altimetry. However, at the mesoscale-to-submesoscale (< 30-50 km) the altimetry methods have limitations. Promising new method resides with the SAR based range Doppler velocity mapping.

Ocean dynamic topography (Sea surface topography) is deviation of the time-averaged sea level from the geoid, after corrections for tides and atmospheric pressure effects, caused by the ocean currents. Physical unit including accuracy unit is [cm]. In general, the shape of the dynamic ocean topography at a spatial scale >100-200 km change little with time since the major ocean currents are stable at these scales.

Ocean/Sea Surface Height (SSH; Sea level) is actual and local sea level in [cm] inclusive of sea level anomaly, mean sea surface and known geophysical perturbations (tides, air pressure, etc.). Traditionally, permanent sea level stations around the world have been primarily devoted to tide and mean sea level monitoring, providing both near-real time (< 3 hours) and off-line (delayed) delivery. Importance of the SSH observations increases due to the higher demand for tsunamis, storm surges and coastal flooding forecasting and warning systems, but also for assimilation into ocean circulation models. Therefore, lately the requirements have been extended on making the SSH data available in near-real time.

Ocean/Sea Surface Salinity (SSS) is a measure of the content of anion chlorine in the upper layer (~ 0.5 m - 1 m). The physical unit is Absolute Salinity (adopted by the Intergovernmental Oceanographic Commission at its 25th Assembly in June 2009) given in g/kg (mass fraction of salt in seawater) as opposed to Practical Salinity Unit (psu), which is essentially a measure of the conductivity of seawater. Salinity plays a key role in the determination of the thermodynamic properties of seawater. The new absolute salinity unit provides a consistent and effective approach for dealing with relationships between salinity and these thermodynamic properties. High-resolution and high quality SSS observations are required for studies of climate change, to narrow the uncertainties of evaporation minus precipitation in the ocean and for ocean forecasting systems (assimilation into and validation of the ocean models). SSS in the coastal and inland regions have a larger variability due to influences by persistent coastal systems (e.g. upwelling/downwelling processes) and river discharge, and also enhanced evaporation in shallow regions.

Ocean/Sea Surface Temperature (SST) of the seawater at the depth of 2 m is usually named 'bulk' temperature, while at depth of < 1 mm it is called 'skin' temperature. Physical unit including accuracy is [K or °C]. The high-resolution SST observations are required to study thermohaline circulation and heat fluxes, and also to address the global and regional numerical weather prediction, the seasonal to inter-annual weather forecast, the ocean forecasting systems (assimilation in and validation of ocean models), and the marine services. SST in the coastal and inland regions have a large variability due to the diurnal cycle of solar radiation, which enhances differences in surface characteristics of the land and sea, and forces land-air-sea interactions (i.e., land-sea breezes).

Sea state (Wind-Wave) parameters: the observational requirements for global and regional wave modelling are depended on the applications for which the data are needed, which includes: assimilation into wave forecast models, validation of wave forecast models, calibration/validation of satellite wave sensors, and ocean wave climate and its variability on seasonal to decadal time scales. Additionally, wave observations are also required for now casting and issuing/cancelling warnings, and very-short-range forecasting (up to 12 hours) of extreme waves associated with, for instance, extra-tropical and tropical storms and wave-current interaction. Whilst now casting is largely based on observational data, very-short-range forecasting is being generated based on high-resolution regional wave models. Long-term, stable time series of repeat observations are required for climate applications. The key required sea state parameters are: *significant wave height* (average amplitude of the 30% highest waves in [m]), *dominant wave direction* (direction of the most energetic wave of the ocean wave spectrum in [°]), and *dominant wave period* (period of the most energetic wave of the ocean wave spectrum in [s]). The *crossing seas* and basin scale *swell tracking* are additional important products.

Surface wind: wind conditions are the key parameters for the momentum exchange between the atmosphere and ocean, for hurricane monitoring, for wave generation, for surface drift, for forcing ocean models, and for now cast and forecast marine meteorological and oceanographic conditions. *Wind vector over sea surface* represents the motion of the air mass over the sea, described by wind speed and the wind direction (given from where the wind is blowing). *Wind speed over sea surface* is the horizontal component of the 3-D wind with physical unit [m/s]. Surface wind observations are, at the coast, strongly influenced by the coastal topography and land-sea interaction. Coastal area is also the preferred location of offshore wind farming and, therefore, accurate and high-resolution information on coastal winds is important. Improvements of wind retrieval methods in fetch-limited conditions will be in future of higher importance.

The second part of Table 2.1 present in alphabetical order required specifications of the following biological and biogeochemical oceanography variables:

Inherent Optical Properties (IOP) include light absorption, scattering, and backscattering. They are defined as optical properties independent of variations in the angular distribution of the incident light.

Marine biodiversity and habitat properties stand for various biological variables that can be derived from the water leaving radiance observations to indicated actual status of costal waters and coral reefs.

Water-leaving radiance is the upwelling radiance just below the sea surface, which is a function of the view angle. *Normalized water-leaving radiance* approximates the radiance that would leave the sea surface in the absence of an atmosphere, and with sun at the zenith.

The *ocean colour* observations can detect several types of marine pollutions, harmful algae and phytoplankton blooms. *Colour Dissolved Organic Matter* (CDOM; formerly called 'yellow substance') is indicative of biomass undergoing decomposition processes. Physical unit is [m^{-1}] with accuracy unit [%] at a specific concentration (e.g., 1 m^{-1}). *Suspended sediment concentration* of river outflow measures re-suspension or pollution of other-than-biological origin. Physical unit is [g/m^3]

with accuracy unit [%] at a specific concentration (e.g., 1 g/m^3). Finally, *ocean chlorophyll concentration* is an indicator of the living phytoplankton biomass with physical unit [mg/m^3] and accuracy unit [%] at a specific concentration (e.g., 1 mg/m^3). The algorithms to separate the ocean colour signal among different *phytoplankton functional types* are currently under development. This is a new scientific product of high importance that, in most cases, considers phytoplankton functional types in oceanic waters, and it refers often to separation by size class.

Particle Size Distribution (PSD), expressing the number or mass of common mineral particles as a function of their size, is another experimental product from remote sensing. Although many users are aware of the importance to retrieve this variable from space, the application into climate models has not been yet explored.

Photosynthetically Active Radiation (PAR) is amount of the photosynthetically active photons of the wavelengths between 400-700 nm that diffuses through the water compared to the downwelling at-surface flux. PAR is important for the dynamics of the photic zone, typically 1-5 meters below the surface, and leads to an understanding of photosynthesis, toxic algae blooms, and eutrophication. PAR measurements can be used to calculate the euphotic depth in the ocean.

Spectral attenuation coefficient for downwelling irradiance provides the underwater rate of decrease of the irradiance with unit distance, and per unit incident flux.

Table 2.1. Most demanding (Min), most frequent (Mod), and most relaxed (Max) goal and threshold observational requirements for ocean programs and projects reviewed by the SEN4SCI project (for definitions see Appendix 1).

Nr	*Variable*	*Goal Spatial Reso-lution (Min-Mod-Max in km)*	*Thresh. Spatial Reso-lution (Min-Mod-Max in km)*	*Goal Temporal Sampling (Min-Mod-Max)*	*Threshold Temporal Sampling (Min-Mod-Max)*	*Goal Acuracy (Min-Mod-Max)*	*Thresh. Acuracy (Min-Mod-Max)*	*No. of Pro-jects*	*Projects with require-ments*	*Esti-mated Confi-dence **
Physical oceanography										
1	***Dominant wave direction (Sea state)*** /climate research/	10	30	1 h	6 h	10°	20°	1	GOOS	Firm
	/IGOS Themes/	1	10	3 h-1 d	1-3 d	5-10°	10-30°	2	IGOS Coastal, IGOS Coral	
	/operational product for meteorology/	5-50	40-250	0.5-3 h	6-12 h	10-20°	20-30°	3	HR NWP, SynopMet, GNPW	
2	***Dominant wave period (Sea state)*** /climate research/	10	30	1 h	6 h	0.5 s	1 s	1	GOOS	Firm
	/operational product for meteorology/	5-50	40-250	1-3 h	6-12 h	0.25-0.5 s	1 s	3	HR NWP, SynopMet, GNPW	
3	***Ocean circulation (Surface currents)*** /climate research/	1-10-50	20-50-100	1-2-5 d	2-5-10 d	2-5 cm/s	5-10-20 cm/s	2	BALTEX, CLIVAR	Firm
	/IGOS Themes/	0.3	1	1 h	1 d	3 cm/s	10 cm/s	1	IGOS Coastal	

	/operational product for meteorology/	10	50	6 h	6 d	0.5 cm/s**	1 cm/s**	1	NWC-VSRF	
4	***Ocean dynamic topography (Sea surface topography)*** /climate research/	25-100	100-300	1-7-10 d	10-30 d	1-2 cm	5-10 cm	3	GCOS, GOOS, WCRP - CLIVAR	Firm
	/operational product for meteorology/	25	100	7 d	30 d	1 cm	4 cm	1	S&IA	
5	***Ocean/Sea surface height (Sea level)*** /climate research/	0.1	5-10	1 d	2-7 d	2 cm	2-10 cm+	2	WRCP-CLIVAR, WMO	Reason.
	/IGOS Themes/	1	5-15	1-10 d	10-30 d	4-10 cm+	6-30 cm+	2	IGOS Coastal, IGOS Coral,	
6	***Ocean/Sea surface salinity*** /climate research/	100-200	250-500	7-10-30 d	30-60 d	0.05-0.1 psu	0.3-1 psu	3	WCRP-CLIVAR, GCOS, GOOS,	Firm
	/IGOS Themes/	1	25-100	1-8 d	7-30 d	0.1 psu	0.3-1 psu	2	IGOS Coral, IGOS Coastal	
	/operational product for meteorology/	5-100	250	1-30 d	60 d	0.1 psu	0.3 psu	2	GNWP, S&IA	
7	***Ocean/Sea surface temperature*** /climate research/	1-10-50	5-50-500	1-6-24 h	6h-1d-30d	0.1-0.5 K	0.2-1-2 K	4	CLIVAR, GCOS, GOOS, WCRP	Firm
	/IGOS Themes/	0.1-0.2	1	3 h-1 d	6 h-2 d	0.1-0.2 K	0.5 K	2	IGOS Coral, IGOS Coastal	
	/operational product for meteorology/	1-5-50	40-50-250	1-3 h	6h-1d-5d	0.1-0.5 K	0.5-1-2 K	5	GNWP, HR NWP, SynopMet, S&IA, NWC-VSRF	
8	***Significant wave height (Sea state)*** /climate research/	25-100	250	3-12 h	6 h-1 d	0.1-0.5 m	1-2 m	2	GCOS, WCRP	Reason. /Firm
	/IGOS Themes/	1	10	3 h	1 d	0.2 m	0.2 m	1	IGOS Coastal	
	/operational product for meteorology/	5-15	40-250	0.5-1 h	6-12 h	0.1 m	0.2-0.5 m	2	HR NWP, GNWP	
9	***Wind speed over sea surface*** /climate research/	10-25	100-500	1 h -1 d	1-7 d	0.5-1 m/s	1-2 m/s	2	GOOS, GCOS	Firm
	/IGOS Themes/	0.3-2	5-10	1 h-1 d	6 h-2 d	0.5-1 m/s	2 m/s	2	IGOS Coastal, IGOS Coral	

	/operational product for meteorology/	0.5-20	20-250	0.25-1 h	3-12 h	0.5-2 m/s	2-5 m/s	4	GNWP, HR NWP, SynopMet, NWC-VSRF	
10	***Wind vector over sea surface*** /climate research/	4-25-50	50-100-500	1-12-24 h	6 h-1d-7 d	0.5-1-2 m/s	2-5 m/s	1	WCRP-CLIVAR, GOOS, GCOS	Firm
	/operational product for meteorology/	2-20	40-250	0.25-0.5-1 h	3-12 h	0.5-1-2 m/s	3-5 m/s	4	GNWP, HR NWP, SynopMet, NWC-VSRF	
Biological and biogeochemical oceanography										
11	***Colour dissolved organic matter/yellow substance (Ocean colour)*** /climate research/	0.1-1-100	5-10-500	1 d	2-7 d	5%	10-20-25%	4	GOOS, WCRP-CLIVAR, TACE, OC-CCI ♣	Firm
	/IGOS Themes/	0.1	0.5-1	1 h	2 h-1 d	30%	40%	2	IGOS Coastal, IGOS Carbon	
	/operational product for meteorology/	100	500	1 d	6 d	5%	20%	1	S&IA	
12	***Inherent optical properties*** /climate research/	-	0.1-1-10	-	1-7 d	-	10-25%	1	OC-CCI ♣	Unspec.
13	***Marine biodiversity and habitat properties*** /IGOS Themes/	0.001	0.01	3 d	12 d	-	-	2	IGOS Coastal, IGOS Coral	Unspec.
14	***Normalised water-leaving radiance*** /climate research/	-	0.1-100	-	1-30 d	-	10-25%	1	OC-CCI ♣	Unspec.
15	***Ocean chlorophyll (Ocean colour)*** /climate research/	0.1-1-100	5-100-500	1 d	3-7 d	0.1-5%	0.5-20-25%	4	GCOS, GOOS, WCRP – CLIVAR, OC-CCI ♣	Firm
	/IGOS Themes/	0.1-0.2	0.5-1	1 h-1 d	2 h-3 d	10-20%	30%	2	IGOS Coastal, IGOS Coral	
	/operational product for meteorology/	25	100	1 d	3 d	5%	20%	1	S&IA	
16	***Particle size distribution*** /climate research/	-	0.1-1-10	-	7 d	-	10-25%	1	OC-CCI ♣	Unspec.
17	***Photosynthe-tically Active Radiation*** /climate research/	1-10	5-50	1 h	1 d	5%	20%	1	GOOS	Firm

	/IGOS Themes/	0.1-1	0.5-5	1 h	2 h-1 d	5-10%	20%	2	IGOS Coastal, IGOS Coral	
18	***Phyto-plankton functional types (Ocean colour)*** /climate research/	-	1-10	-	7 d	-	10-25%	1	OC-CCI ♣	Unspec.
19	***Spectral attenuation coeff. for downwelling irradiance*** /climate research/	-	0.1-1-10	-	1-7 d	-	10-25%	1	OC-CCI ♣	Unspec.
20	***Suspended sediment concentration (Ocean colour)*** /climate research/	100	500	1 d	6 d	5%	20%	1	WCRP - CLIVAR	Specu-lative
	/IGOS Themes/	0.1	0.5	1 h	2 h	30%	40%	1	IGOS Coastal	
	/operational product for meteorology/	100	500	1 d	6 d	5%	20%	1	S&IA	

* Estimated Confidence is adopted from WMO documentation and revised during the public SEN4SCI Internet review.
** Oceanography experts pointed out during the public SEN4SCI Internet review that these values are unrealistic and probably mistaken in the original source (i.e. CEOS observational requirements).
\+ More accurate estimates are actually achievable.
♣ Requirements of OC-CCI are not of final nature as they were obtained from draft the OC-CCI user requirement document (URD, 2011).

Acronyms:

BALTEX	Baltic Sea Experiment
CLIVAR	Climate Variability and Predictability
GCP	Global Carbon Project
GCOS	Global Climate Observing System
GNWP	Global Numerical Weather Prediction
GOOS	Global Ocean Observing System
HR NWP	High-Resolution Numerical Weather Prediction
IGOS	Integrated Global Observing Strategy
NWC-VSRF	Nowcasting and Very Short Range Forecasting
OC-CCI	Ocean Colour Climate Change Initiative
SynopMet	Synoptic Meteorology
S&IA	Seasonal and Inter-annual Forecasting
TACE	Tropical Atlantic Climate Experiment
WCRP	World Climate Research Programme

Thresh. = Threshold
Reason. = Reasonable
Unspec. = Unspecified

Global Climate Observing System (GCOS, 2010) defined the following eleven ocean surface Essential Climate Variables (ECVs) that are required to support research of the United Nations Framework Convention on Climate Change (UNFCCC) and the Intergovernmental Panel on Climate Change (IPCC) related to the global climate change: *Sea-surface temperature, Sea-surface salinity, Sea level, Sea state, Sea ice, Surface currents, Ocean colour, Carbon dioxide partial pressure, Ocean acidity, Phytoplankton*. Besides Carbon dioxide partial pressure and Ocean acidity our analysis covers the majority of the ocean surface ECVs.
A tentative list of the future potential ECV candidates was proposed by the ocean experts at the SEN4SCI workshop based on continuity of the related satellite missions, maturity of the generating algorithms, and possibility of the in-situ validation and the per-pixel uncertainty estimation. The following variables were found to have high score for becoming the next generation of ECVs: *Normalized water leaving reflectance, Chlorophyll concentration (for Case 1 – open ocean waters),*

Diffused spectral attenuation coefficient, Aerosol optical thickness (AOT), Euphotic depth and depth of the mixed layer, and Fluorescence line height. The first four mentioned variables could be operationally derived from the Sentinel 3 imaging spectroradiometrs.

2.3. Present and future European satellite missions for ocean science

The GMES Sentinel 1-2-3 missions will allow development of new scientific applications based on:

- Better performance of instruments,
- Improved sensor modes and extensions,
- Possible synergy of instruments allowing to study complex interaction on different spatial and temporal scales,
- Long time series perspective,
- Characterisation and reduction of uncertainties.

Capabilities of the current and future European satellite mission, i.e. GMES Sentinels (1-2-3), Earth Explorers, other ESA mission, and MetOp satellites, to provide 20 defined ocean surface variables are given in Table 2. Data in Table 2 is indicating not only the type of sensor and the mission with sensor name, but also the spatial resolutions of the sensor and the product accuracy achieved (if known), as stated in the CEOS EO Handbook (2010) and the CEOS Systems Database (2011).

Table 2.2. Observational capabilities of Sentinel 1-2-3, approved Earth Explorers, and other ESA and MetOp missions for ocean surface physical, biological and biogeochemical variables.

Nr	*Variable*	*Sensor type**	*Sentinel mission / sensor (spatial resolution / accuracy)*	*Earth Explorer / sensor (spatial resolution)*	*Other ESA mission / sensor (spatial resolution/ accuracy)*	*MetOp (SG) (spatial resolution / accuracy)*
Physical oceanography						
1	***Dominant wave direction (Sea state)***	SAR	S-1/C-BandSAR (from 2x2km to 20x20km depending on mode / 12°)		Envisat/ASAR (IM mode 2 x 2km / 12°) & ERS-2/AMI &SAR (2x2km / 12°)	
2	***Dominant wave period (Sea state)***	SAR	S-1/C-BandSAR (from 2x2km to 20x20km depending on mode / 30m)		Envisat/ASAR (IM mode 2x2km / 30m)	
3	***Ocean circulation (Surface currents)***	RA, SAR	S-1/C-BandSAR (from 2x2km to 5x5km depending on mode / 30cm/s)	GOCE/EGG (-)	Envisat/ASAR (wide swat mode 4x8km / 30cm/s)	
4	***Ocean dynamic topography (Sea surface topography)***	RA	S-3/SRAL (- / -)	GOCE/EGG (-)	Envisat/RA-2 (- / <4.5 cm)	
5	***Ocean/Sea surface height (Sea level)***	RA, POD	S-3/SRAL (- / -) & POD	CryoSat2/ DORIS-NG (-)	Envisat/RA-2 & DORIS-NG (- / <4.5 cm), ERS-2/RA (footprint 16-20 km / <10 cm)	
6	***Ocean/Sea surface salinity***	MWR (L-band)		SMOS/ MIRAS (33 - 50 km)		
7	***Ocean/Sea surface temperature***	MROI (IR), MWI, IS	S-3/SLSTR (1 km / 0.2 K)		Envisat/AATSR (1 km / <0.5 K) ERS-2/ATSR-2 (20 km / <0.5K)	IASI (1-30 km / 0.5-2 K), AVHRR/3 (1.1 km / -), HIRS/4 (20.3

						km / -)
8	***Significant wave height (Sea state)***	RA, SAR	S-1/C-BandSAR (from 2x2km to 20x20km depending on mode / 30cm), S-3/SRAL (- / -)		Envisat/ASAR (Image mode 2x2km / 0.3m) & RA-2 (- / <0.25 m), ERS-2/RA (footprint 16-20 km / 0.5 m) & AMI (2x2km / 0.3m)	
9	***Wind speed over sea surface***	RA, SCAT, SAR	S-1/C-BandSAR (from 500m to 1km depending on mode / 1.7m/s), S-3/SRAL (- / -)		Envisat/RA-2 (- / 35 d / -) & ASAR (1km / 1.7m/s), ERS-2/RA (footprint 16-20 km / -) & AMI (1km / 2 m/s)	ASCAT (25-37 km, 50 km / 2 m/s), AMSU-A (48 km / -)
10	***Wind vector over sea surface***	SAR, SCAT	S-1/C-BandSAR (5x5, 5x20, 20x40 m / -),		Envisat/ASAR (10, 30, 150 m & 1 km / -), ERS-2/AMI (50 km / -) & SAR (30 m / -)	ASCAT (25-37 km, 50 km / -)
Biological and biogeochemical oceanography						
11	***Colour dissolved organic matter/yellow substance (Ocean colour)***	MROI (ocean colour instruments)	S-3/OLCI (0.3, 1.2 km / -)		Envisat/MERIS (0.3, 1.2 km / -)	
12	***Inherent optical properties***	MROI	S-3/OLCI (0.3, 1.2 km / -) & SLSTR (0.5, 1 km / -)		Envisat/MERIS (0.3, 1.2 km / -)	
13	***Marine biodiversity and habitat properties***	HROI	S-2/MSI (10, 20, 60 m / -)		Proba/CHRIS (18, 36 m / -)	
14	***Normalized water-leaving radiance***	MROI, HROI	S-3/OLCI (0.3, 1.2 km / -) & SLSTR (0.5, 1 km / -), S-2/MSI (20, 60 m / -),		Envisat/MERIS (0.3, 1.2 km / -)	
15	***Ocean chlorophyll (Ocean colour)***	MROI (ocean colour instruments)	S-3/OLCI (0.3, 1.2 km / -)		Envisat/MERIS (0.3, 1.2 km / -)	
16	***Particle size distribution***	MROI	S-3/OLCI (0.3, 1.2 km / -)		Envisat/MERIS (0.3, 1.2 km / -)	
17	***Photosyntheti-cally Active Radiation***	MROI, HROI	S-3/OLCI (0.3, 1.2 km / -), S-2/MSI (20, 60 m / -),		Envisat/MERIS (0.3, 1.2 km / -)	
18	***Phytoplankton functional types (Ocean colour)***	MROI (ocean colour instruments)	S-3/OLCI (0.3, 1.2 km / -)		Envisat/MERIS (0.3, 1.2 km / -)	

19	***Spectral attenuation coeff. for downwelling irradiance***	MROI, HROI	S-3/OLCI (0.3, 1.2 km / -) & SLSTR (0.5, 1 km / -), S-2/MSI (20, 60 m / -),		Envisat/MERIS (0.3, 1.2 km / -)	
20	***Suspended sediment concentration (Ocean colour)***	MROI (ocean colour instruments)	S-3/OLCI (0.3, 1.2 km / -)		Envisat/MERIS (0.3, 1.2 km / -)	

* Sensor types:

HROI	High resolution multispectral optical imager	Source:
IS	Infrared sounder	http://database.eohandbook.com/
MROI	Medium resolution multispectral optical imager	http://ceos-sysdb.com/
MWR	Microwave radiometer	
MWI	Multispectral imaging microwave radiometer	
POD	Precise orbit determination	
RA	Radar altimeter	
SAR	Synthetic aperture radar	
SCAT	Scatterometer	

Table 2.2 shows that the future GMES Sentinel 1-2-3 missions will be able to directly address 19 of 20 reviewed ocean surface variables. The Sentinel-1 (S-1) C-band Synthetic Aperture Radar (SAR) will contribute mainly to the physical oceanography research of sea state, ocean circulation (currents), and high resolution near surface wind measurements. The Sentinel-2 (S-2) Multi Spectral Instrument (MSI) will provide input images for the high-resolution marine biodiversity and habitat mapping and estimation of ocean PAR, but also support products primarily derived from the Sentinel-3 (S-3) data (normalized water-leaving radiance, spectral attenuation of downwelling irradiance). Sensors aboard of S-3 will be strongly contributing to the ocean research in combination with S-1 and S-2. The optimized viewing ability of the Ocean Land Colour Instrument (OLCI), a spectroradiometer operating in 21 bands from ultraviolet to near-infrared wavelengths, will provide high quality optical ocean observations (normalized water-leaving radiance, inherent optical properties, spectral attenuation of downwelling irradiance, PAR, particle size distribution), from which some can be used for retrieval of the ocean colour variables (colour dissolved organic matter - CDOM, suspended sediment and chlorophyll concentrations, phytoplankton functional types). The S-3 Synthetic Aperture Radar Altimeter (SRAL) will contribute to the measurements of sea surface height (SSH), ocean dynamic topography, surface geostrophic current and significant wave height. Finally, the S-3 Sea Land Surface Temperature Radiometer (SLSTR) is designed for sea surface temperature measurements, but it can also support retrieval of products related to the irradiance-water interactions. The only ocean measurement not being directly addressed by the first three Sentinels is Sea Surface Salinity.

Three currently operational ESA Earth Explorer missions are contributing to the ocean observations. The Soil Moisture and Ocean Salinity (SMOS) is an opportunity mission observing the ocean surface salinity by capturing images of emitted microwave radiation around the frequency of 1.4 GHz (L-band) by the Microwave Imaging Radiometer using Aperture Synthesis (MIRAS) instrument. Cryosat2 is a dedicated 'ice' mission. However, it is also contributing to the coastal sea level and ocean currents monitoring. Finally, combining the Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) data with the satellite altimetry measurements gives the difference between the geoid height and the mean sea-surface height, which provide insight into the dynamic sea surface topography.

Three other ESA satellite missions are currently delivering data for ocean observations. The radar altimeters (RA) aboard Envisat and ERS-2, and also the Envisat's DORIS-NG, are providing data for the Sea level measurements. The TIR bands of the Envisat's Advanced Along-Track Scanning Radiometer (AATSR) and the European Remote Sensing (ERS-2) satellite Along Track Scanning Radiometer (ATSR-2) measure the Sea surface temperature, Advanced Synthetic-Aperture Radar (ASAR) detects and manifests expressions of the mesoscale ocean processes associated with frontal dynamics and eddies. The Envisat's Medium Resolution Imaging Spectrometer (MERIS) is able to address most of the biogeochemical ocean products (i.e., the Ocean colour parameters, PAR, and products describing the interactions of solar irradiation with the ocean/sea water bodies). Sea surface topography is observed by the RA-2 carried by the Envisat platform. Similarly, the Sea state and the Wind sea surface variables are obtained from the radar altimeters, synthetic aperture radars, and the Active Microwave Instrumentation (AMI) of Envisat and ERS-2. Finally, the Marine biodiversity and habitat properties can be derived from the Compact High Resolution Imaging Spectrometer (CHRIS) aboard the PROBA satellite.

The MetOp missions contribute to the observation of three ocean surface parameters. Data of Infrared Atmospheric Sounding Interferometer (IASI), Advanced Very High Resolution Radiometer/3 (AVHRR/3), and High Resolution Infra-red Sounder/4 (HRIS/4) are used to monitor the Sea surface temperature, while the Advanced Scatterometer (ASCAT) and Advanced Microwave Sounding Unit - A (AMSU-A) observations are used to measure the Wind speed and Wind vector over sea surface.

2.4. Proposed priorities for satellite products on ocean variables

A priority proposal for ocean surface satellite products required by the research programs and projects was suggested based on information in Table 2.1 and Table 2.2, and presented during the international SEN4SCI workshop. Table 2.3 shows which of 20 reviewed ocean variables can be addressed by the Sentinel 1-2-3, Earth Explorer, and MetOp sensors. Table provides minimum-maximum intervals of the threshold spatial and temporal resolutions (as required by the reviewed programs and projects), and the relevant product auxiliary data (i.e., other data inputs needed to generate the required product) together with the space mission/sensor providing auxiliary data.

Using own programs, ESA initialized several scientific projects demonstrating feasibility and supporting the development of processing chains for several ocean products. The ESA programs contributing to the pool of ocean space-borne scientific products are:

- ESA Data User Element (DUE, 2011; http://due.esrin.esa.int/),
- ESA Support to Science Element (STSE, 2011; http://wfaa-dat.esrin.esa.int/stse/),
- ESA Climate Change Initiative (CCI).

For defining priorities of the future Sentinel Scientific Products the liaison with these programmes is important. Therefore, ESA DUE, STSE, and CCI projects dealing with the required ocean variables are stated in the Table 2.3 as 'Heritage activity'.

Priority estimation took into the account the following attributes:

- Scientific importance, matching the requirements for ECVs (GCOS, 2010) and meeting the scientific challenges of the ESA Living Planet Programme (ESA, 2006).

- Exploitation of the potentials of the Sentinel missions complemented by other ESA missions and third party missions (TPM).
- Feasibility to generate thoroughly validated geophysical products (Level-2, Level-3), matching the requirements of the scientific community in terms of accuracy and data continuity.

Applying these criteria, Table 2.3 presents a priority grade per listed product. *High priority* (H) is assigned to the scientifically highly important products generated by a solid and validated retrieval algorithm. *Medium priority* (M) is attached to scientifically important products with an immature (developing or experimental) retrieval algorithm that still needs a further validation. Ocean experts reviewed the priority ranking during the SEN4SCI scientific workshop. They did suggest any significant change, but provided few important comments. Similarly, the open public Internet review did not bring any change in the priority grading as presented in Table 2.3.

Table 2.3. List and priority rating of the ocean product deliverable by Sentinel 1-2-3 together with Earth Explorers (EE) and MetOp missions.

Nr	*Variable*	*Required Min.-Max. Threshold spatial and temporal resolution*	*Sentinel mission (EE, MetOp) /sensor*	*Auxiliary data*	*Synergy mission /sensor*	*Heritage activity*	*Priority**
Physical oceanography							
1	***Dominant wave direction (Sea state)***	10-250 km, 6 h-3 d	S-1/C-BandSAR		Radarsat	DUE GlobWave SOWWC (R&D)	H (ECV)
2	***Dominant wave period (Sea state)***	30-250 km, 6-12 h	S-1/C-BandSAR		Radarsat	DUE GlobWave SOWWC (R&D)	H (ECV)
3	***Ocean circulation (Surface currents)***	1-50 km, 1-6 d	S-1/C-BandSAR S-3/SRAL	Geoid, Mean Sea Surface, Geostrophic current	GOCE/ EGG , Alti-meters	INCUSAR SOWWC (R&D)	H (ECV)
4	***Ocean dynamic topography (Sea surface topography)***	100-300 km, 10-30 d	S-3/SRAL	Geoid, Mean Sea Surface, Geostrophic current	GOCE/ EGG , Alti-meters	GOCE User Toolbox COASTALT	H
5	***Ocean/Sea surface height (SSH) (Sea level)***	5-15 km, 2-30 d	S-3/SRAL, POD (CryoSat2/DORIS-NG)			CCI Sea Level CRYOSAT-SAMOSA COASTALT	H (ECV)
6	***Ocean/Sea surface salinity (SSS)***	25-500 km, 7-60 d	(SMOS/MIRAS)		Aquarius	STSE SMOS+	H (ECV)
7	***Ocean/Sea surface temperature (SST)***	1-500 km, 6 h-30 d	S-3/SLSTR (Metop/ IASI, AVHRR/3, HIRS/4)			CCI SST DUE GHRSST DUE GlobWave MEDSPIRATION MICROWAT STARS	H (ECV)
8	***Significant wave height (Sea state)***	10-250 km, 6 h-1 d	S-1/C-BandSAR S-3/SRAL		Radarsat and alti-meters	DUE GlobWave CRYOSAT-SAMOSA COASTALT SOWWC (R&D)	H (ECV)
9	***Wind speed over sea surface***	5-500 km, 3 h-7 d	S-1/C-BandSAR S-3/SRAL (Metop/ASCAT, AMSU-A)	Wind vectors (from ECMWF)	Radarsat and alti-meters	DUE GlobWave INCUSAR SOWWC (R&D)	M
10	***Wind vector over sea surface***	40-500 km, 3 h-7 d	S-1/C-BandSAR (in special	Wind vectors (from		MICROWAT INCUSAR	M

			cases)	ECMWF)		SOWWC (R&D)	

Comments from SEN4SCI scientific workshop:

- Sentinel sensors have a high potential to reduce the uncertainty in the sea level products.
- Ocean motions at sub-mesoscale to mesoscales are key players of the upper ocean dynamic.
- Validated estimation of uncertainties will improve product analysis and assimilation into the models.
- Few, if any, studies on altimetry, radiometry, spectrometry, scatterometry, and SAR synergies are limiting our ability to connect 2-D surface expressions with upper layer 3-D ocean dynamics.

Biological and biogeochemical oceanography

11	***Colour dissolved organic matter/yellow substance (CDOM) (Ocean colour)***	0.5-500 km, 2 h-7 d	S-3/OLCI	Cloud screening, Atmospheric correction	S-3/ SLSTR	DUE GlobColour DUE CoastColour CCI Ocean Colour	H (ECV)
12	***Inherent optical properties***	0.1-10 km 1-7 d	S-3/OLCI	Cloud screening, Atmospheric correction	S-3/ SLSTR	DUE GlobColour CCI Ocean Colour	H
13	***Marine biodiversity and habitat properties***	0.01 km 12 d	S-2/MSI				M
14	***Normalized water-leaving radiance***	0.1-100 km 1-30 d	S-3/OLCI S-2/MSI	Cloud screening, Atmospheric correction	S-3/ SLSTR	DUE GlobColour CCI Ocean Colour	H
15	***Ocean chlorophyll (Ocean colour)***	0.5-500 km 2 h-7 d	S-3/OLCI	Cloud screening, Atmospheric correction	S-3/ SLSTR	DUE GlobColour DUE CoastColour CCI Ocean Colour	H (ECV)
16	***Particle size distribution***	0.1-10 km 7 d	S-3/OLCI	Cloud screening, Atmospheric correction	S-3/ SLSTR	DUE GlobColour CCI Ocean Colour	M
17	***Photosynthe-tically Active Radiation***	0.5-50 km 2 h-1 d	S-3/OLCI S-2/MSI	Cloud screening, Atmospheric correction	S-3/ SLSTR		M
18	***Phytoplankton functional types (Ocean colour)***	1-10 km 7 d	S-3/OLCI	Cloud screening, Atmospheric correction, Temperature for parameter.	S-3/ SLSTR	DUE GlobColour CCI Ocean Colour	H
19	***Spectral attenuation coeff. for downwelling irradiance***	0.1-10 km 1-7 d	S-3/OLCI S-2/MSI	Cloud screening, Atmospheric correction	S-3/ SLSTR	DUE GlobColour CCI Ocean Colour	H
20	***Suspended sediment concentration (Ocean colour)***	0.5-500 km 2 h-6 d	S-3/OLCI	Cloud screening, Atmospheric correction	S-3/ SLSTR	DUE GlobColour DUE CoastColour MOCCASSIN POWERS CCI Ocean Colour	H (ECV)

Comments from SEN4SCI scientific workshop:

- Concurrent mapping of chlorophyll and temperature (S-3) helps to explore coupled dynamics of the ocean system.
- Improved spectral attenuation coefficient has potential to represent better the contributions to light penetration from substances better other than phytoplankton.
- Full-resolution image data (S-3, S-2) are needed to explore variability at scales hitherto inaccessible.
- A concerted effort in collecting the relevant in-situ data (incl. permanent long-term super-sites) is necessary for obligatory product validation.

* H ~ High priority, M ~ Medium priority; ECV ~ Essential Climate Variable.

The *physical oceanography* Sentinel observations are primarily focused on global mapping (S-1, S-3), but are able to bring new assets also for coastal monitoring. For instance, satellite-derived SST is a mature and robust measurement, but it would still benefit from improved resolution in both space and time. The wider dual-swath of SLSTR operated simultaneously aboard two Sentinel-3 units has the potential to provide daily SST product with per-pixel uncertainty estimates. More than 1-year overlapping operational periods of two SLSTR sensors will support independent measurement stability (0.05 K / decade). It is expected that the Sentinel-3 SRAL altimeter will be operated in SAR mode over the ocean regions of high mesoscale variability and in the coastal zones. When compared to the Low-Rate Mode (LRM) technique, the future SRAL SAR altimetry holds potential to track the ocean wind-wave parameters, e.g. significant wave height (sea state), with a significantly higher accuracy. New features and synergies of the Sentinel instruments will allow development and retrievals of new higher level (Level 3) ocean products, as for instance: wave period (SAR), precipitation rate (combination of C-band with K_u-band altimeters), global frontal detector, detection of convergence/divergence zones (negative correlation between SST and chlorophyll concentration), etc. Continuity of the measurements is also a concern. Plans for Sentinel fleet operability include a long-term commitment. Launch of Sentinel-1A and 3A units is planned for 2013, both satellites being operational until 2020. The second 1B unit will accompany 1A in mid-2015, with foreseen operational time until 2022. The 3B unit will follow in 2017, delivering data until 2024. The planned third unit 1C and 3C should be providing data from 2019 until 2026, and from 2021 until 2028, respectively. Finally, synergy of space-borne physical oceanography with measurements from ground mobile and in-situ platforms (i.e. sea level, surface currents, stream/tide gauges, precipitation, wind, river discharge, etc.) must be properly established to ensure calibration and quality validation of the ocean Sentinel products.

Traditionally, multi-spectral satellite sensors (e.g., MERIS, MODIS and also the Sentinel-3 OLCI) are primarily designed for global *biological and biogeochemical oceanography*. The asymmetric view of OLCI operated simultaneously from two S-3 units, will offer sun-glint free images with improved spatial coverage and frequency. Full spatial overlap of the OLCI with SLSTR acquisitions aboard of the S-3 satellites will allow designing so-far unfeasible synergistic approaches. The instrument synergy provides new possibilities for filling gaps in cloud-contaminated observations, for improvement of image atmospheric corrections, and also for advancement of the algorithms retrieving the in-water biogeochemical properties (e.g., primary production, mapping of slicks). The additional OLCI spectral wavebands hold promise of potentially improved products, as for instance in the case of phytoplankton functional types. Coastal (case-2) waters are optically more complex than open ocean (case-1) waters, therefore, they require a multi-spectral satellite sensor with adequate spatial resolution to fully resolve and discriminate their optical constituents. The Sentinel-2 MSI instrument could answer this challenge, under the condition that the acquisitions would cover the sea surface from the coastline to the limits of the continental shelf (i.e., in some cases more than 100 km from the sea shoreline). Main role of MSI will be to support mapping of marine biodiversity indicators (especially in case of coral reefs) and monitoring of coastal habitat changes. It will also play a high socio-economic role in timely assessment of the natural hazard impacts (e.g., coastal flooding after tsunami events). As these coastal applications are in need of frequent long-time observational time-series, mission of two simultaneous Sentinel-2 satellites will provide global revisit time of 5 days (2-3 days in extended mode). The end of 2013 should bring launch of the first Sentinel-2A unit, which should stay operational until 2020. The second 2B satellite will accompany the first unit in 2016, staying operational until 2023. Finally, the third 2C satellite is planned for the time span between 2020-2027. Similarly to the geophysical variables, in-situ observations are required to support the Sentinel product calibration and validation for monitoring of the open ocean and costal waters.

2.5. Recommendations of the ocean scientific experts during SEN4SCI workshop

In addition to identifying scientific user requirements and ocean product priorities, the ocean splinter group at the SEN4SCI workshop made the following science-related *recommendations*:

Understanding the ocean processes
Physical and biological remote sensing oceanography should join their forces together with in-situ monitoring and 3-D modelling to understand the complex interaction between physical and bio-geochemical ocean processes. Further investigation of ocean-atmosphere interactions is crucial to fully comprehend the ocean system.

Recommended attributes and access to the global datasets
Understanding the climate-driven changes and their relation to global changes in the physical environment requires data records (time-series) that are global, long-term (multi-decadal), and highly accurate (undergoing the proper calibration and stability monitoring during the entire life of Sentinel missions). The data archives should be ready for regular and timely reprocessing. Easy access to the data archives and an availability of the common standardized processing tools (e.g., open-source toolboxes) should be provided to foster the advance in the global ocean science.

Cooperation between science and operational services
Challenging operational issues spawn good science, and new scientific discoveries open the door to novel operational applications. Therefore, there is a need for an avenue to channel new scientific achievements rapidly into Sentinel operational services. A direct and effective link between operational engineers and scientists would help to explore efficiently new capabilities of the Sentinel instruments. These capabilities need to be scientifically investigated first, and then implemented into the processing chains of operational products.

Synergies across the Sentinel missions
The Sentinel observations should be exploited in the synergistic manner to better understand the mesoscale-to-submesoscale upper ocean dynamics and coupling between the physical and bio-geochemical parts of ocean and the atmosphere. This synergistic exploitation should be supported by a new generation of processing toolboxes (including shared libraries in C, Matlab, Python, etc.). For instance, the surface current parameters (including fronts, eddies, convergence/ divergence) cannot be retrieved by a single existing instrument, and therefore requires a distinct synergetic approach. Thus, a proper and stable cross-calibration among the Sentinel instruments is required.

Calibration/Validation and uncertainty estimation activities
The scientific community should be actively involved in development of the sensor long-life

calibration/validation procedures. These should be published in the peer-reviewed publications to ensure a wide acceptance of products. This can, however, only be done if the access to the instrument calibration and other technical specifications is granted. The permanent long-term supported ground monitoring super-sites or ocean hot spots should be established for algorithm calibration and error validation. Finally, methodologies for consistent per-pixel uncertainty estimations of Sentinel products should be established to ensure the long-term data consistency for the climate ocean research.

Support actions for Sentinel science
Clear interface between ESA and the science community would strengthen links between the international science teams. The coordinated scientific studies, in frame of the ESA and European Commission projects and programmes (offering user workshops, toolboxes, symposia, and expert working groups), should be supported to develop processing algorithms and Sentinel product prototypes.

2.6. Selection of ocean variables as Sentinel product examples

In total eight variables of physical oceanography and seven variables of biological and biogeochemical oceanography were ranked of high scientific priority. The ocean research community that was present at the SEN4SCI Workshop stressed the importance of all these variables to obtain comprehensive information on ocean processes and ocean/climate interactions. Necessity to limit the number of variables resulted in only two variables that were selected as examples for further development of their processing chains using the Sentinel 1-2-3 observations as the inputs, and for outlining their potential validation schemes. The main criterions applied for selecting these variables as the important Sentinel scientific products were the same as in case of the land and solid Earth variables, i.e.: i) serving a wide scientific community, ii) possibility to develop innovative processing method based on technical specifications of the Sentinel 1-2-3 instruments, and iii) the potential synergistic use of the data provided by any or several Sentinel 1-2-3 and Earth Explorer instruments. The *ocean surface currents* and the *inherent optical properties* were chosen based on the following reasoning:

I. A synergy of Sentinel 1 (Doppler velocity measurement) with Sentinel 3 (sea level anomaly measurement via radar altimetry) and GOCE Earth Explorer (mean dynamic topography) can be scientifically exploited to produce the ECVs, absolute *ocean surface* geostrophic *currents*. Further, SST and ocean colour products derived from the Sentinel 3 observations can be used for the product indirect investigation and validation.

II. Although the product of *inherent optical properties* (*IOP*) is not being considered as one of the ECVs, it is the starting point for many advanced ocean colour parameters. For instance, the slope of the particle size distribution is derived from the spectral slope of the backscattering coefficient, which is one of the *IOP* parameters. Other two *IOP* variables are the CDOM absorption coefficients in the blue part of the electromagnetic spectrum (usually at wavelength of 412 nm) and the phytoplankton absorption (usually at wavelength of 443 nm). Synergy between OLCI and SLSTR can improve accuracy of the atmospheric corrections of the Sentinel 3 optical data and consequently also the accuracy of products derived from *IOP*.

Although these two variables are of high importance for ocean research, it should be mentioned that also other variables listed as the essential climate variables, e.g. *sea state*, *SSH*, *SST*, and *ocean colour* variables, can be in future provided by the sensors aboard of the Sentinel 1-2-3 missions.

3. Summary

The first phase of the SEN4SCI project resulted a document draft stating scientific needs and requirements of 20 ocean variables that are observable from space. Document was based on review of 70 research international programs and projects that are reflecting the science objectives of ESA's Living Planet Programme outlined in the The Changing Earth study (ESA, 2006). The extensive review of observational requirements was followed up by the gap analysis identifying 19 ocean scientific variables that can be delivered by the Sentinel 1-2-3 sensors alone or in a synergistic cooperation with other European satellite missions (i.e. Earth Explorers and MetOp missions). The public open Internet peer-review, conducted after interactive discussions of SEN4SCI workshop participating scientists, assessed 14 ocean potential Sentinel products as of high priority and 5 ocean products as of medium priority.

Besides discussing the domain-specific scientific issues, the experts participating at the SEN4SCI workshop postulated the following general conclusions and recommendations for a future scientific exploitation of Sentinel observations:

- Comprehensive spatial and temporal coverage, long-term overall duration, new technical capabilities of the Sentinel 1-2-3 instruments, and also potential synergistic use of Sentinel data jointly with observations of other related missions offer a unique opportunity for development of new scientific products and applications.
- Global science requires data records (satellite time series) that are of global nature, long-term (multi-decadal), and accurate (i.e., undergoing the inter-calibration and stability monitoring during the entire life of the space borne mission constellation).
- Both on-board and external calibration/validation and quantification of per-pixel measurement accuracy and uncertainty should be performed using the standardized protocols and the dedicated sites within a fully funded operational context.
- Scientific input into the development of new products, applications, and calibration/validation protocols is essential for success of all Sentinel missions, both prior to and after their launch.

The following two ocean representative variables were selected from all the reviewed requirements to demonstrate ability of Sentinel 1-2-3 to generate important science products: *ocean surface currents*, and *inherent (ocean) optical properties*. Two external scientific experts were asked to prepare a more detailed study proposing processing chain and potential validation scheme of these satellite products, while paying a special attention to the innovative contribution and synergistic use of the Sentinel 1-2-3 missions. It is important to mention, that the selected variables are not indicating the most required satellite products by scientific community, but should be considered just as demonstrators providing the concrete examples how the GMES Sentinel 1-2-3 missions can contribute to advance the state-of-the-art Earth system science.

4. References

CEOS EO Handbook, 2010. http://database.eohandbook.com/, last access: Feb. 21, 2011.

CEOS Systems Database, 2011. http://ceos-sysdb.com/CEOS/, last access: Feb. 21, 2011.

DUE, 2011. ESA Data User Element, http://due.esrin.esa.int/, last access: Feb. 21, 2011.

GCOS, 2010. GCOS Essential Climate Variables, http://www.wmo.int/pages/prog/gcos/index.php?name=EssentialClimateVariables, last access: Feb. 21, 2011.

ESA, 2006. The Changing Earth – New Scientific Challenges for ESA's Living Planet Programme, European Space Agency, SP-1304, pp. 1-83.

GCOS, 2010. Implementation plan for the global observing system for climate in support of the UNFCCC. GCOS-138 (GOOS-184, GTOS-76, WMO-TD/No. 1523). http://www.wmo.int/pages/prog/gcos/Publications/gcos-138.pdf

IGBP, 2006. Science Plan and Implementation Strategy, IGBP Report No. 55, IGBP Secretariat, Stockholm, pp. 76.

IGOS-Carbon, 2003. A Strategy to Realize a Coordinated System of Integrated Global Carbon Cycle Observations, pp 61.

IGOS-Coastal Zone, 2006. Report of the Coastal Theme Team, A Coastal Theme for the IGOS Partnership — For the Monitoring of our Environment from Space and from Earth. Paris, UNESCO, pp. 60.

IGOS-Coral Reef, 2003. IGOS Coral Reef Sub-theme Report, A Coral Reef Sub-theme for the IGOS Partnership, pp. 36.

IGOS-Ocean, 2001. Final Report from the Ocean Theme Team, NASA on behalf of the IGOS Partnership, pp. 36.

STSE, 2011. ESA Support To Science Element, http://wfaa-dat.esrin.esa.int/stse/, last access: Feb. 21, 2011.

URD, 2011. Draft of the User Requirement Document, Ocean Colour Climate Change Initiative, Plymouth Marine Laboratory, United Kingdom, pp. 70.

WMO, 2011. Database of Observational Requirements, http://www.wmo.int/pages/prog/sat/Databases.html#User Requirements, last access: April 28, 2011.

5. Appendix

Appendix 1: Definitions of reviewed ocean variables.

Variable	Definition
Physical oceanography	
Dominant wave direction (Sea state)	Direction of the most energetic wave of the ocean wave spectrum in [°].
Dominant wave period (Sea state)	Period of the most energetic wave of the ocean wave spectrum in [s].
Ocean circulation (Surface currents)	Large-scale horizontal flow of ocean water in [m/s] that is persistent and driven by atmospheric circulation. Spatial changes in water mass density properties also trigger ocean motion along the density front.
Ocean dynamic topography (Sea surface topography)	Deviation of the time-averaged sea level from the geoid, after corrections for tides and atmospheric pressure effects, caused by the ocean currents. Physical unit including accuracy unit is [cm].
Ocean/Sea surface height (SSH) (Sea level)	Actual and local sea level in [cm] inclusive of sea level anomaly, mean sea surface and known geophysical perturbations (tides, air pressure, etc.).
Ocean/Sea surface temperature (SST)	Temperature of the seawater at the depth of 2 m (‘bulk’ temperature; < 1 mm ~ ‘skin’ temperature). Physical unit including accuracy is [K].
Significant wave height (Sea state)	Average amplitude of the highest 30 of 100 waves in [m].
Wind speed over sea surface	Horizontal vector component of the 3D wind vector over the sea surface with physical unit [m/s].
Wind vector over sea surface	Motion of the air mass over the ground, described by wind speed and the inverse of wind direction.
Biological and biochemical oceanography	
Colour dissolved organic matter (CDOM) (Ocean colour)	Indicator of biomass undergoing decomposition processes. Physical unit is [m^{-1}] with accuracy unit [%] at a specific concentration (e.g., 1 m^{-1}).
Inherent optical properties	Light absorption, scattering, and backscattering independent of variations in the angular distribution of the incident light.
Marine biodiversity and habitat properties	Various biological variables derived from the water leaving radiance and indicating the actual status of costal waters and coral reefs.
Normalized water-leaving radiance	Water-leaving radiance is the upwelling radiance just below the sea surface, which is a function of the view angle. Normalized water-leaving radiance approximates the radiance that would leave the sea surface in the absence of an atmosphere, and with sun at the zenith.
Ocean chlorophyll (Ocean colour)	Living photosynthetically active phytoplankton biomass with physical unit [mg/m3] and accuracy unit [%] at a specific concentration (e.g., 1 mg/m^3).
Particle size distribution	Number or mass of common mineral particles as a function of their size.
Photosynthetically	Amount of the photosynthetically active photons of the wavelengths

Active Radiation	between 400-700 nm that diffuses through the water compared to the downwelling at-surface flux.
Phytoplankton functional types (Ocean colour)	Experimental product that, in most cases, considers phytoplankton functional types in oceanic waters and refers often to separation by size class.
Spectral attenuation coeff. for downwelling irradiance	Underwater rate of decrease of the irradiance with unit distance, and per unit incident flux.
Suspended sediment concentration (Ocean colour)	Re-suspension or pollution of other-than-biological origin. Physical unit is [g/m3] with accuracy unit [%] at a specific concentration (e.g., 2 g/m^3).

6. List of Abbreviations

2-D	Two Dimensional
3-D	Three Dimensional
AATSR	Advanced Along-Track Scanning Radiometer
ACIA	Arctic Climate Impact Assessment
ADM	Atmospheric Dynamics Mission
ALADIN	Atmospheric LAser Doppler INstrument
ALOS	Advanced land observing Satellite
AMI	Active Microwave Instrument
AMMA	African Monsoon Multidisciplinary Analyses
AMSR	Advanced Microwave Scanning Radiometer
AMSU	Advanced Microwave Sounding Unit
AOPC	Atmospheric Observation Panel for Climate
AOT	Aerosol Optical Thickness
ASAR	Advanced Synthetic Aperture Radar
ASCAT	Advanced Scatterometer
ATSR	Along Track Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
BALTEX	Baltic Sea Experiment
C-GTOS	Coastal Global Terrestrial Observing System
CAL/VAL	Calibration/Validation
CCI	Climate Change Initiative
CDOM	Colour Dissolved Organic Matter
CEOS	Committee on Earth Observation Satellites
CHRIS	Compact High Resolution Imaging Spectrometer
CIRES	Cooperative Institute for Research in Environmental Sciences
CLIVAR	Climate Variability and Predictability
CoP	Community of Practice
DAAC	Distributed Active Archive Center
DEM	Digital Model of Elevation
Dev	Deliverable
DiNSAR	Differential SAR Interferometry
DMSP	Defense Meteorological Satellite Program
DORIS	Doppler Orbitography and Radio-positioning Integrated by Satellite
DUE	Data User Element
DWSS	Defense Weather Satellite System
ECVs	Essential Climate Variables
EE	Earth Explorer
EGG	European GOCE Gravity
ENV-CAN	Environment Canada
EO	Earth Observational
EORC	Earth Observation Research Center
EPS	EUMETSAT Polar System
ERS	European Remote Sensing
ESA	European Space Agency

EXP	EXPerimental product
FAIRE	Fast Access to Imagery for Rapid Exploitation
G	Goal
G-POD	Grid Processing On Demand
GCOS	Global Climate Observing System
GCP	Global Carbon Project
GEO	Group on Earth Observations
GERB	Geostationary Earth Radiation Budget
GEWEX	Global Energy and Water Cycle Experiment
GMES	Global Monitoring for Environmental Security
GNWP	Global Numerical Weather Prediction
GOCE	Gravity field and steady-state Ocean Circulation Explorer
GOOS	Global Oceanic Observing System
GTOS	Global Terrestrial Observing System
H	High priority
HIRS	High Resolution Infrared Radiation Sounder
HR	High Resolution
HROI	High Resolution multispectral Optical Imager
HRSOI	High Resolution Stereo Optical Imager
IASI	Infrared Atmospheric Sounding Interferometer
ICSU	International Council of Scientific Unions
IGOS	Integrated Global Observing Strategy
InSAR	Interferometric Synthetic Aperture Radar
IOP	Inherent Optical Properties
IPCC	Intergovernmental Panel on Climate Change
IR	Infrared
IS	Infrared sounder
IWS	Interferometric Wide Swath
JAXA	Japan Aerospace Exploration Agency
JERS	Japan Earth Resources Satellite
JPSS	Joint Polar Satellite System
LA	Laser Altimeter
LIDAR	LIght Detection And Ranging
LRM	Low-Rate Mode
LROI	Low Resolution multispectral Optical Imager
M	Medium priority
MACC	Monitoring Atmospheric Composition & Climate
Max	Maximum
MERIS	MEdium Resolution Imaging Spectrometer
Min	Minimum
MIR	Middle Infrared
MIRAS	Microwave Imaging Radiometer using Aperture Synthesis
Mod	Modus
MODIS	Moderate Resolution Imaging Spectroradiometer
MROI	Medium Resolution multispectral Optical Imager
MSI	Multi-Spectral Instrument
MWI	Imaging Microwave Radiometer

MWR	Microwave Radiometer
NA	Not Available
NACP	North American Carbon Programme
NASA	National Aeronautics and Space Administration
NESDIS	National Environmental Satellite, Data, and Information Service
NMA	No Mature algorithm or sensor Available
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NR	Not Rated
NWC-VSRF	Nowcasting and Very Short Range Forecasting
NWP	Numerical Weather Prediction
OC-CCI	Ocean Colour Climate Change Initiative
OD	Produced On Demand
OLCI	Ocean and Land Colour Imager
OOPC	Ocean Observations Panel for Climate
OP	Operational Product
PALSAR	Phased Array type L-band Synthetic Aperture Radar
PAR	Photosynthetically Active Radiation
POD	Precise Orbit Determination
PR	PRoduct generation for project
PSD	Particle Size Distribution
PSI	Persistent Scatterer Interferometry
PSU	Practical Salinity Unit
RA	Radar Altimeter
RS	Remote Sensing
RSL	Remote Sensing Laboratories
S-1	Sentinel 1
S-2	Sentinel 2
S-3	Sentinel 3
S&IA	Seasonal and Inter-annual Forecasting
SAR	Synthetic Aperture Radar
SCAT	Scatterometer
SEN4SCI	Sentinels for Science
SG	Second Generation
SIRAL	SAR Interferometric Radar Altimeter
SLE	Sea Level Equivalent
SLSTR	Sea and Land Surface Temperature Radiometer
SMOS	Soil Moisture and Ocean Salinity
SOLAS	Surface Ocean-Lower Atmosphere Study
SPARC	Stratospheric Processes And their Role in Climate
SRAL	SAR Radar Altimeter
SSE	Support to Science Element
SSH	Sea Surface Height
SSM/I	Special Sensor Microwave Imager

SSS	Sea Surface Salinity
SST	Sea Surface Temperature
SWIR	Shortwave Infrared
SynopMet	Synoptic Meteorology
T	Threshold
TACE	Tropical Atlantic Climate Experiment
TEC	Total Electron Content
TIR	Thermal Infrared
TOA	Top Of Atmosphere
TOPC	Terrestrial Observation Panel on Climate
TPM	Third Party Missions
UN	United Nations
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
URD	User Requirements Document
UTAS	University of Tasmania
UV	Ultraviolet
UZH	University of Zurich
VIS	Visible
WCRP	World Climate Research Programme
WGSF	Working Group on Surface Fluxes
WMO	World Meteorological Organization
WOAP	WCRP Observation and Assimilation Panel
WS	Wide Swath