ESA-CLIC
EARTH OBSERVATION AND ARCTIC SCIENCE PRIORITIES

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Editors:
Jenny Baseman
Diego Fernández Prieto

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Report Contributors

Arslan, Ali Nadir – Finnish Meteorological Institute, Finland

Bacon, Sheldon – National Oceanography Centre, United Kingdom

Baeseman, Jenny – Climate and Cryosphere Project (CliC), Norway

Bamber, Jonathan – University of Bristol, United Kingdom

Bartsch, Annett – Central Institute for Meteorology and Geodynamics (ZAMG), Austria

Bouman, Johannes – German Geodetic Research Institute/Technical University of Munich, Germany

Box, Jason – Geologic Survey of Denmark, Denmark

Briggs, Kate – University of Leeds, United Kingdom

Chapron, Bertrand – IFREMER, France

Dierking, Wolfgang – Alfred Wegener Institute, Germany

Drinkwater, Mark – European Space Agency (ESTEC), Netherlands

Duguay, Claude – University of Waterloo, Canada

Eldevik, Tor – University of Bergen, Norway

Engdahl, Marcus – European Space Agency (ESRIN), Italy

Essery, Richard – University of Edinburgh, UK

Fernández Prieto, Diego – European Space Agency (ESRIN), Italy

Flato, Gregory – Environment Canada, Canada

Forsberg, Rene – National Space Institute, Technical University of Denmark, Denmark

Gerland, Sebastian – Norwegian Polar Institute, Norway

Gourmelen, Noel – University of Edinburgh, United Kingdom

Grabak, Ola – European Space Agency (ESRIN), Italy

Hamon, Gwenaelle – CliC International Project Office

Heim, Birgit – Alfred Wegener Institute, Germany

Helm, Veit – Alfred Wegener Institute, Germany

Hogg, Anna – University of Leeds, United Kingdom

Hollands, Thomas – Alfred Wegener Institute, Germany

Hughes, Nick– Norwegian Meteorological Institute, Norway

Humbert, Angelika – Alfred Wegener Institute, Germany

Kääb, Andreas – University of Oslo, Norway

Karvonen, Juha – Finnish Meteorological Institute, Finland

Krinner, Gerhard – LGGE (CNRS/UJF Grenoble), France

Kohler, Jack – Norwegian Polar Institute, Norway

Langley, Kristy – University of Oslo, Norway

Lauknes, Tom Rune – Norut-Northern Research Institute, Norway

Linow, Stefanie – Alfred Wegener Institute, Germany

Macelloni, Giovanni – Nello Carrara Institute of Applied Physics National Research Council, Italy

Malnes, Eirik – Norut-Northern Research Institute, Norway

Markku, Similä – Finnish Meteorological Institute, Finland

Marko, Mäkynen – Finnish Meteorological Institute, Finland

Marzeion, Ben – Institute of Meteorology and Geophysics, University of Innsbruck, Austria

Matsuoka, Kenny – Norwegian Polar Institute, Norway

Meister, Rakia – National Space Institute, Denmark

Moholdt, Geir – Norwegian Polar Institute, Norway

Orsolini, Yvan – Norwegian Institute for Air Research, Norway

Pedersen, Leif Toudal – Danish Meteorological Institute, Denmark

Rixen, Michel – World Meteorological Organization, Switzerland

Rösel, Anja – Norwegian Polar Institute, Norway

Sandven, Stein – Nansen Environmental and Remote Sensing Center, Norway

Sasgen, Ingo – German Research Centre for Geosciences, Germany

Schuler, Dagrun Vikhamar – Norwegian Meteorological Institute, Norway

Seifert, Frank Martin – European Space Agency (ESRIN), Italy

Shepherd, Andrew – University of Leeds, United Kingdom

Shutler, Jamie – Plymouth Marine Laboratory, United Kingdom

Sobiech-Wolf, Jennifer – Alfred Wegener Institute, Germany

Solberg, Rune – Norwegian Computing Center, Norway

Spreen, Gunnar – Norwegian Polar Institute, Norway

Steinhage, Daniel – Alfred Wegener Institute, Germany

Stroeve, Julienne – US National Snow and Ice Data Center/UK Centre for Polar Observation and Modelling

Surdu, Cristina – European Space Agency (ESRIN), Italy

Van Oostveen, Jelte – Norwegian Polar Institute, Norway

Vitale, Vito – Institute of Atmospheric Sciences and Climate (ISAC) of the Italian National Research Council (CNR), Italy

Wagner, Penelope – Norwegian Meteorological Institute, Norway

Wesche, Christine – Alfred Wegener Institute, Germany

Westermann, Sebastian – University of Oslo, Norway

Wouters, Bert – University of Bristol, United Kingdom

List of Abbreviations

AMAP	Arctic Monitoring and Assessment Programme
AMOC	Atlantic Meridional Overturning Circulation
AP	Antarctic Peninsula
CAFF	Conservation of Arctic Flora and Fauna
CALM	Circumpolar Active Layer Monitoring
CCI	Climate Change Initiative
CCN	Cloud Condensation Nuclei
CliC	Climate and Cryosphere Project
DEM	Digital Elevation Model
DIC	Dissolved Inorganic Carbon
EAIS	East Antarctic Ice Sheet
ECMWF	European Centre for Medium-Range Weather Forecasts
ECV	Essential Climate Variable
EIA	Environmental Impact Assessment
EO	Earth Observation
EU	European Union
FWF	FreshWater Fluxes
GCOS	Global Climate Observing System
GEO	Group on Earth Observation
GEOSS	Global Earth Observation System of Systems
GIA	Glacial Isostatic Adjustment
GICs	Glaciers and Ice Caps
GL	Grounding Line
GOCE	Gravity field and steady-state Ocean Circulation Explorer
GRACE	Gravity Recovery And Climate Experiment
GTN-P	Global Terrestrial Network – Permafrost

IICWG	International Ice Charting Working Group
IMBIE	Ice sheet Mass Balance Inter-comparison Exercise
IC	Ice Concentration
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
LST	Land Surface Temperature
MSFD	Marine Strategy Framework Directive
NDVI	Normalized Difference Vegetation Index
NRT	Near Real-Time
NWP	Numerical Weather Prediction
PSTG	Polar Space Task Group
SAON	Sustaining Arctic Observing Networks
SAR	Synthetic Aperture Radar
SIOS	Svalbard Integrated (Arctic Earth) Observing System
SLSTR	Sea and Land Surface Temperature Radiometer
SMB	Simulated Moving Bed
SMOS	Soil Moisture Ocean Salinity
SOLAS	Safety of Life at Sea
STSE	Support To Science Element
SWE	Snow Water Equivalent
TOPS	Terrain Observation with Progressive Scans
UNCLOS	United Nations Convention on the Law of the Sea
UNFCCC	United Nations Framework Convention on Climate Change
WCP	World Climate Programme
WIGOS	WMO Integrated Global Observing System
WMO	World Meteorological Organization
YOPP	Year of Polar Prediction

Summary

This documents aims at collecting and elaborating on the major discussion points gathered during the ESA/CliC scientific consultation meeting on Earth Observation (EO) and Arctic Science Priorities held on 20 January 2015 at the Fram Centre in Tromsø, Norway.

The meeting aimed at reviewing and discussing the existing scientific knowledge gaps and research priority areas for the Arctic where EO may contribute for the next decade.

The outcome of the meeting and its conclusions will contribute to guide scientific activities on Arctic research, including ESA's programmatic priorities for the time frame 2017-2021. Despite not covering all components of the Arctic cryosphere, discussions covered a fairly large spectrum of research areas where EO may contribute.

Research topics that require immediate attention include:

Sea ice:

- **Ensure future sea ice thickness observation capabilities**: There is a need to: 1) address sea-ice thickness measurements in summer months, when operational needs for the data are greatest, as current techniques using CryoSat-2 and SMOS fail to work; 2) ensure more frequent and near real time (NRT) observations; 3) enhance current observation capability over the Arctic with new radar and LiDAR systems in a synergistic manner or jointly on the same platform and 4) need for continuous validation against airborne EM ice thickness and subsurface moored, or AUV-based, upward-looking sonar (ULS) ice draft measurements.
- **Snow on sea ice:** Snow on sea ice is a major source of uncertainty in both ice thickness and ice concentration retrieval from satellite data. Activities towards improved estimation of snow thickness over sea ice (e.g., based on dual-frequency SAR and combined laser and radar altimetry) are needed.
- **Sea-ice mass balance:** Sea-ice mass is an important measure of quantity because it offers the most direct link to environmental changes. A formal inter-comparison exercise to establish the extent to which these various measurements agree is therefore timely, and will lead to improved confidence in assessments of sea-ice mass balance.
- **Polynyas, thin and marginal ice processes:** dedicated research and monitoring efforts are needed, involving coordinated ice, oceanographic and meteorological *in situ* instrumentation, and the use of various satellite sensors (i.e. optical, thermal, microwave at different spatial resolution) to address key research questions including: production rate of sea ice (e.g., brine release and transportation), quantification of ice mass production, the effect of katabatic winds on the ice drift and deformation, atmospheric boundary layer processes, and the development and improvement of more realistic and complex polynya models.

- **Sea-ice drift/deformation/directional strength:**. The synergistic use of different satellite sensors in combination with advanced high-resolution models exploiting new rheologies (e.g., the elasto-brittle rheology) opens the door to new prediction capabilities in support of science and operational services. Advanced EO-based products on ocean drift/deformation/directional ice strength are needed to initialize, validate and eventually assimilate satellite data in such models.

The Arctic Ocean and its interactions:

- **Arctic sea state:** dedicated research efforts are required to better understand and characterize the different processes and interactions of sea-ice, atmosphere and ocean state: e.g., feedback of sea-ice cover reduction on sea state (e.g., increasing turbulence, augmenting the fetch) accelerating the loss of sea ice and affecting the formation rates; Impact of storms and possibly leading to a positive feedback that affects sea-ice formation.
- **Freshwater fluxes:** Freshwater fluxes (FWF) play an important role in ocean stratification and circulation: Riverine runoff into the Arctic Ocean, the Greenland Ice Sheet and Canadian Arctic contributions as well as precipitation-evaporation (P-E) play a central role in modulating the FWF. Observational evidence from both satellites and *in situ* data indicates significant changes in the freshwater balance of Arctic seas. SAR data together with Satellite altimetry, SMOS (despite the fact that L-band radiometry presents problems of sensitivity in high-latitude cold waters), and sea-surface temperature can provide key information about FWF into and out of the Arctic seas.
- **Arctic Ocean circulation:** the observation of the Beaufort Gyre spin-up indicates the potential for the Arctic Ocean circulation to change dramatically consequent to changes in atmospheric circulation and sea ice. A future summer ice-free Arctic Ocean will likely circulate faster as momentum transfer from the atmosphere to the ocean becomes more efficient. Future measurement programs will therefore need to include *in situ* and remotely-sensed ice and ocean measurements of temperature, salinity and velocity, as well as ice-specific parameters such as area/concentration and thickness to better understand and monitor this process.
- **Ocean-atmosphere heat flux:** Energy exchanges between the Arctic Ocean and the atmosphere are key climatic processes that drive oceanic and atmospheric circulation, timing and extent of heat redistribution from the lower latitudes to the Poles, as well as global and regional precipitation (liquid and solid) patterns. In order to determine the Earth's energy balance and the rate to which it is warming or cooling, high-spatial resolution observations (i.e. satellite-based sea-surface temperature and near-surface winds, atmospheric humidity) are a prerequisite.
- **Ocean-atmosphere gas exchanges:** key areas for investigation where EO may play a major role include: i) changes in atmosphere-ocean exchanges of gas between the Atlantic and Arctic waters (i.e. at Arctic gateways); ii) phytoplankton bloom dynamics (i.e. phenology, succession and poleward movement) and their impact on atmosphere-ocean gas exchanges at the gateways in the Arctic Ocean; iii) studying the impact of increased air-sea gas exchanges as a result of Arctic sea ice loss and exchanges within ice floes and marginal ice zones; iv) studying the changes in freshwater inputs and dissolved inorganic carbon (DIC) from Arctic rivers and

melting ice, and their impact on air-sea gas fluxes and the net CO_2 sink (e.g., changes in salinity, freshwater pools, increased DIC inputs from rivers); v) the study of marine aerosols and Cloud Condensation Nuclei (CCNs) generation within Arctic waters; vi) studying and characterizing the long-term variability of the CO_2 uptake by the Arctic and sub-arctic waters and vii) exploring the potential of satellite technique to contribute to observe and quantify methane seeps from the frozen Artic ocean floor.

- **Ocean acidification in the Arctic:** priority areas include: i) developing novel methods for monitoring alkalinity and air-sea CO_2 flux and studying their monthly to inter-annual variations; ii) characterizing seasonal dynamics at the lower latitude Arctic gateways to link primary production observations (and food webs) with other factors including ice cover, carbonate chemistry and air-sea gas exchange; and iii) developing upwelling indices that can identify when and where upwelling events occur along coasts (lower-temperature water upwelled with lower pH) and ice edges (warmer water upwelling with higher pH) and to characterize which coasts and regions are most at risk from this phenomenon;

Arctic hydrology:

- **The Arctic water cycle:** Despite considerable progress in terms of gaining more knowledge about the Arctic environment and the existing feedback loops at high latitudes, there are still many knowledge gaps that need to be further addressed: i) Precipitation (solid and liquid) retrieval and monitoring has been identified as a major gap for the Arctic; ii) A pan-Arctic monitoring of high-latitude lakes and the study of their long-term behaviour, and impacts on climate is needed; iii) More accurate knowledge about inflows (timing, location, amount) is essential as freshwater inputs to the Arctic Ocean alter its salinity and density and thus the general ocean circulation; iv) Snow redistribution and quantification is an important yet poorly quantified process; v) the development of enhanced observational capabilities is essential to better understand and monitor permafrost related processes and its impacts (See dedicated section below).
- **Arctic lakes and rivers:** There is a need to i) develop a long-term and sustainable observational network of lake/lake ice monitoring sites across the Arctic based on satellite remote sensing; ii) Efforts are required to prepare for a large exploitation of Sentinel-1, -2 and -3 (excellent for lake/lake ice monitoring), and to explore their synergies for the retrieval of lake-relevant geophysical parameters; iii) EM modelling of iced lakes (covered or not covered by snow) is poorly known and efforts are needed to improve it for a better understanding of SAR data and geophysical parameters retrieval; iv) There is an urgent need to develop baseline datasets of lake-relevant geophysical parameters from existing ESA and non-ESA satellite missions for select lake regions of the Arctic. These datasets are required for climate and permafrost monitoring as well as the evaluation and improvement of land surface schemes (e.g., representation of surface water-permafrost connectivity) in climate models; v) River fluxes and river ice need to be studied as they act as freshwater inputs to the ocean and freshwater outputs in permafrost regions; vi) Spring river ice break-up (flooding) is poorly covered; vii) River runoff and the impact of the freshwater balance can be eventually addressed with river ice tracking/discharge

measurements and altimetric river gauging using Sentinel-3, for large rivers in particular.

- **Permafrost:** A focused effort on improving the pan-Arctic representation of permafrost and high-latitude land surface, including wetlands, in climate models, with specific emphasis on their role in the global carbon cycle has been requested. This includes:
    - assessment of the magnitude, timing and form of carbon-based greenhouse gas release to the atmosphere from thawing permafrost and how to better incorporate this information into Earth System and Global Climate Models.
    - Land surface change resulting in the modification of terrain is a further issue. Studies focusing on such changes would benefit from uniform high-resolution, high-accuracy DEMs of the northern latitudes, modified by surface and subsurface disturbances from permafrost thaw.
    - With permafrost warming it is imperative to consider CO_2 and CH_4 emissions into the atmosphere as a result of thawing organic-rich permafrost and warming soils. The improvement of observational capacities from space to address this gap is a major need.
    - Satellite data should be utilized to also support the identification and further development and exploration of in-situ networks (e.g., identifying "hot spots" of surface change and thus advice on extension of *in situ* monitoring network; providing higher resolution (spatial and temporal) measurements in the proximity of long-term *in situ* monitoring sites ('cold spots') and north-south transects; iii) placing the *in situ* measurements into a wider spatial and temporal context)
    - To support upscaling/downscaling monitoring of permafrost regions and the spatial extrapolation/interpolation of field measurements in those regions, more investigations using a combination of SAR, optical, and thermal image products acquired at different spatial resolutions are needed.

Terrestrial snow:

- **Snow mass and water equivalent:** There is an urgent need to determine a robust method for providing information on global terrestrial snow mass and snow water equivalent (SWE), existing spaceborne sensors are unable to meet current requirements: e.g., daily or every 2-day northern hemisphere coverage at a moderate, ~1 km, resolution for operational land surface data assimilation, Numerical Weather Prediction (NWP) and hydrological forecasts. Dual or multi-frequency approaches from lower frequency L-band systems to higher frequency Ka-band systems (including exploiting the interferometric phase and tomography techniques) are needed. New dedicated missions should be explored.
- **Snow albedo:** There is an urgent need for the development of a 'climate data record' of the global snow surface albedo. Observations from climate station networks, for example on Greenland, offer validation capabilities for albedo retrievals.
- **Snow density, grain size and impurities:** There is a major need to develop advanced and robust methodologies to retrieve key parameters of snow, such as density, grain size and snow impurities, which play a major role in the snow

interactions with energy and represent important elements to enhance the performance of models, and reduce uncertainties in the estimates of other snow parameters such as SWE and albedo.

- **Snow-vegetation interactions:** Changes in Arctic vegetation will have impacts on carbon, energy and water budgets. Sentinel-2 and -3 need to be exploited to provide new characterizations of the spectral characteristics of Arctic land surfaces for monitoring of vegetation changes, complementing existing products at lower spatial resolutions from AVHRR and MODIS.

Glaciers and ice caps (GICs):

Priorities include: i) improve our observation capabilities to determine changes in elevation heights over small GICs; ii) compile data from old airphoto flights as the only practical means to extend time series of glacier volume and position into the pre-satellite era; iii) enable and coordinate systematic satellite optical stereo acquisitions for generation of repeat DEMs; iv) develop modern technologies to three-dimensionally co-register and combine heterogeneous multi-temporal elevation information towards consistent time series of glacier volume change (e.g., from airphoto flights, laser scanning, satellite altimetry, satellite stereo); v) exploit Sentinel-1 and -2 together for dense time series of glacier and calving dynamics, and couple these with observed volume changes; vi) establish a consistent long-term data record of relevant EO datasets, especially to cover Arctic glaciers – a Climate Change Initiative (CCI) and/or similar efforts are of great value to establish long-term data records of glacier information; and vii) support the improvement of regional GICs mass balance models by model verification/validation/intercomparison and eventually assimilation of EO datasets. Efforts have been started to exploit CCI data. This should be further supported and encouraged.

The Greenland ice sheet mass balance:

Key priorities include:

- **Retrievals of accumulation rates** over the ice sheets still represent a major gap in observations that impact corrections applied to satellite based methods; hence the uncertainty of mass balance estimates. There is a need to investigate and develop novel retrieval methods that may take advantage of the latest research developments (e.g., polarimetric SAR);
- **Better estimation of (snow) penetration depth** of the radar altimeter signal is required, accounting for the spatial variability and difference in penetration depth in snow/firn.
- **Fully exploit novel capabilities of Cryosat-2** for mass balance studies (e.g., swath mode shows great potential to overcome some of the limitations of traditional altimetry).

- **Continuity of high-resolution radar altimetry** (CryoSat-2) with an overlap with satellite-based laser altimetry or a future mission combining both types of sensors represents a major requirement.
- **The potential of Sentinel-1 Terrain Observation with Progressive Scans (TOPS)** mode for grounding line (GL) detection needs to be further developed and validated.
- **Sentinel-3 OLCI and Sentinel-2** offer valuable capabilities retrieving snow-covered area on glaciers, snowline position, surface albedo, all of fundamental importance in supporting surface mass balance monitoring and modelling.
- **Better GIA estimates** are needed, both from forward and inverse approaches, as currently large uncertainty exists at the global scale. In this context, the integration with GPS measurements is required.
- For future mass balance estimates, **improved integration between modelling and observations is required.**
- Future research should also focus to foster the use of **EO based products into ice sheet models** for model verification and data assimilation for reanalysis and forecasting.
- A better understanding of **year-to-year variations of ice flow speed** is needed for mass balance studies and ice sheet dynamics, as well as ice-ocean interactions.
- Studies focusing on **enhancing GRACE resolution and GOCE/GRACE combinations** represent a value added to current efforts to enhance mass balance estimates over small basins and are meant to understand how to continue with similar missions in the future.
- For Greenland, the **detection/observation of supraglacial melt ponds and streams** is a priority area that may increase our ability to better characterise ice sheet dynamics and ice-ocean interactions.

Other general key messages:

- **Supersites:** The creation of a network for Arctic supersites ensuring coordination of co-located *in situ*, airborne and satellite observations is a need in order to support basic science as well as satellite observations and Cal/Val activities.
- **Near Real-Time Observations:** The scientific community demands *near real-time* in order to be able to monitor ongoing events in a timely fashion (a few hours from acquisition).
- **Enhancing Predictability in the Arctic:** attention should be dedicated to support the WCRP Polar Climate Predictability Initiative and the WWRP Polar Prediction Project, which is stimulating the Year of Polar Prediction (YOPP) in 2017-18.
- **Reinforcing the exploitation of EO long-term consistent datasets by the modeling community** is a major requirement not only for the validation/verification and potential enhancement of model parameterizations, but

also to foster data assimilation and improving model predictability in consistency with observations.

- **Creating an Integrated Observing System for Arctic Products** has the potential to address the needs of several communities (e.g., LST, snow cover, SWE, high-resolution LC and LCC, subsidence maps, inundation/wetlands/water bodies and dynamics, lake and river ice, lake-water temperature).

Meeting abstracts

A link to all meeting abstracts can be found here:

http://www.climate-cryosphere.org/media-gallery/1383-2015-clic-esamtg-presentationsabstracts

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1. Objective of this document

This documents aims at collecting and elaborating on the major discussion points gathered during the ESA/CliC scientific consultation meeting on Earth Observation (EO) and Arctic Research Priorities held on 20 January 2015 at the Fram Centre in Tromsø, Norway.

The meeting, with a participation of approximately 50 experts, aimed at reviewing and discussing the existing scientific knowledge gaps and research priorities areas for the Arctic where EO may contribute for the next decade.

The outcome of the meeting and its conclusions will contribute to guide scientific activities on Arctic research, supporting the Arctic scientific community, CliC strategic objectives and the GEO cold region initiative. This document, together with additional inputs, will contribute to establish a strong Arctic component in the upcoming programmatic elements of ESA (in the timeframe 2017-2021) and other funding organizations including the European Commission (EC).

The ultimate target is to foster a coordinated European contribution to Arctic science and research. Coordination in Europe is foreseen through a strong collaboration between ESA, the Directorate-General for Research and Innovation (DG-RTD) of the EC and national programmes, aligning programming and developing a coherent work plan of complementary investments. This document will contribute to build a common basis for this collaborative effort and should be further developed/updated in time, as a living document, in cooperation with the scientific community, CliC, the EC and its relevant projects (e.g., EU-PolarNet. See www.eu-polarnet.eu).

The current document elaborates on the meeting discussions as well as on the different information exchanges with the participants and other experts during and after the meeting.

It is worth mentioning that the meeting did not cover all areas of research and science in the context of Arctic research, and that this document only provides a partial outlook, addressing some of the main Earth Observation contributions to Arctic science priorities. Key research domains such as biodiversity in the Arctic or atmospheric processes and chemistry have not been extensively discussed at the meeting and as such will not be considered in this paper. Those specific areas will be covered by two dedicated workshops taking place in 2015 and 2016:

- ATMOS2015: Advances in Atmospheric Science and Applications, University of Crete (Greece - Heraklion) from 08-12 June 2015.
- EO and Biodiversity, ESA-ESRIN, Frascati, 2016.

These will also be complemented by inputs provided by the international Arctic science agenda derived from the International Conference on Arctic Research Planning III

(ICARP III) process and major events such as the Arctic Science Summit Week 2015 and International Symposium on Arctic Research-4.

The meeting and this document are mainly focusing on scientific aspects and research needs. Needs for the services and operational aspects were not discussed in detail at the meeting and are only mentioned in this document when pertinent but are not described at length.

Although services are not discussed in this document, the scientific advances and research developments discussed below (in terms of novel missions, new methods and algorithms, innovative products, and enhanced knowledge of Earth system processes) represent some of the main areas to be further developed for the next generation of EO applications and information services for the Arctic.

2. Introduction

The Arctic is a complex region encompassing different physical and biogeochemical processes and interactions among several components of the Earth system (e.g., sea ice, ocean, glaciers, ice caps, the Greenland Ice Sheet, snow, lakes and river ice, permafrost, vegetation, complex interactions with the atmosphere, people, etc.). Changes in the Arctic have a strong impact on the Earth's climate system, the global energy budget, ocean circulation, the water cycle, gas exchanges, sea level, and biodiversity (AMAP, 2011). Considering that all of Earth's inter-connected components respond to changes in temperature, the Arctic is a sensitive indicator of climate variability and change.

The global climate system is revealing evidence of rapid change, largely amplified over recent decades (Yoo and D'Odorico, 2002; Schindler and Smol, 2006; IPCC, 2013). Possible explanations exist, with several stating that current changes complement one another and lead to cascading effects on a global scale; other changes may function individually and act as local or regional climatic contributing factors. In both situations, the explanations may refer to either natural variability of the climate system or to anthropogenic-related drivers. In this context, the Arctic region, highly sensitive to climate variations and extremely responsive to external forcings, is experiencing rapid changes. Understanding the different processes, their variability and the different feedback mechanisms within the Arctic system, (i.e. interactions between ocean, sea ice, atmosphere and land) represents a mandatory step towards better predictions, EO being a critical tool to provide part of the required observations.

As reported in (IPCC, 2013), observed changes in the Arctic show that over the last three decades (1979-2015), the Arctic sea ice has continued to decrease in extent at a rate of 3.5-4.1 % per decade, with loss of perennial ice extent occurring at a rate of 11.5% (±2.1%) per decade. At the same time, average winter ice thickness has decreased by 1.3-2.3 m (1980-2008), this being consistent with the decrease in perennial and multi-year ice extent. The current trend from 1979 to 2014 in September ice extent of -87,200 km^2 yr^{-1}, or a rate of -13.7% dec^{-1}. The 8 lowest September extents have all occurred in the last 8 years. Reconstructions of past sea ice conditions from terrestrial proxies (e.g. ice cores, tree-rings, lake sediments) show that the current decline in the sea ice cover is likely unprecedented for the past 1450 years (Serreze and Stroeve 2015, Kinnard et al 2011). Satellites have revealed that peripheral glaciers and ice caps (PGICs) have continue to shrink worldwide, with most of the ice loss occurring for glaciers in Alaska, the Canadian Arctic and the periphery of the Greenland ice sheet (Zdanowicz et al., 2012; Lenaerts et al., 2013). Satellite data combined with climate modelling also suggest that mass loss from the Greenland Ice Sheet has been accelerating since mid-1990s (Rignot et al, 2011; Shepherd et al., 2012) and is now the single largest mass contributor to sea level rise. Satellite records (1967-2012) also show that the annual mean snow-cover extent in the Northern Hemisphere has decreased significantly, with the greatest change occurring in June (-40% to -66%) (IPCC, 2013). Satellite records of NDVI since 1982 have shown increasing greenness over large parts of the Arctic where summer warmth has increased (Bhatt et al., 2013), consistent with ground-based and airborne observations of increases in forest-type vegetation. The limited observations of freshwater ice in lakes and rivers indicate that due to later freeze-up and earlier break-up, the duration of the lake-ice season has shortened. For example, model simulations and satellite synthetic aperture radar (SAR) observations for over 400 lakes near Barrow, North Slope of Alaska indicate that between 1991-2011, lake-ice season duration decreased by ~1 day per year, lake ice thickness declined by a total of 18-22 cm, and fewer lakes froze to the bed (grounded ice), with an overall reduction in grounded ice of 22% (Surdu et al., 2014). Following an increase in permafrost temperatures in most regions during the last decades, a general ice-rich permafrost degradation has been observed from both *in situ* and satellite observations, with significant changes in the Russian European North. There, warm permafrost up to 15 km thick completely thawed and the southern boundary of the discontinuous permafrost moved northwards by 80 km, while that of the continuous permafrost advanced northwards by 50 km (IPCC, 2013).

Despite considerable research progress in understanding the Arctic region over the last decade, many gaps remain in observational capabilities and scientific knowledge. These gaps limit present ability to understand and interpret on-going processes, prediction capabilities and forecasting in the Arctic region, thereby hampering evidence-based decision making. Addressing these gaps represents a key priority in order to establish a solid scientific basis for the development of future climate services for the Arctic, as outlined in the Roadmap for Climate Services published by the European Commission (EC, 2015).

Higher-spatial/temporal resolution and continuous observations, and improved understanding of Arctic processes shall be also integrated into future operational information services supporting coast guards executing search and rescue missions, shipping companies planning trans-Arctic passages, engineers building new infrastructure, native communities undertaking hunting and fishing expeditions, and oil and gas companies undertaking exploration/production operations. All the above need timely and reliable information, which EO satellites along with complementary *in situ* data and model simulation may contribute to deliver.

3. The Political Drivers

This section aims at listing a number of policies and policy-relevant initiatives and reports that may drive future requirements of EO in the context of Arctic research and applications. The list is not intended to be exhaustive, but to provide the reader with an overview of the major developments in this context.

The different policies, instruments, initiatives and reports are categorised in 1) Environment & climate, 2) transportation, safety & infrastructures and 3) sustainable growth.

On top of these three categories below, it is worth noting that, at an overarching level, in 2012, the European Commission and the High Representative issued a Joint Communication on "Developing an EU Policy towards the Arctic region: progress since 2008 and next steps". This communication sets out the case for increased EU engagement in Arctic issues and aims to further develop the EU's policy toward the Arctic. This will represent an overarching policy framework for the EU.

To consider:

Environment & Climate

- Transatlantic Ocean Research Alliance (Galway statement)
- UN Framework Convention on Climate Change (UNFCCC)
- Arctic Biodiversity Conservation (CAFF/RAMSAR, UNCBD)
- Climate risk management and adaptation (Global Framework for Climate Services/Global Cryosphere Watch)
- Arctic Climate Impact Assessment (AMAP/CAFF)
- Snow, Water, Ice, Permafrost in the Arctic (AMAP) (www.amap.no/swipa)
- Adaptation Actions for a Changing Arctic (Arctic Council) (www.amap.no/arctic-climate-impact-assessment-acia)
- Arctic Freshwater Synthesis (CliC/IASC/AMAP)

Transportation, Safety & Infrastructures

- Maritime safety and Marine environment impact (Polar Code, SOLAS, SAR, MARPOL, CISE, PAME)
- Northern Dimension Partnership on Transport & Logistics (NDPTL)
- Maritime Jurisdiction (UNCLOS)
- Ballast Water Management (MARPOL)
- Arctic Marine Shipping Assessment (2009) (www.pame.is/index.php/projects/arctic-marine-shipping/amsa)

Sustainable Growth

- Blue Growth Strategy (MSFD, EIA, Habitats DIR, ISO 1996, UNCLOS)
- EU-Greenland partnership (EIA, Habitats DIR)
- Northern Dimension Environmental Partnership
- Marine Biodiversity in international waters

The implementation of these policies and initiatives requires different types of environmental or climate-related data that may provide timely and reliable information to policy makers. To date, EO technology represents a key (and sometimes the only) source of information to address several data needs over the complex and remote Arctic environment. Furthermore, the synoptic, near real-time capability of EO observations makes them essential for many operational applications that have commercial and environmental security relevance.

In this context, a strong EO scientific component is needed as a key platform to build upon the novel applications and the next generation of information services for the Arctic. This science component shall follow the end-to-end approach and embrace different aspects of science, from the development of novel retrieval methods and new observational principles for future missions, passing though the development of novel EO-based products and datasets, to the utilization of this data by scientists and modelers in Earth science and process studies. New information may allow us to gain a better knowledge of the Arctic system and the different processes and changes that take place at high latitudes. This science component will also require a holistic view across disciplines involving EO experts, biologists, hydrologists, oceanographers, glaciologists, atmospheric scientists, and Arctic residents and stakeholders, along with modelers and climate researchers.

The following sections address some of the existing needs and gaps in Arctic research where EO may contribute. Addressing these science priorities is a critical requirement in order to build a solid scientific foundation for the next generation of information services in Europe and worldwide.

4. EO and Science Priorities for the Arctic

4.1 Sea ice

Sea ice is a significant component of the global climate system. It can cover up to approximately 10% of the global ocean surface, creating an insulating barrier between the relatively warm ocean water and the cold atmosphere, impacting exchanges of heat, water vapor and other gases.

Sea ice typically covers up to 15 million km^2 of the Arctic Ocean during winter months decreasing to less than half that in summer. The seasonal cycle of sea ice is one of the most dynamic components of the Earth's climate system. Satellite records show a strong downward trend in Arctic sea ice extent during all seasons, in particular during summer, with the minimum to date being recorded in the autumn of 2012 (NSIDC, 2014).

Even though being mainly driven by a temperature gradient, the global ocean thermohaline circulation is significantly influenced by seasonal changes in sea ice. As the seawater freezes and sea ice forms, the salinity and density of the surface seawater increases. This density increase causes the surface waters to sink and to effectively act as a pump, driving deep ocean currents toward the Equator and away from the polar regions. To compensate for this loss, a return flow of warmer, less dense surface water is drawn polewards from low to high latitudes. As ice melts, there is an influx of fresh water into the surrounding ocean. This reduces the salinity and consequently, water density decreases. This ocean circulation system in the North Atlantic keeps parts of northwestern Europe about 3°C warmer than it would be in its absence.

In this context, it is essential to further advance on the development of comprehensive enhanced data products and future observations systems for sea-ice (and sea-ice snow cover) thickness, extent, concentration and mass in order to improve and feed sea-ice models both for short-term to seasonal sea ice forecasts and for processes and long-term climate studies.

In this context, priority areas for future research have been identified:

- **Future sea ice thickness observation capabilities:** Sea-ice thickness is one of the most important geophysical parameters as it has a direct implication on the determination of sea-ice volume and on the evaluation of sea-ice mass balance. Sea-ice thickness influences a number of important fluxes such as the heat flux between the atmosphere and the ocean surface. Changes in sea-ice thickness/volume reflect changes in the heat budget of the Arctic and exchanges of fresh water between sea ice and the ocean. Global climate simulations predict that the decline in Arctic sea-ice thickness, due to anthropogenic greenhouse gas forcing, will be greater than that of the decay of sea-ice extent. The seasonal and inter-annual evolution of sea-ice thickness does not necessarily follow the variations of sea-ice extent (demonstrated by the CryoSat-2 mission). The same applies to the multi-year and first-year ice as they follow different thermodynamic responses to the seasonal and inter-annual drivers.

  On daily and seasonal timescales, pan-Arctic knowledge of sea-ice thickness/volume throughout the year is important for assimilation and forecasting models, and it is becoming a priority for shipping companies to safely operate in all Arctic waters. Sea-ice thickness distribution is important for ships and icebreakers since there is an upper limit to the thickness of ice that ships can sail through. Oil and gas companies are increasing their off-shore exploration activities in the Arctic. As such, they require quantified and qualified information about seasonal and long-term evolution of sea-ice thickness for their business and investment plans, including statistical information about iceberg calving, which can only be provided by high-frequency spaceborne observations systems covering all latitudes. For this reason, new near real-time (NRT) sea-ice thickness products and prompt service information will increasingly be required in the forthcoming decades.

The evolution and continuity of sea-ice thickness observations is of paramount importance in the Arctic context. CryoSat-2 represents a significant advance in this context. Additionally, recent developments in the use of SMOS L-band information to map the distribution of thin sea ice is opening the door to new scientific and future operational developments. Moreover, IceSat-2, expected to be launched in 2017, will continue the successful record of LiDAR measurements over polar regions.
However, there is a major need to ensure the continuity and further improvement of dedicated sea-ice thickness observations and to develop new generations of mission and instruments that address this important topic in the future. In particular, there is a need to:

- Address sea-ice thickness measurements in summer months, when operational need for the data is greatest, as current techniques using CryoSat-2 and SMOS fail to work.
- Ensure more frequent and NRT observations;
- Enhance current observation capability over the Arctic with new radar and LiDAR systems in a synergistic manner or jointly on the same platform.
- Data should also be extensively validated against airborne EM ice thickness and subsurface moored, or AUV-based, upward-looking sonar (ULS) ice draft measurements.

- **Snow on sea ice:** Snow on sea ice was identified by the Global Climate Observing System (GCOS) as a major source of uncertainty in both ice thickness and ice concentration retrieval from satellite data. As such, a much larger effort should be put into using all available data (active/passive microwave, optical, *in situ*/airborne) to quantify key snow parameters (e.g., thickness, concentration). Snow parameters are not only important for processing of remote sensing data but also for thermodynamic (and even some dynamic) processes. Due to its low thermal conductivity, the presence of snow on sea ice greatly modifies its thermodynamics, affecting seasonal accretion and ablation rates (Massom, 2001). Because of its high albedo compared with that of sea ice, snow dominates the surface shortwave energy exchange. Also, by smoothing the ice surface, snow greatly modifies the ice-air drag coefficient and the bulk transfer coefficients for latent and sensible heat. It also has a first-order effect on the microwave properties of the surface, leading to ambiguity in retrievals of sea-ice type and concentration from satellite data. Snow thickness on sea ice is still poorly known and current thickness estimation with satellite passive microwave radiometer data has poor accuracy due to the sensitivity of the data to ice surface roughness (Stroeve et al., 2013). Activities towards improved estimation of snow thickness over sea ice (e.g., based on dual-frequency SAR and combined laser and radar altimetry) are needed. The availability of complementary data from CryoSat-2 and AltiKa (35.75 GHz) and also from the forthcoming 2016 Sentinel-3 (13.57 GHz altimeter) along with scatterometers may offer a starting point to explore this capability. In addition, the availability of ICESat-2 mission from 2017 in combination with CryoSat-2 should allow snow depth retrieval in cold conditions.

- **Sea-ice mass balance:** Sea-ice mass is an important measure of quantity because it offers the most direct link to environmental changes. In fact, changes in other attributes, such as sea-ice extent or thickness, can arise with no net change in sea-ice mass amount (and vice versa).

  Satellite observations have delivered routine assessments of sea-ice extent for decades and historically, relatively sparse airborne or submarine-based observations of sea-ice thickness have been used to develop estimates of sea-ice volume change. Over the past decade, a range of satellite-based estimates of sea-ice thickness has become available from a number of sensors, making systematic assessments of sea-ice volume achievable (Armitage et al., 2014; Kern et al., 2015).

  However, computing sea-ice mass is a rather complex task for satellites. Sea ice is covered by snow, which complicates retrievals and assessments, as it is needed to determine where the fluctuations in mass are taken place (sea ice vs. snow). With the aid of model base approaches, it is possible to discriminate between changes in volume arising through fluctuations in snow and ice, in order to determine changes in sea-ice mass.

  Given the variety of satellite- and model-based approaches for estimating changes in sea-ice extent, thickness, and snow depth, differences between assessments of sea-ice mass balance are to be expected. A formal inter-comparison exercise to establish the extent to which these various measurements agree is therefore timely, and will lead to improved confidence in assessments of sea-ice mass balance. This shall be supported by a strong *in situ* component, exploiting snow thickness radars and EMI data.

- **Polynyas, thin and marginal ice processes:** For climate science and ocean dynamics, polynyas are key regions as they are locations of highly dynamic processes in the sea-ice cover, sources of heavy ice growth and associated release of brine into the underlying water column, and of strong exchanges of heat, matter, and momentum between the ocean and the atmosphere. Understanding these processes and interactions are critical element to understand sea ice formation and dynamics.

A meaningful set of process studies and a sustainable monitoring program is needed, involving coordinated ice, oceanographic and meteorological *in situ* instrumentation, and the use of various satellite sensors (i.e. optical, thermal, microwave at different spatial resolution). Key research questions include production rate of sea ice (e.g., brine release and transportation), quantification of ice mass production, the effect of katabatic winds on the ice drift and deformation, atmospheric boundary layer processes, and the development and improvement of more realistic and complex polynya models.

- **Sea-ice drift/deformation/directional strength:** Sea-ice dynamics represent a main area of research with important implications for Earth science and operational applications. In the years to come, the availability of a whole suite of different satellite sensors (e.g., scatterometers, radiometers, radars, optical sensors, LiDARs, altimeters) open new opportunities for the development of advanced synergistic products characterising sea-ice dynamics including drift, deformation, and directional strength.

The synergistic use of different satellite sensors in combination with advanced high-resolution models exploiting new rheologies (e.g., the elasto-brittle rheology) opens the door to new prediction capabilities in support of science and operational services. Advanced EO-based information on ocean drift/deformation/directional ice strength is needed to initialize, validate and eventually assimilate satellite data in such models. Different sea-ice conditions (e.g., ice thickness, ice concentration) and environmental aspects (e.g., blocking effects from the coast,from fast ice or wind field) have to be considered. Key regions have to be selected where buoy arrays and devices for measuring distances and dynamics in the sea ice need to be deployed for acquisition of complementary data on sea-ice deformation. The important point about deformation analysis is that it has to be carried out at different spatial and temporal scales, and in a systematic manner.

4.2 The Arctic Ocean and its interactions

In the Arctic, rapid economic, social and political development coincides with environmental transformations (i.e. in sea-ice extent, ice thickness and drift patterns, coupled with an evolving sea-state climate). In this context, better understanding and quantification of the interaction between the Arctic Ocean/sea ice, atmosphere and land (e.g., ice albedo feedback, evaporation, river outflows) represents a major area of research where EO technology can make a significant contribution. The availability of long-term satellite SAR, altimeter, optical and passive microwave data, along with the availability of data from newly/to-be-launched missions (CryoSat-2, SMOS, Sentinel-1/2/3), represents a major opportunity for further advancements in this important area.

Combining data (e.g., scatterometers, radiometers, SAR, and altimeters, LiDARs) not only enables inference of key ice properties but also provides information on ocean circulation and wave characteristics within and outside the marginal ice zone.

With a particular emphasis on the Arctic, potential exists to bring a greater benefit to investigations related to near-ice processes, evolution of the ice edge and its climate implications. This can complement the on-going *in situ* and numerical modelling efforts regarding the atmosphere, ocean, ice and waves.

Six major research areas have been identified. It is worth noting that the six areas below are intimately related and all are components/drivers of the ocean/sea ice-atmosphere-land interactions. They in fact represent various aspects of a complex process that includes different feedback mechanisms and exchanges of matter, heat and momentum between the different components of the Arctic system.

- **Arctic sea state:** The Arctic Ocean has been a “serene region” for decades with the sea ice layer dampening waves. However, this situation is changing as summer sea-ice extent is diminishing. The rapid loss of summer sea-ice cover is changing the way that the sea ice, ocean and atmosphere interact at different levels.

  The reduction of sea-ice cover extent fosters the formation of internal waves in Arctic waters that could perhaps accelerate the loss of sea ice. Woodgate et al. (2015) report that Arctic waters along continental shelves are becoming more turbulent as the summer sea ice disappears and waves start churning the water as in other oceans. These underwater waves have different impacts on the Arctic Ocean. On one hand, they increase the turbulent behavior of the ocean, making it more productive and bringing nutrients from deep waters closer to the surface. On the other hand, a more turbulent Arctic Ocean could accelerate the melting of Arctic sea ice. In particular, unlike any other ocean basin, the Arctic is fresh and cold at the surface from melted ice (halocline layer), while it is very salty and slightly warmer below (100 m). If turbulence mixes these waters, the warmer surface could accelerate the melting of sea ice.

  Furthermore, a reduced sea-ice extent increases the forcing of the atmosphere on the ocean surface augmenting the fetch and surface sea state that interacts with the sea ice and may affect the formation rates. In particular, ice break-up enhances ice melt rate by increasing the area of open water for absorption and providing a larger surface area for lateral melting. Wave conditions also alter the refreezing process (Doble, 2009). If the current trend in sea-ice extent reduction continues, a larger fetch for wave development will be available. This increased fetch will promote the formation of larger waves of lower frequency and higher energy (Hasselmann et al., 1973), waves that were associated with a reduced ice cover in the Arctic Ocean during recent years (Thomson and Rogers, 2014). Since lower-frequency waves propagate farther into the ice pack, there is potential for more wave energy to affect a larger area of sea ice and potentially increase the breaking-up of the sea ice cover (Kohout et al., 2014). The consequences and magnitude of this feedback mechanism remain an open question.

  Storms, characterized by strong winds and high waves, may also play a major role in this process, leading to vertical mixing processes that can affect the cold halocline layer and possibly leading to a positive feedback that affects sea-ice formation. Understanding the impact of these events on climate is still unknown and needs to be investigated.

- **Freshwater fluxes:** Freshwater fluxes (FWF) play an important role in ocean stratification and circulation. In the Arctic and sub-polar North Atlantic, they are also important for marine productivity. Changes in ocean circulation, in the strength of the Atlantic Meridional Overturning Circulation (AMOC) in particular, can have impacts on the climate system at global scale. As a consequence oceanographic observational transects have been established to monitor the strength of the AMOC at key latitudes. These observations, however, provide limited information on the causes of changes. Large fluxes of freshwater are transported out of the Arctic Ocean each spring via sea-ice export through the Fram Strait. Riverine runoff into the Arctic Ocean (the Riverine Coastal Domain) is also a key contributor to the FWF and nutrient balance of the Arctic that can be better estimated by a combination of satellite altimetry, river outline mapping, near-simultaneous space imagery, and in-situ measurements.

  In the last two decades, FWF from the Greenland Ice Sheet and Canadian Arctic have been steadily increasing into both the Arctic and North Atlantic Oceans. Finally, precipitation-evaporation (P-E) also plays a central role in modulating the FWF and, as a consequence, the hydrography of the region. Observational evidence from both satellites and *in situ* data indicates significant changes in the freshwater balance of Arctic seas. Satellite altimetry can provide information on geostrophic flow, spin-up of the ocean and mesoscale variability.

  SAR data have proved to be invaluable for accurately tracking sea-ice transport, while SMOS might provide measurements of surface salinity changes (despite the fact that L-band radiometry presents problems of sensitivity in high-latitude cold waters). Combined with data on sea-surface temperature, this provides important information about thermohaline flow and mixing of surface waters. The mass imbalance of the Greenland Ice Sheet, and hence its freshwater input into the Arctic Ocean, can be determined from satellite altimetry. Thus a combination of satellite observations can provide key information about FWF into and out of the Arctic seas.

  SAR data could be also useful for iceberg monitoring which could be fundamental for a better understanding of their contribution to freshwater flows. Iceberg monitoring with SAR data would also ensure safer maritime travel and drilling operations in the Arctic. It has been recognized that there is an operational need to better understand iceberg movement, sources and effect of climate change on populations, and include forecasting of trajectories into operational meteorological-ocean models.

- **The Arctic Ocean circulation:** The well-reported increase in Arctic Ocean freshwater storage over the past 15 years is directly related to Ekman pumping and consequent spin-up of the Beaufort Gyre (Giles et al., 2012). While summers are confidently predicted to become ice-free by the end of the century, a substantial area of sea ice still survives through the winter at present. Even so, the observation of gyre spin-up indicates the potential for the Arctic Ocean circulation to change dramatically consequent to changes in atmospheric circulation and sea ice. A future summer ice-free Arctic Ocean will likely circulate faster as momentum transfer from the atmosphere to the ocean becomes more efficient. It is therefore further possible that the current very low level of ocean turbulent mixing will increase. Should this mixing become strong enough, it would bring sub-surface heat from the Atlantic water layer up to the surface (Rippeth et al., 2015). If it did, it could prompt further decline in the sea ice cover, perhaps impacting seasons outside summer. In addition to improved physical understanding of atmosphere, ice and ocean physics, key future measurement programs will therefore need to include *in situ* and remotely-sensed ice and ocean measurements of temperature, salinity and velocity, as well as ice-specific parameters such as area/concentration and thickness.

- **Ocean-atmosphere heat flux:** Energy exchanges between the Arctic Ocean and the atmosphere are key climatic processes that drive oceanic and atmospheric circulation, timing and extent of heat redistribution from the lower latitudes to the poles, as well as global and regional precipitation (liquid and solid) patterns. In order to determine the Earth's energy balance and the rate to which it is warming or cooling, high-spatial resolution observations (i.e. satellite-based sea-surface temperature and near-surface winds, atmospheric humidity) are a prerequisite.

- **Ocean-atmosphere gas exchanges:** The atmosphere-ocean (air-sea) movement (flux) of greenhouse gases is a critical part of the climate system and a major factor in the oceanic biochemical evolution. The Arctic Ocean makes up only ~1% to the global ocean volume but it is considered to account for 5-14% of the total oceanic sink for anthropogenic carbon dioxide (CO_2) (Bates and Mathis, 2009), a process which begins via air-sea gas exchange. Despite CO_2 receiving the most attention, other greenhouse gas fluxes that are inter-linked with the carbon cycle include methane (CH_4) and nitrous oxide (N_2O) and thus studying these fluxes can aid our understanding of CO_2. Equally, characterizing dimethyl-sulphide (considered to provide cloud condensation nuclei (CCN)) and oxygen gas fluxes (which can be used to estimate ocean primary production) are also important to help our understanding of the changing Arctic. For example, increased CCN could lead to increased cloud generation, leading to further warming in the Arctic and increased loss of sea ice.

The harsh weather, remote location and heterogeneous nature of the Arctic makes it difficult and expensive to rely solely on *in situ* observations for monitoring and understanding this changing environment. Synergistic use of satellite observations, in conjunction with *in situ* data and models, provide a solution to obtaining more spatially complete observations. Such data can be used for driving innovative process studies (Land et al., 2013), climate model evaluation and data assimilation, and developing monitoring methodologies.

Gas exchanges comprise and are controlled by chemical, physical and biological processes, and satellite Earth observation can be used to support the study of all three, in relation to both the forcing and the impacts. Issues highlighted by the international community (e.g., Hofman et al., 2014) where satellite Earth observation can be exploited in relation to Arctic gas exchanges research include: i) the need to understand and characterize changes in atmosphere-ocean exchanges of gas between the Atlantic and Arctic waters (i.e. at Arctic gateways); ii) characterization of phytoplankton bloom dynamics (i.e. phenology, succession and poleward movement; Winter et al., 2013) and their impact on atmosphere-ocean gas exchanges (Shutler et al., 2013) at the gateways in the Arctic Ocean; iii) studying the impact of increased air-sea gas exchanges as a result of Arctic sea ice loss and exchanges within ice floes and marginal ice zones (e.g., using Sentinel-1); iv) studying the changes in freshwater inputs and dissolved inorganic carbon (DIC) from Arctic rivers and melting ice, and their impact on air-sea gas fluxes and the net CO_2 sink (e.g., changes in salinity, freshwater pools, increased DIC inputs from rivers); v) the study of marine aerosols and CCN generation within Arctic waters; vi) studying and characterizing the long-term variability of the CO_2 uptake by the Arctic and sub-arctic waters (e.g., using the ESA SST, ocean color Climate Change Initiative data in conjunction with GlobWave and *in situ* data) and vii) exploring the potential of satellite techniques to contribute to observe and quantify methane seeps from the frozen Artic ocean floor.

- **Ocean acidification in the Arctic:** Approximately a quarter of the anthropogenic CO_2 emitted into the atmosphere is absorbed by the ocean. This oceanic uptake of CO_2 leads to a change in marine carbonate chemistry resulting in a decrease of seawater pH and carbonate ion concentration, a process commonly called "ocean acidification" (Land et al., 2015).

  Cold water can absorb more CO_2 than warmer water, and so the polar oceans are taking up CO_2 at a faster rate than elsewhere on the planet. One of the additional issues with the Arctic Ocean is the potential for enhanced ocean acidification in the future as a result of the increased input of freshwater, as sea ice retreats and the planet warms. It is hypothesized that the addition of freshwater into the Arctic will dilute the ocean’s ability to cope with higher acidity but this is yet to be tested and verified by observations.

  Baseline data are required to understand the current carbonate chemistry and biology in the Arctic, and the processes that could potentially enhance the rate of ocean acidification. Without this knowledge, it is difficult to make predictions about how ecosystems will respond to ocean acidification in the future, and this impedes our ability to mitigate change, as well as to manage the environment. In this context, research priority areas include:

i) developing novel methods for monitoring alkalinity (e.g., SMOS; Land et al., 2015) and air-sea CO_2 flux and studying their monthly to inter-annual variations;
ii) characterizing seasonal dynamics at the lower latitude Arctic gateways to link primary production observations (and food webs) with other factors including ice cover, carbonate chemistry and air-sea gas exchange;
iii) developing upwelling indices that can identify when and where upwelling events occur along coasts (lower-temperature water upwelled with lower pH) and ice edges (warmer water upwelling with higher pH) and to characterize which coasts and regions are most at risk from this phenomenon; and
iv) further improvements and advances in estimating sea-ice areal coverage, thickness, snow depth and sea-ice densities (e.g., reliable snow depth and density, sea-ice densities improving estimates of ice thickness). The enhanced retrievals of these parameters in the marginal ice zones is especially important, as this is where gas exchanges are likely to occur.

4.3 Arctic hydrology

- **The Arctic water cycle:** The water cycle at high latitudes contributes to regulating the planetary heat balance and circulation of the global oceans. Arctic hydrology, comprised of both a marine (sea ice, snow on sea-ice, ocean water) and a terrestrial system (glaciers/ice caps and ice sheets, snow, permafrost, lakes and rivers) is extremely complex and is driven by intricate linkages and interactions between ocean, land, and atmosphere. Despite considerable progress in terms of gaining more knowledge about the Arctic environment and the existing feedback loops at high latitudes, there are still many knowledge gaps that need to be further addressed:

i) Summer precipitation comprises a significant part of the mean annual total precipitation (solid and liquid), and Arctic precipitation and the fraction of liquid to solid precipitation has increased during recent decades due to higher temperatures (Screen and Simmonds, 2012). Precipitation (solid and liquid) retrieval and monitoring has been identified as a major gap for the Arctic and as such impacts the accuracy of precipitation forecasts at high latitudes. Dedicated observation capabilities are required to cover this gap;
ii) Regional/local climates are affected by the presence of water bodies and their ice regimes (e.g., lakes and ponds). A pan-Arctic monitoring of high-latitude lakes and the study of their long-term behaviour, and impacts on climate is needed. The availability of long-term SAR archives and the recent availability of Sentinel-1 and the upcoming Sentinel-2 provides new observational capabilities to address this gap (See dedicated section below);
iii) Approximately two thirds of the freshwater flux comes from land and considerable runoff occurs in a short period following spring ice break-up. More accurate knowledge about inflows (timing, location, amount) is essential

as freshwater inputs to the Arctic Ocean alter its salinity and density and thus the general ocean circulation;

iv) Snow redistribution and quantification is an important yet poorly quantified process. Advances in the observation of snow parameters including snow cover, snow grain size, snow pollution and SWE are needed (See dedicated Section below);

v) Permafrost degradation impacts the terrestrial Arctic water cycle, with the potential of the Arctic freshwater system to transition from mainly occurring at the surface to being a groundwater-dominated system (Rawlins et al., 2013). The development of enhanced observational capabilities is essential to better understand and monitor permafrost related processes and its impacts (See dedicated section below).

- **Arctic lakes and rivers:** Lakes that form a seasonal ice cover are a major component of the terrestrial landscape with estimates of their areal coverage reaching up to 40-50% in some regions of the Arctic and sub-Arctic. Lakes have the highest evaporation rates of any high-latitude terrestrial surface. Their abundance and size greatly influence the magnitude and timing of landscape-scale evaporative and sensible heat inputs to the atmosphere and are important to regional climatic and meteorological processes. The duration of lake ice in particular, controls the seasonal heat budget of lake systems thus determining the magnitude and timing of evaporation. The presence of ice cover on large lakes during the winter months has also an effect on both regional climate and weather events (e.g., thermal moderation and lake-effect snow).

  In an Arctic that is warming at almost twice the rate of the rest of the world, model simulations predict that lakes will develop thinner ice covers that stay for a shorter period. Already there are signs that open water season duration is increasing and ice thickness is decreasing on shallow water bodies (ca. less than 4 m deep), having an impact on hydrologic connectivity and storage, permafrost, carbon fluxes and biodiversity in the Arctic system. There has therefore been growing interest from the scientific community regarding the status of shallow water bodies, as their growth or disappearance may be an indication of the effects of a changing climate. Further, whether such shallow lakes freeze through or not, and changes in this condition over time, strongly influences the biological activity at the lake bottom and with that the potential emission of greenhouse gases. Higher air temperatures have accelerated permafrost thaw in many regions of the circumpolar Arctic, leading to a drying of upland areas and an impounding of drainage in subsiding areas. Surface water in the landscape presents a positive feedback that enhances permafrost degradation in wet areas, which may either increase the availability of water to lakes and ponds or increase hydrologic connections between lakes and their surroundings, causing them to drain.

  A few studies have used remote sensing to document trends and variability in lake surface areas and ice cover over the past 60 years. However, there is an overall paucity of observations on the fate of the many shallow water bodies across the Arctic, and variability across regions is poorly known. Research is needed to determine whether expansion or drainage of these water bodies will dominate various types of permafrost landscapes over the coming decades, and which regions of the Arctic will be affected by these changes. In addition, there is a need to monitor changes not only in surface area/extent of water bodies but also other parameters indicative of their dynamics (e.g., fraction of bedfast ice, ice freeze-up/break-up dates and duration, surface water temperature, water turbidity/chemistry, and water level). Long-term monitoring at multiple locations across the circumpolar Arctic is urgently needed to assess the trajectory and magnitude of changes in these parameters.

In addition, although latest versions of global and regional climate models are now able to simulate near-surface permafrost interactively, the hydrologic effects of lakes and wetlands in permafrost regions are currently not represented in these models. Work towards improvement of the representation of river-lake/wetland/permafrost connectivity in climate models is only beginning. Improved models can then be used to study the influence of lakes/wetlands/permafrost on the spatial and temporal distribution of water and energy fluxes in current and future climates. Satellite observations are a critical data source for evaluating and improving climate models in permafrost regions during both ice-covered and open-water seasons.

In this context:

i) There is a need to develop a long-term and sustainable observational network of lake/lake ice monitoring sites across the Arctic based on satellite remote sensing (SAR and optical in daylight and no-clouds conditions) in view of recent and upcoming satellite missions of ESA and other space agencies;

ii) Efforts are required to prepare for a large exploitation of Sentinel-1, -2 and -3 (excellent for lake/lake ice monitoring), and to explore their synergies for the retrieval of lake-relevant geophysical parameters (e.g., surface area/extent, fraction of bedfast ice, ice freeze-up/break-up dates and duration, surface water temperature, water turbidity, and water level) from large to small Arctic lakes (e.g., perennially ice-covered lakes, shallow thermokarst lakes). Moreover the EM modelling of iced lakes (cover or not covered by snow) is poorly know and effort are needed to improve it for a better understanding of SAR data and geophysical parameters retrieval;

iii) There is an urgent need to develop baseline datasets of lake-relevant geophysical parameters from existing ESA and non-ESA satellite missions for select lake regions of the Arctic. These datasets are required for climate and permafrost monitoring as well as the evaluation and improvement of land surface schemes (e.g., representation of surface water-permafrost connectivity) in climate models;

iv) River fluxes and river ice need to be studied as they act as freshwater inputs to the ocean and freshwater outputs in permafrost regions;

v) Spring river ice break-up (flooding) is poorly covered;

vi) Sentinel-1 is an excellent tool for river ice monitoring;

vii) River runoff and impact of freshwater balance can be eventually addressed with river ice tracking/discharge measurements and altimetric river gauging using Sentinel-3, for large rivers in particular.

4.4 Permafrost

Permafrost is one of the Essential Climate Variables (ECV) defined by the Global Climate Observing System (GCOS) and acknowledged by World Meteorological Organization (WMO) and United Nations Framework Convention on Climate Change (UNFCCC). Its monitoring as part of the cryosphere has been identified as a Grand Challenge by the World Climate Research Programme (WCRP) Joint Science Committee and a draft white paper on this topic was published in 2012 (Kattsov et al., 2012). A focused effort on improving the representation of permafrost and high-latitude land surface, including wetlands, in climate models, with specific emphasis on their role in the global carbon cycle has been requested. This was further discussed during the WRCP and CliC workshop in Tromsø, Norway, 16-18 October 2013 (Pope and Baeseman, 2014) and the DUE Permafrost User Workshop in Frascati, 11-13 February 2014. The latter contributed to a community white paper in response to the WMO-Polar Space Task Group (Bartsch et al., 2014). In this context, plans for assessment of the magnitude, timing and form of carbon-based greenhouse gas release to the atmosphere from thawing permafrost and how to better incorporate this information into Earth System and Global Climate Models have been discussed. The global implementation of a permafrost monitoring system has been identified as feasible in 2004 (GCOS implementation plan) within the 10-year baseline and as having a high impact on UNFCCC requirements. The International Permafrost Association responded to this need initiating and managing the Global Terrestrial Network for Permafrost (GTN-P) to monitor the active layer thickness (ALT) and the thermal state of permafrost (TSP). It has recently been upgraded with a fully operational online database (see Biskaborn et al., 2015), which collects, standardizes, quality controls and disseminates these two parameters. However, comprehensive monitoring and assessing the warming of permafrost requires a high variety of parameters, including:

i) permafrost extent and patchiness;
ii) ground temperature profiles;
iii) permafrost ice content;
iv) active layer thickness;
v) thickness of permafrost;

Land surface change resulting in the modification of terrain is a further issue. Studies focusing on such changes would benefit from uniform high-resolution, high-accuracy DEMs of the northern latitudes. Permafrost-related terrain changes, including geo-hazards in lowlands and mountain areas, are: seasonal surface heave and subsidence of the active layer, long-term permafrost thaw subsidence, and rapid disturbances associated with landslides (including active layer detachment slides, retrogressive thaw slumps, rock slides), themokarst thermo-erosion as well as coastal erosion. All are related to the loss of ground ice due to permafrost thaw. Transport of carbon mobilized from thawing permafrost to lakes, rivers and oceans needs to be better quantified. Permafrost extent and state can be estimated with models that may ingest satellite derived geophysical parameters such as land-surface temperature and snow water equivalent/depth. Land cover and terrain datasets provide boundary conditions. Soil properties need to be known in order to account for changes related to climate change. This includes carbon and ice/water content. Carbon exchange with the atmosphere over permafrost regions need to be measured with flux towers, airplanes, and satellite missions to quantify source and sink characteristics. Implications for infrastructure, specifically related to northern communities as well as extraction of natural resources as well as indigenous societies need to be addressed in this context. Indigenous peoples and Arctic residents are affected as ecosystems and the hydrological systems are continuously modified by surface and subsurface disturbances from permafrost thaw.

With permafrost warming it is imperative to consider CO_2 and CH_4 emissions into the atmosphere as a result of thawing organic-rich permafrost and warming soils. The improvement of observational capacities from space to address this gap is a major need.

Current monitoring sites represent in general locations that are more easily accessible but in some cases are not necessarily those regions where significant changes occur. Satellite data should be utilized to:

i) identify "hot spots" of surface change and thus advice on extension of *in situ* monitoring network;
ii) support modelling of sub-surface conditions;
iii) provide higher resolution (spatial and temporal) measurements in the proximity of long-term *in situ* monitoring sites ('cold spots') and north-south transects;
iv) place the *in situ* measurements into a wider spatial and temporal context;
v) map and monitor systematically at high-resolution the coastlines in high latitudes, and
vi) generate regional scale analysis of permafrost disturbances and their rates and trends.

The implementation of a comprehensive cryosphere observing network of reference "CryoNet" sites has been identified as an action item as part of the WMO Integrated Global Observing System (WIGOS) Implementation Plan for the Evolution of Global Observing Systems (EGOS-IP, 2013). Currently four out of the global list of CryoNet-defined supersites are located in a polar permafrost environment. Three of these (Zackenberg, Barrow, Tiksi) are the focus of long-term environmental research (*in situ*). However, many sites that are not included in CryoNet are regularly monitored as part of the Global Terrestrial Network for Permafrost (GTN-P). GTN-P developed a database for the two ECV's: permafrost temperature (TSP – Thermal State of Permafrost) and active layer thickness (CALM Circumpolar Active Layer Monitoring). In this framework, at least 23 remote flux stations operate continuously in permafrost regions, measuring releases of CH_4 and CO_2 directly.

About 50 locations ('cold spots') have been identified where permafrost (Arctic and Antarctic) *in situ* monitoring has been taking place for many years or where field stations are currently established (through, for example the Canadian ADAPT program). These sites have been proposed as part of the community white paper (Bartsch et al., 2014) to the WMO Polar Space Task Group (PSTG) as focus areas for future monitoring by satellite data.

To support upscaling/downscaling monitoring of permafrost regions and the spatial extrapolation/interpolation of field measurements in those regions, more investigations using a combination of SAR, optical, and thermal image products acquired at different spatial resolutions are needed. For SAR, this means combining wide-swath mode, strip-map mode, and spotlight mode and different radar frequencies. The objective is to collect "pure" signatures of different land cover units (vegetation and bare surface types, lakes, rivers) and their variations due to changing environmental and meteorological conditions in key regions with sufficient infrastructure for ground measurements. The reason is that land cover types can change at rather small spatial scales, on the order of a few tens of meters. Hence, "clean reference" signatures are needed to improve the retrieval of bio-geophysical parameters from coarse-resolution radar images, which provide the necessary spatial coverage and temporal resolution to monitor long-term trends in land-cover changes.

Regional interferometric SAR (InSAR) studies are needed over cold spot regions to quantify rates and trends in surface subsidence related to permafrost thaw. A key to monitoring understanding and permafrost dynamics is the exploitation of decadal scale time series of imagery from multiple satellite/sensor systems, such as combinations of Landsat with future Sentinel-2 time series.

4.5 Terrestrial Snow, snow and ice albedo and SWE

Snow is the brightest natural surface and it plays, therefore, a critical role in modulating the planetary albedo. Snow presence and snow water equivalent (SWE) retrieval has been identified as a major gap in EO. General consensus was achieved on the need for snow products, including albedo, thickness/depth, and SWE.

Satellites provide key observations for monitoring global snow processes for climate research, hydrological, meteorological and other operational applications. This allows for studies on the evolution of seasonal snow cover (SWE, snow extent, snow and ice albedo and fractional snow cover) and the effect on carbon cycling, radiation balance and hydrological and meteorological forecasting. ESA has provided support to important activities in relation to snow parameter retrieval and snow products from active and passive remote sensing data, such as the ESA DUE GLOBSNOW activity or activities in the framework of the Phase A activities for CoReH2O (an Earth Explorer 7 candidate mission). Furthermore, there has been a considerable effort in the development of new objective measurement techniques (i.e. snow micro-CT, snow micro-penetrometers (EMP), and laser-induced reflectance to characterize snow microphysics), and of new technologies for investigating unique stratigraphic contributions to emission/backscattering (i.e. radar tomography). Recent advancements have focused on better understanding of the interactions between microwaves (active and passive) and snow through field observations coupled with advances in snow emission and backscatter modelling.

- **Snow mass and water equivalent:** Although there is an urgent need to determine a robust method for providing information on global terrestrial snow mass, existing spaceborne sensors are unable to retrieve this parameters at high spatial and temporal resolution scales. Indeed the observational needs in terms of spatial and temporal resolution, have been addressed in the IGOS Cryosphere Theme Report (2007) cannot be met by conventional/current satellites and products (e.g., daily or every 2-day northern hemisphere coverage at a moderate, ~1 km, resolution for operational land surface data assimilation, NWP and hydrological forecasts). In order to meet the accuracy requirements of SWE for the different states of the global snow cover, dual or multi-sensor approaches, including formation flying with existing and planned missions should be assessed through experimental campaigns and theoretical studies. This includes investigations of dual or even multi-frequency observables from lower frequency L-band systems to higher frequency Ka-band systems (including exploiting the interferometric phase and tomography techniques) for the determination of key snow and cryospheric parameters. The need of a new mission based on different techniques must be also evaluated. Airborne LiDAR data might provide an exceptionally valuable suborbital data source for Cal/Val and process studies of snow depth. Furthermore, a better integration of snow retrievals with physical and electromagnetic snow/soil models is required as well as coordinated field experiments on the representation of the snow microstructure and its evolution. Special attention should be paid to the development of robust algorithms on mountainous regions where retrievals are more challenging.

- **Snow albedo:** Reflectivity is the primary control of sunlight absorption, determining for example 80% of surface-melt energy for Greenland. Over terrestrial snow cover and sea ice, the amplitude of climate sensitivity to albedo is even higher than over land ice. Black carbon and other contaminants with their link to anthropogenic activities and their seasonality affect snow reflectivity and albedo increasing the complexity of the problem (see below). In this context, there is an urgent need for the development of a 'climate data record' of the global snow surface albedo. Observations from climate station networks, for example on Greenland (Steffen et al., 1996; Ahlstrøm et al., 2008; van de Wal et al., 2012) offer validation capabilities for albedo retrievals (e.g., Stroeve et al., 2014). But only satellite observations provide the spatial coverage needed to monitor albedo.

- **Snow density, grain size and impurities:** In addition to snow albedo, other key parameters of snow, such as density, grain size and snow impurities, play a major role in the snow interactions with energy and represent important elements to enhance the performance of models, and reduce uncertainties in the estimates of other snow parameters such as SWE and albedo. Snow density and grain size represent important inputs for the retrieval of SWE and play a significant role in determining the snow albedo. On the other hand, snow pollution and impurities (e.g., back carbon) is a major factor that affects snow melting and may link anthropogenic activities to snow melting rates in affected areas. In this context, there is a major need to develop advanced and robust methodologies to retrieve these parameters and develop dedicated EO-based products. The availability of Sentinel-3 with OLCI and SLSTR on-board may open new possibilities to retrieve snow grain size at medium spatial resolutions. Preliminary efforts exist to exploit SMOS L-band measurements to retrieve snow bulk densities, but further research is needed to advance existing approaches. Further research is also needed to develop novel approaches that may allow the estimation and monitoring of snow pollution.

- **Snow-vegetation interactions:** Changes in Arctic vegetation will have impacts on carbon, energy and water budgets. Tall vegetation masks the albedo of the underlying snow. Shrubs trap snow and increase soil temperatures by increasing insulation in winter but shade the surface and reduce soil temperatures in summer. Sentinel-2 and -3 will provide new characterizations of the spectral characteristics of Arctic land surfaces for monitoring of vegetation changes, complementing existing products at lower spatial resolutions from AVHRR and MODIS. EO applications for monitoring of vegetation changes in the Arctic should be addressed at the ESA-ESRIN EO and Biodiversity workshop.

4.6 Glaciers and ice caps (GICs)

On the global scale, methodological advances and better data availability have led to a reconciliation of mass loss estimates for the recent past (Gardner et al., 2013). These estimates include model results used to reconstruct century-scale mass loss of glaciers and ice caps (GICs) based on climate and documented glacier-length records. Such tests of the model using historic data improve the confidence in these long-term (or centennial?) estimates. There is also good agreement among different models used for projecting future GICs mass loss on a global scale.

However, this agreement on the global scale is partly due to cancellation of (in some places very significant) differences on regional scales; both of century-scale and short-term reconstructions, and also for projections. These differences occur between reconstruction approaches (model-based or observation-based), but also within each approach. The disagreement is generally largest in the Arctic (most notably Svalbard, the Russian Arctic, and northern Greenland).

Considering the relative contribution of glaciers to sea-level rise (approximately the same magnitude as ice sheets and thermal expansion), the scientific community trying to understand and quantify glacier mass changes is small and relatively weakly organized. Over the next few years, progress can be expected in a better understanding the cause of different model-based estimates from the CliC-sponsored Targeted Activity on Glacier Model Intercomparison (GlacierMIP). However, there is a substantial and fundamental lack of knowledge, and of data suitable to direct future research, concerning a number of key processes. These include, but are not limited to:

- calving dynamics that contribute affect a great fraction of the total drained glacier area in the Arctic, has the potential to strongly affect glacier mass balance, but are very poorly understood;
- processes related to density changes of snow and firn, such as percolation of meltwater and refreezing.

Further important knowledge and observational gaps related to glaciers and ice caps include:

- Consistent DEMs, i.e. DEMs representing a short defined time interval and covering substantial areas, for instance an entire archipelago;
- Long-term time series of glacier volume changes in order to reach time scales suitable for climate-related analysis (>30 yr);
- Long-term time series of glacier dynamics and coupling between dynamic variations and changes in calving and volume; (recent research has more and more stressed the importance of the dynamics of Arctic glaciers as a key factor behind mass changes);
- Short-term variations in ice flow, and in particular their relations to calving.

In this context, further efforts are required in order to:

- improve our observation capabilities to determine changes in elevation heights over small GICs. In this context, CryoSat-2 swath mode may bring additional benefits to current techniques increasing the number of observations and improving their resolution with respect to existing altimeter measurements;
- compile data from old airphoto flights as the only practical means to extent time series of glacier volume and position into the pre-satellite era;
- enable and coordinate systematic satellite optical stereo acquisitions for generation of repeat DEMs; (there is currently no scientific stereo mission, and no systematic scientific acquisition of such data);
- develop modern technologies to three-dimensionally co-register and combine heterogeneous multi-temporal elevation information towards consistent time series of glacier volume change (e.g., from airphoto flights, laser scanning, satellite altimetry, satellite stereo);
- exploit Sentinel-1 and -2 together for dense time series of glacier and calving dynamics, and couple these with observed volume changes;
- establish a consistent long-term data record of relevant EO datasets, especially to cover Arctic glaciers. Climate Change Initiative (CCI) and similar efforts are of great value to establish long-term data records of glacier information; and

- support the improvement of regional GICs mass balance models by model verification/validation /intercomparison and eventually assimilation of EO datasets. Efforts have been started to exploit CCI data. This should be further supported and encouraged.

4.7 Greenland ice sheet mass balance

The Greenland ice sheet mass balance represents a major research area in Arctic science. The results of the IMBIE 2012 experiments showed that the agreement between mass balance estimates from radar and laser altimetry, gravimetry and the input-output method is good both in Greenland and Antarctica. In combining the datasets, a 19-year time series of ice sheet mass balance from 1992 to 2011 was generated. Mass loss from the Greenland ice sheet accounts for two-thirds of the combined ice sheet loss in Greenland and Antarctica over this period (Rignot et al., 2011).

Mass loss from Greenland has increased over time. Rates of mass loss were modest during the 1990’s but have sharply accelerated since due to a roughly equal combination of speed-up of glaciers (Rignot and Kanagaratnam, 2006; Joughin et al., 2004) and decreased surface mass balance (van den Broeke et al., 2009; Ettema et al., 2009).

Continuing current efforts to monitor mass balance in Greenland (and Antarctica) as well as improving existing capabilities to reduce uncertainties in mass balance estimates is a major need.

In this context:

- Retrievals of accumulation rates over the ice sheets still represent a major gap in observations that impact corrections applied to satellite based methods; hence the uncertainty of mass balance estimates. Today, this information is provided by regional atmospheric climate models such as RACMO [Vernon et al., 2013]. Dedicated research efforts to develop reliable methods to estimate snow accumulation from satellites is therefore a major priority. Work has been carried out using passive microwave radiometry, scatterometry, and SAR imaging, mostly during the 1990s, to address this challenging problem from satellites. Since then, new sensor technologies and new parameter retrieval concepts have been developed and more detailed knowledge about snow/firn microstructure has been gained (e.g., MICROSNOW workshop in Reading/UK, August 2014, see EOS, Vol. 95, No. 47, 25 November 2014) that should be exploited to develop novel retrieval techniques. For instance, (polarimetric) SAR images (e.g., reveal variations of intensity and polarimetric parameters that are related to changes in snow/firn microstructure) need to be considered in algorithm retrieval. Ground data used for validation and for establishing empirical relationships need to be critically re-assessed. Another major challenge is to include environmental processes (e.g., wind conditions) into the retrieval procedures.

- Better estimation of (snow) penetration depth of the radar altimeter signal is required, accounting for the spatial variability and difference in penetration depth in snow/firn. In this context, a firn-coring campaign is suggested in order to estimate penetration depths by airborne radar (e.g., IceBridge) and *in situ* measurements. Moreover, the potential of satellite altimetry for detecting snow and firn layers and relate them to accumulation rates should be further investigated. Snow penetration needs also to be known for improving the retrieval of accumulation rates and firn properties using side-looking imaging radars, scatterometers, and passive microwave radiometry.

- CryoSat-2 offers new capabilities to address ice sheet mass balance studies. It provides greatly enhanced coverage, compared to conventional altimetry, of the marginal areas of the ice sheet where the largest elevation changes are taking place (Helm et al, 2014). The further development and use of CryoSat-2 swath mode shows great potential to overcome some of the limitations of traditional altimetry. Current efforts to develop new products that may complement existing ones (i.e. high resolution surface elevation changes, and position and ice thickness of the grounding line) exploiting swath mode capability (e.g., overcoming difficulties to apply it over flat terrains) should be further supported and applied over larger areas in a more systematic manner:

- As in the case of sea-ice, also for ice sheet mass balance studies, continuation of high-resolution radar altimetry (CryoSat-2) with an overlap with satellite-based laser altimetry or a future mission combining both types of sensors represents a major requirement to address several important scientific gaps (e.g., quantification of variable snow pack penetration of radar altimeters, detection of surface height changes, improved mass balance studies, detection of active sub-glacial lakes and possibly sub-glacial water routing).
- The potential of Sentinel-1 Terrain Observation with Progressive Scans (TOPS) mode for grounding line (GL) detection needs to be further developed and validated. Comparison of results needs to be done with historical products in order to evaluate how well the current GL detection methods work with Sentinel-1.
- Sentinel-3 OLCI and Sentinel-2 offer valuable capabilities retrieving snow covered area on glaciers, snowline position, surface albedo, all of fundamental importance supporting surface mass balance monitoring and modelling.

- Glacial Isostatic Adjustment (GIA) is one of the major uncertainties in climate modelling and estimates of the sea level rise. Better GIA estimates are needed, both from forward and inverse approaches, as currently large uncertainty exists at the global scale. Current GIA estimations are inconsistent with each other (e.g., there is a 100 Gt difference between all mass balance solutions, depending on the GIA model used) (reference). A combination of available models is sometimes used but the significant spatial variability is being disregarded. In this context, the integration with GPS measurements is required to constrain models. Simulated Moving Bed

(SMB) model corrections are still under development and currently it is difficult to correct geodetic techniques.

- For future mass balance estimates, improved integration between modelling and observations is required. Future research should be focused on combining different data sources (e.g., spaceborne, airborne and ground observations in synergy with models) in an integrated manner. Integrated retrieval schemes (e.g., based on model inversions) that exploits different data source available in a synergistic manner may further reduce the uncertainties in the final mass balance estimates and, importantly, provide more detailed information on the causes and origin of the changes observed (Schoen et al., 2015). Another major challenge is to include environmental processes (e.g., wind conditions) in the retrieval procedures, in particular in conjunction with accumulation rate retrievals.
- Future research should also focus to foster the use of EO based products into ice sheet models for model verification and data assimilation for reanalysis and forecast.
- A better understanding of year-to-year variations of ice flow speed is needed for mass balance studies and ice sheet dynamics, as well as ice-ocean interactions.
- Studies focusing on the enhancing GRACE resolution and GOCE/GRACE combinations represent a value added to current efforts to enhance mass balance estimates over small basins and are meant to understand how to continue with similar missions in the future.
- For Greenland, the detection/observation of supraglacial melt ponds and streams is a priority area that may increase our ability to better characterise ice sheet dynamics and ice-ocean interactions. Greenland has internal collection of meltwater, with roughly 50% being stored in the ice and the other 50% flowing out. In this context, a P-band radar may be an option to monitoring these flows (near-surface aquifers over winter and its possible penetration of surface meltwater to ice-sheet bed).

4.8 Other general key messages

- **Supersites:** A topic that was raised several times during the meeting is the need for an enhanced and systematic acquisition of *in situ* data and airborne measurements collocated simultaneously with satellite data. The creation of a network for Arctic supersites ensuring coordination of co-located *in situ*, airborne and satellite observations is a need in order to support basic science as well as satellite observations and Cal/Val activities. The identification and implementation of a number of supersites (as key regions) for land ice masses, sea ice, ocean and permafrost monitoring for continuous monitoring of different parameters and processes as well as to support the development and validation of novel satellite observations and products will represent a major advancement to ensure a solid basis for science and research. A potential definition for a supersite in the Arctic context may be:

i) a region of significant changes that can be related to key Earth system processes and environmental/climate changes;
ii) the region offers the opportunity to study the interactions between local processes and regional or Arctic wide processes, and to develop corresponding modeling/simulation tools;
iii) an infrastructure for systematic ground measurements is available or can be established; and/or
iv) the region is of interest for different scientific disciplines (e.g., ice shelves for glaciology, sea ice research, oceanography; polynyas for sea ice research, boundary layer meteorology, biology, oceanography)

Some candidate regions to be considered include Svalbard, Greenland inland where Denmark supports since 2007 a network of 20 on-ice sheet observing stations (http://promice.org), or the Canadian High Artic (e.g., Alert, Eureka, Resolute, or the upcoming Canadian High Arctic Research Station (CHARS) in Cambridge Bay).

The planned Svalbard Integrated Arctic Earth Observing System (SIOS, http://www.sios-svalbard.org) can be regarded as a very advanced infrastructure for research in and around Svalbard. The center provides remote sensing data from Fram Strait and east of Greenland. Despite the lack of ground observations, East Greenland is a region that undergoes significant environmental changes that need to be investigated and features a large expanse of stationary fast ice which is ideal for satellite sensor inter-comparison studies (Hughes et al., 2011) as, like a supersite on land, it removes the issue of changing target geometry that occurs when performing studies over drifting sea ice. Ideally, processes would be investigated at a small scale and then be transferred to a larger scale.

The High Arctic is an interesting potential region also because the Greenland ice sheet is currently the single largest source of sea-level rise (Colgan et al., 2015).

- **Near Real-Time Observations:** It was suggested that minimum latency on generating satellite products would be of great benefit. The scientific community demands *near real-time* in order to be able to monitor ongoing events in a timely fashion (a few hours from acquisition).

- **Enhancing predictability in the Arctic:** Over the next several years, attention will be focused on this through the WCRP Polar Climate Predictability Initiative and the WWRP Polar Prediction Initiative, which is stimulating the "Year of Polar Prediction (YOPP) in 2017-18" – with some large Arctic drifting ice camp (Mosaic), icebreaker, and augmented *in situ* measurements. The YOPP will be supported trilaterally by the EU, US and Canada, and the collection of space agencies in the WMO Polar Space Task Group. There is a significant potential to link existing ESA efforts and planned R&D activities to this initiative (e.g., assimilation of CryoSat-2/SMOS NRT thickness) and newly tailored Sentinel products (e.g., albedo or ice surface temperature products from Sentinel-3 and Sentinel-2).

It is worth noting that, in the near future, ESA's contribution to improved polar prediction will also come naturally as part of operational improvements coming from ECMWF assimilation of new wind profile info, from ADM-Aeolus and the aerosol, cloud (cloud phase), and radiation constraints provided by EarthCARE.

- **Reinforcing the exploitation of EO long-term consistent datasets by the modeling community** is a major requirement not only for the validation/verification and potential enhancement of model parameterizations, but also to foster data assimilation and improving model predictability in consistency with observations. Advancing in this direction is a prerequisite to establish a solid scientific basis for potential future information services (e.g., dedicated climate services for the Arctic). This requires dedicated efforts to:

    i) ensure the development of long-term consistent EO-based records of essential variables with a proper uncertainty characterization and error structure information covering a wide variety of parameters and adapted to modelers needs. GCOS Essential Climate Variables (ECVs) are a clear example for that and ESA's CCI initiative is advancing in this direction. Ideally, time-dependent and space-dependent uncertainties should be provided. It is also important to account for the spatial correlation of errors;
    ii) support modeling efforts of model validation/verification/ intercomparison in view of maximizing model consistency with observations, validate model parameterizations and enhance model consistency with observations;
    iii) further advance in the development of data assimilation schemes for different types of EO-datasets (e.g., addressing key issues such as bias correction, observation operator) and testing the impact of different data streams in models; and
    iv) ensure a sustained dialogue between the EO and the modeling community as a prerequisite to advance in this direction;
    v) Maintain and reinforce the open data access and promote data sharing as a best practice to support science;

- **Creating an Integrated Observing System for Arctic-Land Products** has potential to address the needs of several communities (e.g., LST, snow cover, SWE, high-resolution LC and LCC, subsidence maps, inundation/wetlands/water bodies and dynamics, lake and river ice, lake-water temperature).

- This concept can be extended to the full Arctic under an **Integrated Arctic Observing System**, as a component of the GEOSS, serving different scientific and operational communities. Current and planned polar-orbiting EO spaceborne missions (e.g., MetOp, CryoSat-2, Sentinel-1A and upcoming Sentinel missions) are and will be providing important datasets and services addressing the above scientific challenges. However, the demand for better detail and timeliness of information requires enhanced monitoring capabilities for the polar regions. These services are also needed to support assessments such as those conducted by the Arctic Council's AMAP and to implement the Arctic Council and IASC initiative on Sustaining Arctic Observing Networks (SAON). As such, the concept of integrated observing systems shall be developed not exclusively based on spaceborne data but rather integrating different types of information: *in situ*, airborne and other datasets, derived from different techniques and sources, collected and combined in a coordinated manner in order to address informational needs. These datasets can be integrated to obtain a more complete and comprehensive picture of the Earth system and underlying processes that would be beyond the capabilities of single satellite missions.

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